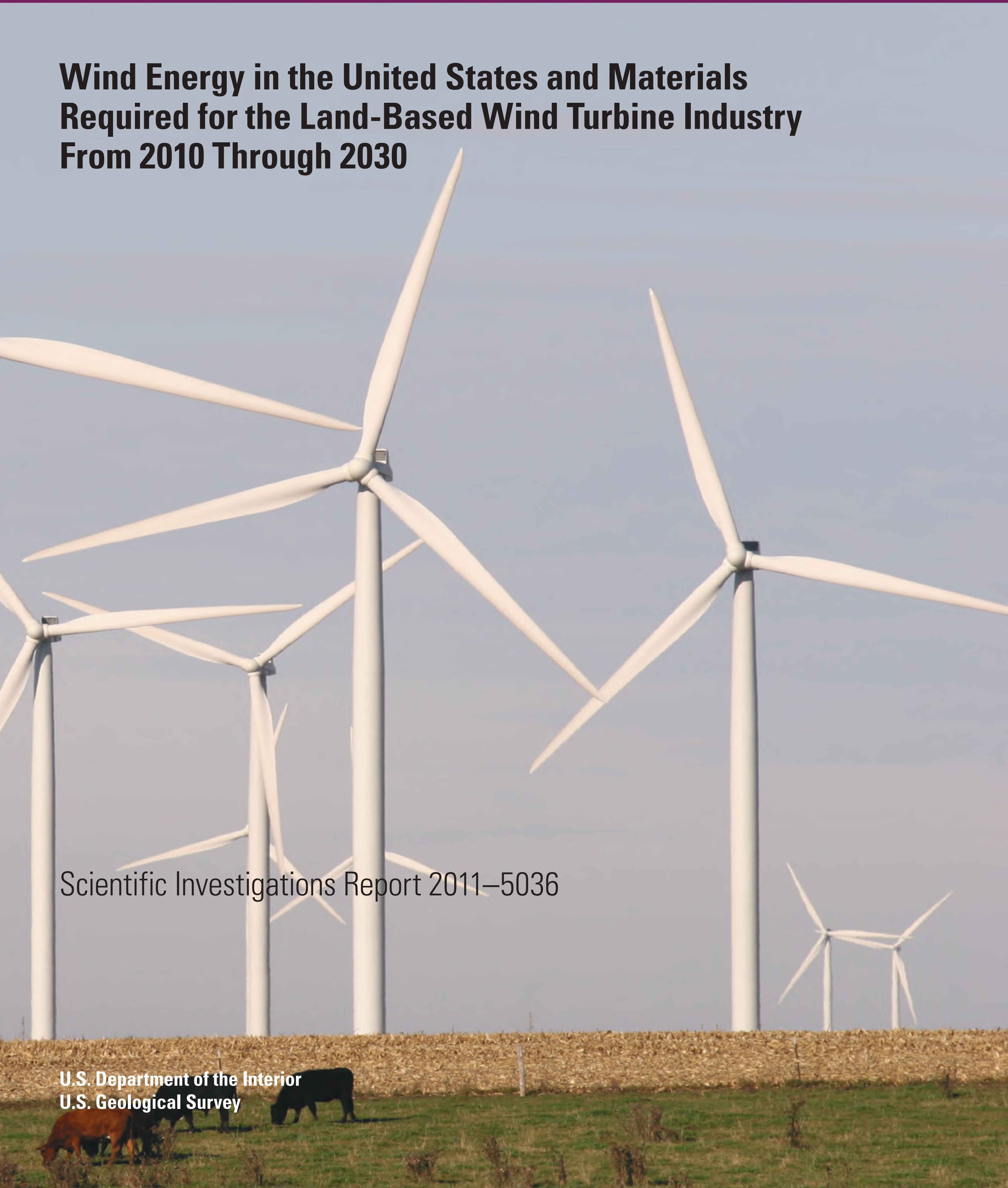

Wind Energy in the United States and Materials Required for the Land-Based Wind Turbine Industry From 2010 Through 2030

Scientific Investigations Report 2011–5036

U.S. Department of the Interior
U.S. Geological Survey

Cover. Photograph of the Twin Groves wind farm in McLean County, Ill., by Guenter Conzelmann, Argonne National Laboratories.

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KEN SALAZAR, Secretary

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Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2011

Suggested citation:
Wilburn, D.R., 2011, Wind energy in the United States and materials required for the land-based wind turbine industry from 2010 through 2030: U.S. Geological Survey Scientific Investigations Report 2011–5036, 22 p.

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Conversion Factors

Multiply	By	To obtain
	Area	
square meter (m^2)	0.0002471	acre
hectare (ha)	2.471	acre
	Mass	
kilogram (kg)	2.205	pound avoirdupois (lb)
megagram (Mg) or metric ton (t)	1.102	ton, short (2,000 lb)
	Energy	
watt (W)	0.00134	horsepower (HP)

Wind Energy in the United States and Materials Required for the Land-Based Wind Turbine Industry From 2010 Through 2030

By David R. Wilburn

Abstract

The generation of electricity in the United States from wind-powered turbines is increasing. An understanding of the sources and abundance of raw materials required by the wind turbine industry and the many uses for these materials is necessary to assess the effect of this industry's growth on future demand for selected raw materials relative to the historical demand for these materials. The U.S. Geological Survey developed estimates of future requirements for raw (and some recycled) materials based on the assumption that wind energy will supply 20 percent of the electricity consumed in the United States by 2030. Economic, environmental, political, and technological considerations and trends reported for 2009 were used as a baseline. Estimates for the quantity of materials in typical "current generation" and "next generation" wind turbines were developed. In addition, estimates for the annual and total material requirements were developed based on the growth necessary for wind energy when converted in a wind powerplant to generate 20 percent of the U.S. supply of electricity by 2030.

The results of the study suggest that achieving the market goal of 20 percent by 2030 would require an average annual consumption of about 6.8 million metric tons of concrete, 1.5 million metric tons of steel, 310,000 metric tons of cast iron, 40,000 metric tons of copper, and 380 metric tons of the rare-earth element neodymium. With the exception of neodymium, these material requirements represent less than 3 percent of the U.S. apparent consumption for 2008. Recycled material could supply about 3 percent of the total steel required for wind turbine production from 2010 through 2030, 4 percent of the aluminum required, and 3 percent of the copper required. The data suggest that, with the possible exception of rare-earth elements, there should not be a shortage of the principal materials required for electricity generation from wind energy. There may, however, be selective manufacturing shortages if the total demand for raw materials from all markets is greater than the available supply of these materials or the capacity of industry to manufacture components. Changing economic conditions could also affect the development schedule of anticipated capacity.

Introduction

As the amount of electricity generated from wind power increases, an understanding of the materials associated with the construction, transportation, installation, operation, decommissioning, and disposal of large wind powerplants[1] (also referred to as wind farms) is essential. The analyses in this report provide policymakers and the public with an overview of factors currently and potentially affecting raw material requirements for land-based wind turbines. As the wind turbine industry modifies turbine designs, the demand for selected materials will also change. This study complements ongoing work by the U.S. Geological Survey (USGS) to evaluate the supply of raw materials available for established and emerging renewable energy technologies being implemented in the United States.

Historical Perspective

A wind-powered energy system transforms the kinetic energy of the wind into mechanical or electrical energy that is harnessed for practical use. Simple windmills were used to pump water in China before 200 B.C. By the 11th century AD, people in the Middle East were using windmills for grinding grain. Merchants returning from the East Indies brought knowledge of windmill technology to Europe, where the Dutch adapted it for driving pumps to remove water from lowland areas. Windmills were introduced to the New World in the 18th century and were used to pump water and grind grain for rural farms and ranches. Wind-driven turbines (wind turbines) are much larger devices that came into use in the

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[1] For the purposes of this report, the term wind powerplant has been used to designate a group of wind turbines interconnected to a common power provider system through a system of distribution lines, substation(s), and transformers. In Europe, the equivalent is known as a generating station.

United States after World War II to generate electricity for houses, businesses, and utility companies.

Technological advancements in the use of wind energy to produce electricity accelerated in the 1970s as one consequence of the Organization of Petroleum Exporting Countries oil embargo of 1973, which generated high fuel prices and stimulated research to find alternatives to nonrenewable sources of energy, such as coal, gas, and oil. The Solar Energy Research Development and Demonstration Act of 1974 led to increased research and development of renewable energy sources; as the costs of competing nonrenewable fuel sources increased, environmental concerns also increased, but so, too, did interest in achieving energy independence and securing sources of supply. The Solar Energy Research Institute (SERI) began operating in 1977. After SERI was consolidated with the Rocky Flats Wind Test Center and research was expanded to include wind energy in 1991, the facility, located in Golden, Colorado, was designated a national laboratory and named the National Renewable Energy Laboratory (NREL).

In the United States, Federal and State investment and production tax credits offered during the 1980s, 1990s, and early 2000s further stimulated the development and use of renewable resources. Other countries also provided incentives for renewable energy development. By 1985, first-generation wind-driven electrical generators were developed with an average rating of 100 kilowatts (kW) (American Wind Energy Association, 2009a, p. 5). A combination of research and development, along with experience gained through deployment of this early technology, has led to larger, lower cost, and more efficient second-generation wind turbines. In 2006, the President endorsed the Nation's need for greater energy efficiency and independence and a more diversified energy portfolio. This led to a collaborative research effort by the U.S. Department of Energy (DOE), Black & Veatch Corporation, and the American Wind Energy Association (hereafter referred to as the DOE wind study) to develop a strategy to increase the contribution of wind energy to the U.S. electrical supply to 20 percent by 2030 (U.S. Department of Energy, 2008, p. 1). Most recently, the American Recovery and Reinvestment Act of 2009 extended the Federal production tax credit for wind energy through 2012.

Description of a Typical Wind Turbine

Wind turbines consist of three principal components, the nacelle, rotor, and tower (fig. 1). The nacelle compartment is connected to the rotor hub by a shaft and contains the generator, gears, and controlling mechanisms that maximize energy collection and conversion. The rotor, usually consisting of three wing-shaped blades connected to a central hub, converts the kinetic energy of the wind into rotational energy. The tower, including the supporting foundation, provides the height necessary to access the wind resource and the conduit required to transfer the turbine-generated electricity to the collection system of the wind powerplant where electricity from all wind turbines is often fed to the power grid.

Although wind turbines come in many sizes and configurations and are constructed from a wide range of

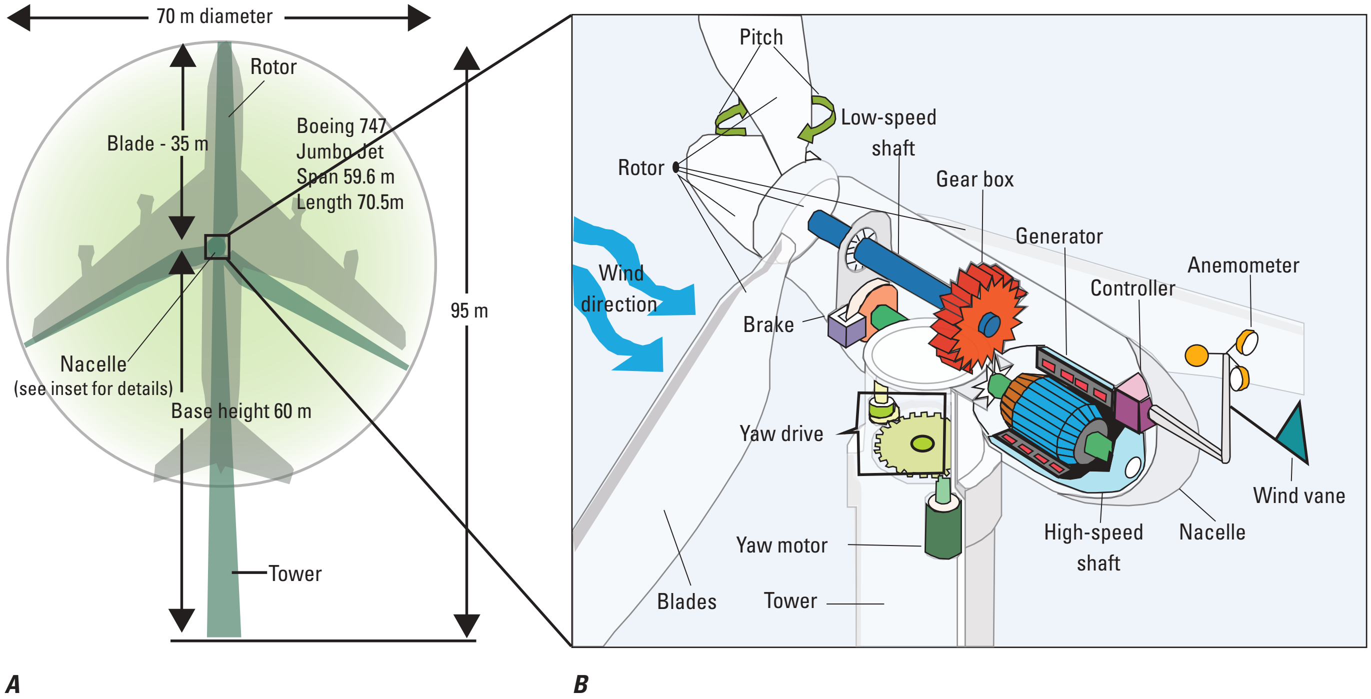

Figure 1. Diagrams of (*A*) a typical large wind turbine and (*B*) major components.

materials, most commercial-utility-scale turbines have installed generator nameplate capacity ratings of 1 to 3 megawatts (MW). The average nameplate capacity of the 3,190 wind turbines installed in the United States during 2007 was 1.65 MW; similarly, the average nameplate capacity of the 5,029 wind turbines installed in 2008 was 1.66 MW, and the average nameplate capacity of the 5,734 wind turbines installed in 2009 was 1.74 MW (Wiser and Bolinger, 2010, p. 26). Utility-scale turbines typically have tower heights ranging from 45 to 105 meters (m), rotor diameters from 57 to 99 m, and rotor blades from 27 to 45 m. The 1.5-MW turbine on an 80-m tower is the most widely used onshore wind turbine, accounting for more than 50 percent of the utility-scale units installed in 2008 in the United States (Wiser and Bolinger, 2009). Most utility-scale turbines are installed in arrays of 30 to 150 units; when these units provide power to the utility grid as a single source of electricity, they are collectively termed a wind powerplant or wind farm. A typical utility-scale 1.5-MW wind turbine has the capacity to generate about 3.4 million kilowatthours per year (kWh/yr) of electricity, equivalent to the annual electrical requirement of 300 households, assuming an individual household use of 11,300 kWh/yr (Saint Francis University, 2007; U.S. Energy Information Administration, 2008). Table 1 shows several historical estimates of the total capital cost as a percentage of the initial capital investment for components of a typical 1.5-MW wind turbine.

Table 1. Estimates of the costs for components of a typical 1.5-megawatt wind turbine.

[Estimates are expressed in terms of the percent of total capital cost of a wind turbine. Inc., included in reported subtotal for component; NA, not available; XX, not applicable]

Component	Part	NAICS[1] code	Cost (percent)[2]				
Reference year			**2001[3]**	**2002[4]**	**2003[3]**		**2009[5]**
Rotor	Blade	326199	20–30	14.1	28	16.6	22.2
	Blade extender	331511	Inc.	NA	Inc.	NA	NA
	Hub	331511	Inc.	4	Inc.	7.2	1.37
	Pitch drive	335312	Inc.	3.9	Inc.	4	2.66
	Subtotal	**XX**	**20–30**	**22**	**28**	**27.8**	**26.23**
Nacelle (excluding drivetrain machinery)	Case	326199	Inc.	1.9	Inc.	1.9	1.35
	Frame	331511	Inc.	8.6	Inc.	3.8	2.8
	Anemometer	334519	Inc.	NA	Inc.	NA	NA
	Brakes	333613	Inc.	0.3	Inc.	0.6	1.32
	Controller	334418	Inc.	3.2	Inc.	3.4	NA
	Convertor	335999	Inc.	5.55	Inc.	2.5	5.01
	Cooling system	333412	Inc.	1.7	Inc.	0.3	NA
	Sensors	334519	Inc.	Inc.	Inc.	0.8	NA
	Yaw drive	335312	Inc.	1.85	Inc.	1.8	1.25
	Subtotal	**XX**	**25**	**21.2**	**22**	**15.1**	**11.73**
Drivetrain components (contained in the nacelle)	Shafts	333613	Inc.	1.9	Inc.	2.3	1.91
	Bearings	332991	Inc.	1.1	Inc.	1.3	1.22
	Couplings	333613	Inc.	NA	Inc.	0.7	0.96
	Gear boxes	333612	10–15	14.1	17.3	13.4	12.91
	Generators	333611	5–15	9.1	7	6.7	3.44
	Subtotal	**XX**	**20–30**	**26.2**	**24**	**24.4**	**20.44**
Tower	Tower	332312	10–25	13.6	26	20.6	26.30
	Tower flange	331511	Inc.	NA	Inc.	NA	1.04
	Tower foundation	238110	Inc.	4.25	Inc.	5.4	Inc.
	Power electronics	335999	Inc.	11	Inc.	6.7	3.59
	Subtotal	**XX**	**10–25**	**28.9**	**26**	**32.7**	**30.93**

[1] North American Industry Classification System (NAICS) as reported by the NAICS Association.

[2] Percent of total capital cost for a typical turbine with blades 45.3 meters in length and a tower 100 meters in height.

[3] Data are from Sterzinger and Svrcek (2004). [4] Data are from Fingersh and others (2006). [5] Data are from European Wind Energy Association (2009).

Profile of Electricity Generation in the United States From Wind Power

Wind power is the conversion of wind energy into a useable form, such as electricity. The electricity-generating capacity of wind power contributed about 1.3 percent of the total U.S. electricity supply in 2008 and 1.8 percent in 2009 (American Wind Energy Association, 2010a, p. 5–6). For comparison, coal was the source for 45 percent of U.S. electricity supplied in 2009; natural gas, 23 percent; nuclear power, 20 percent; and hydroelectric power, 7 percent. The electricity-generating capacity of wind power contributed less than 2 percent of the new electricity-generating capacity in the United States in 2004, but accounted for 42 percent of newly commissioned capacity in 2008 and 39 percent in 2009 (Wiser and Bolinger, 2010).

The annual electricity-generating capacity of the United States from wind power increased from 2.5 gigawatts (GW) in 2000 to more than 35 GW in 2009 (American Wind Energy Association, 2010a), an average annual growth rate of about 23 percent (fig. 2). The top 10 States for generating electricity from wind turbines in 2009 were, in descending order, Texas, Iowa, California, Washington, Oregon, Minnesota, Illinois, New York, Colorado, and North Dakota.

Wind energy is generally considered to be abundant but highly variable, and production capacity varies widely from State to State. Many factors must be considered when determining the site for a wind powerplant. A thorough understanding of the dynamics of the wind available to the project is one necessary component contributing to the economic success and production efficiency of a wind power project. Accurate estimates of wind direction, distribution, duration, gradient, and speed are essential to the proper location of a wind powerplant. Areas with average annual wind speeds at or greater than 23.4 kilometers per hour (14.5 miles per hour) at an 80-m height above the ground (the height of a typical wind turbine rotor) are generally considered to have a suitable wind resource for possible development (U.S. Department of Energy, 2009, p. 1). The DOE has published wind maps by State showing areas with a gross wind capacity factor (without losses) at an 80-m height above the ground that may be suitable for wind power generation. Statewide estimates of the potential capacity in megawatts that could be installed and the annual energy in megawatthours that could be produced from the capacity estimates are provided. From these and other data sources, utilities and other developers initiated projects so that, by 2009, 14 States had an installed capacity of more than 1,000 MW each, and 36 States had operational utility-scale wind projects (American Wind Energy Association, 2010a, p. 3).

An increasing number of foreign wind turbine manufacturers are supplying the U.S. market, and an increasing number of foreign manufacturers have established

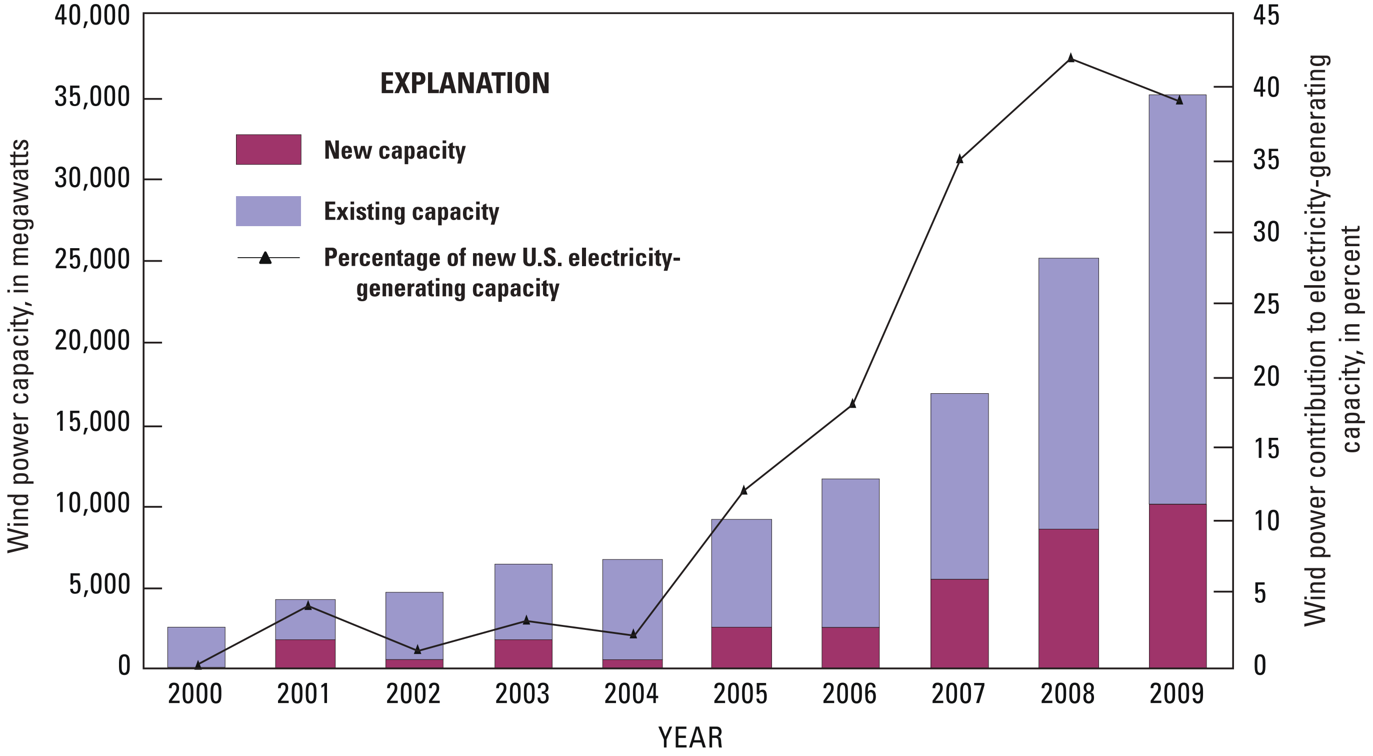

Figure 2. Graph showing the growth of the U.S. wind power industry in terms of electricity-generating capacity and the contribution of wind turbines to new U.S. electricity-generating capacity. Data are from American Wind Energy Association (2010).

manufacturing facilities in the United States. Six of the top 10 global utility-scale wind turbine manufacturers have a U.S. manufacturing presence. More than 70 manufacturing facilities for wind turbine components were opened, expanded, or announced from 2007 through 2008, 13 were opened or expanded in 2009, and 21 more were planned for production by the end of 2010 (David, 2009b). Nearly 50 percent of the components used in wind turbines installed in 2009 were manufactured in the United States, an increase from less than 30 percent in 2005 (American Wind Energy Association, 2010b; Wiser and Bolinger, 2010). In 2009, 10 manufacturing facilities of rotors or blade components were opened or planned by original equipment manufacturers (OEMs; 60 percent) or suppliers (40 percent), 11 nacelle manufacturing component facilities were opened or planned by OEMs, 15 tower component manufacturing facilities were opened by suppliers (87 percent) or OEMs (13 percent), and 2 miscellaneous component plants were opened or planned by suppliers (David, 2009b).

The utility industry uses the capacity factor as a measure of rating a powerplant's performance in terms of its actual electrical production over a period of time compared with the amount of electricity the plant would have produced if it had been operating at full capacity for the same period. The capacity factor for a fossil fuel-powered electricity-generating plant typically ranges from 40 to 80 percent, operating most of the time unless it is idled by equipment problems or scheduled maintenance. A wind powerplant, however, operates when the wind is blowing, and it operates at less than nameplate capacity when the wind is blowing less than the wind speed for which the plant turbines are rated. Although modern utility-scale wind turbines typically operate 65 to 90 percent of the time, turbines installed in 2009 had capacity factors ranging from 15 to 45 percent (Wiser and Bolinger, 2010). The performance of a wind turbine is dependent on turbine design and wind characteristics, so variation occurs based on project location and turbine vintage. Since 1999, the megawatt capacity of wind turbines has been increasing, which can be attributed primarily to increasing hub heights and larger rotor diameters relative to nameplate capacity (Wiser and Bolinger, 2010).

Another measure of wind plant efficiency is the availability factor—the percentage of time the wind-powered plant is available to generate electricity. Because modern wind turbines require limited maintenance, wind turbines have an availability factor of more than 98 percent, if times when the wind is not blowing at a level sufficient to generate electricity are not taken into account. The availability factor for wind turbines is higher than for many other types of powerplants (Canadian Wind Energy Association, 2009).

A wind turbine that is found to be efficient and economical from a technical standpoint in one location may not be in another location because of variation in the characteristics of wind resources at each location. Consequently, the cost effectiveness of a specific wind generator system depends on effectively pairing the correct turbine design with the characteristics of the wind at a site (Herbert and others, 2007).

Much has been reported about the advantages and disadvantages of wind energy as a source of electric power when compared with other renewable and nonrenewable power sources, including cost and the demand for raw materials. Table 2 summarizes arguments commonly cited for or against increased use of wind turbines as a source of electricity generation in the United States. In general, wind energy has been considered by many to be abundant, renewable, ecofriendly, and increasingly economically competitive with other energy sources. Disadvantages cited for wind energy include a high initial capital cost, the possible disruption in the supply of construction materials, a large land requirement, resource variability, and environmental characteristics related to aesthetics, bird hazard, and noise.

Life Cycle of a Wind Turbine

Life cycle assessments of wind turbines have been used by the USGS to estimate and compare energy and mineral and (or) material resource requirements from various sources. Detailed assessments of the life cycle of utility-scale wind turbines have been conducted, including assessments by Elsam Engineering A/S (2004), Nalukowe and others (2006), U.S. Department of Energy (2008), and Vestas Wind Systems A/S (2006a,b), so only background information and their most significant findings as they relate to industry requirements for minerals and materials are reported here.

The life cycle of a wind turbine can be divided into the following five phases:

- construction—the acquisition of all raw materials and the production of components that make up the wind turbine, as well as ancillary materials necessary for site development
- transportation—the equipment and supplies necessary to transport the raw materials from extraction, processing, fabrication, and manufacturing facilities; the transport of manufactured components to the site of the wind powerplant; and the transport of maintenance supplies and replacement parts during turbine operation
- installation—erecting the wind turbine onsite and connecting the turbine to other turbines at the powerplant and to the electrical energy grid
- operation—the operation and maintenance of the utility-scale turbine during its expected operating life of 20 to 30 years; a turbine can be refurbished to extend its lifespan by an additional 15 years or more, making the expected operating life of a wind turbine comparable to the 30 to 50 years for coal-generated powerplants and 40 to 50 years for nuclear powerplants
- decommissioning and disposition—dismantling the turbine and the subsequent disposal of its components; this phase includes the transport of equipment to recycling or remanufacturing facilities or to landfills

Table 2. Principal advantages and disadvantages of wind power.

[Sources: American Wind Energy Association (2009e), U.S. Department of Energy (2010), *Windturbinesnow.com*, *Windustry.org*, Wiser and Bollinger (2010)]

Advantage	Disadvantage
Wind power is becoming increasingly cost competitive with other power-generation sources.	The initial capital cost of a wind power plant is substantial, with installed costs ranging from $900 to $2,500 per kilowatt.
The unit cost of wind power is likely to decrease relative to other energy sources as wind production increases and fossil fuel costs increase.	As of 2009, the life cycle cost of onshore wind power (including capital and operating costs) is higher than the life cycle cost of fossil fuels.
Wind power is abundant, widely available, indigenous, and not subject to long-term disruption of supply.	Wind power is variable and often located in rural areas far from demand; thus transmission and transportation distances are long.
Wind power plants can be sited to be compatible with other rural land uses such as farming or cattle ranching. Lease royalties can provide supplemental income to landowners.	Large areas of land are required for wind power plants. The land often cannot be utilized productively during construction or decommissioning.
Wind energy is renewable and has many environmental benefits, has a smaller environmental footprint than other fuel sources, and does not emit materials harmful to humans or the environment.	Concerns about the environmental effects on birds, electronic signals, noise pollution, and long-term storage need to be evaluated. Also, large wind power plants are considered by some to be aesthetically displeasing because of turbine size and the possible restriction of scenic views.
Wind power plants can be granted a permit and built more quickly than a conventional power-generation plant.	Permitting times vary from State to State, depending on local ordinances and State regulatory policies.
Once constructed, the overall "footprint" for wind- generated electricity is relatively small. It does not pose mining or security issues. The construction phase accounts for about 80 percent of emissions. The consumption of fossil fuels and water during the production phase is low compared with other power sources. Greenhouse gas emissions are low in comparison with most other sources of power.	The consumption of fossil fuels and water during construction and decommissioning can be significant. Transportation of oversized equipment can be expensive and hazardous. Although energy storage issues have yet to be solved, recent studies suggest that wind-generated electricity could supply more than 20 percent of the U.S. demand without the need for energy storage.
In anticipation of increased demand for products associated with wind power, manufacturers are constructing domestic facilities in support of the U.S. wind power generation industry, creating new jobs and increasing the local tax base for communities.	Wind power currently requires the manufacturing of large pieces of equipment from foreign sources. As demand increases, supply disruptions of selected equipment and materials may occur if manufacturing or supply capacity can not keep up with anticipated demand for these materials.

Data collected by Vestas Wind Systems A/S in 2006 for its 1.65-MW and 3-MW onshore wind turbines summarizes resource consumption estimates per kilowatthour produced for significant fuel, mineral, and freshwater resources (Vestas Wind Systems A/S, 2006a,b), when considering the entire life cycle of a wind turbine. Table 3 lists estimates of the lifetime consumption of selected materials that are required for processes associated with generating electricity from two sizes of wind turbines. These estimates include the resources used in raw material extraction, component manufacturing and transport, wind turbine installation and operation, and decommissioning and disposal of turbine components at the end of their life cycle. For wind turbines, the lifetime consumption of water and fossil fuels is low when compared with other energy sources (U.S. Department of Energy, 2005).

Life cycle assessments provide data on emissions and the environmental burden associated with electricity-generation from various sources. Although a detailed analysis is beyond the scope of this study, a 2007 compilation of onshore wind turbine data by the European Wind Energy Association suggested that the overall environmental footprint for wind-generated electricity is relatively small when compared with other sources of energy and that the construction and initial transport phases account for about 80 percent of total lifetime wind turbine emissions (European Wind Energy Association, 2007). A brief discussion of emissions rates for selected energy sources is provided in appendix 1.

Transportation Logistics

Costs and logistics associated with transportation can represent obstacles to establishing wind powerplants. The rapid growth of the wind turbine industry has contributed to transportation and logistics challenges for manufacturers and developers that can also cause delays in turbine development, namely the short-term availability of equipment large enough to manufacture, transport, and erect these large components, and the local availability of experienced personnel to manufacture, construct, and operate this equipment. Because

Table 3. Lifetime resource consumption per kilowatthour produced for representative onshore wind turbines in Europe.

[Source: Vestas Wind Systems A/S (2006a,b). MW, megawatt; g/kWh, grams per kilowatthour]

Turbine size	1.65 MW	3 MW
Resource	Consumption estimates, in g/kWh	
Water (fresh)	38	51
Stone	3.6	3.5
Hard coal	1.1	0.64
Quartz sand	0.12	0.59
Crude oil	0.71	0.54
Natural gas	0.53	0.42
Lignite	0.23	0.34
Limestone	0.33	0.10
Rock salt	0.14	0.08
Clay	0.05	0.05

component sections are large and heavy, they are difficult to transport and require special handling. Wind turbines are often located in remote areas distant from major transportation hubs. The cost of transportation and erection is therefore expensive, and the cost of routine maintenance and unscheduled repairs can be higher than for facilities located near urban areas. Efforts are ongoing to develop tower configurations that are less costly and more easily transported and installed. Tower research includes onsite tower fabrication, self-erecting tower technologies, slip-formed concrete bases, and truss tower sections (Thresher and Laxson, 2006).

A single turbine may require eight to ten hauls to deliver the components (one nacelle, one hub, three blades, and three to five tower sections) to the site of the wind powerplant. When one considers that about 8,500 MW of wind-powered capacity was installed in 2008, this new construction likely required more than 40,000 transportation hauls during the year (American Wind Energy Association, 2009d). As more turbine components are manufactured in assembly plants in States with favorable wind profiles, the capital cost of wind powerplant construction has decreased by reducing the distance the wind turbine components must be transported.

Recent Technological Advancements

Wind turbine research continues to focus on identifying the most efficient and cost effective combinations of turbine design and energy capture by refining component design to incorporate stronger, lower cost materials while achieving high-volume production rates and maintaining or improving efficiency. Research is focusing on using lighter weight components in blades and towers. Larger wind turbines tend to have larger and heavier components. Gearboxes and brushings are expensive and historically have required frequent maintenance or replacement. Research into smaller, multiple-drive generator-and-drivetrain configurations may reduce the cost, maintenance, and size of gearboxes. Research suggests that the use of direct-drive permanent magnet generators, which eliminate the gearbox and thus the need for frequent maintenance, may be advantageous in remote areas where maintenance costs are expensive. Recent technology trends have been summarized in table 4 for the principal wind turbine components.

In 2008, the DOE wind study (U.S. Department of Energy, 2008) determined that reaching a 20 percent market share from wind energy by 2030 was achievable, although the researchers noted several challenges to achieving this goal (David, 2009a; U.S. Department of Energy, 2010), including the following:

- continued efforts to make wind turbines cost competitive with other energy sources through technological advances and improved performance
- environmental, political, and social concerns related to land disturbance, proximity to population centers, sound and wildlife issues, and visual effect
- effective integration into the Nation’s electrical energy transmission system
- consistent long-term regional plans among Federal, State, and local entities
- difficulties associated with permits and the transport of turbine components
- growing the manufacturing sector to remedy any short-term shortage of parts and materials

Material Requirements of Wind Turbines

A typical wind turbine is reported to contain 89.1 percent steel, 5.8 percent fiberglass, 1.6 percent copper, 1.3 percent concrete (primarily cement, water, aggregates, and steel reinforcement), 1.1 percent adhesives, 0.8 percent aluminum, and 0.4 percent core materials (primarily foam, plastic, and wood) by weight (U.S. Department of Energy, 2008). In 2008, utilities and manufacturers installed more than 5,000 utility-scale wind turbines in the United States, requiring more than 1.1 million metric tons (Mt) (1 million short tons) of iron and steel, 920,000 cubic meters (1.2 million cubic yards) of concrete, 2.4 million steel bolts, and 43,000 kilometers (km) (27,000 miles) of reinforced steel rebar (American Wind Energy Association, 2009b).

As the use of wind turbines increases and research leads to the development of new technologies, requirements for materials for wind turbines will likely change, and the cumulative amount of these materials required by this

Table 4. Principal components of a wind turbine and areas of research for each component.

[Data are from Sterzinger and Svrcek (2004), de Vries (2008), Abreu and others (2009), and Sakki (2009). NAICS, North American Industry Classification System; NA, not available; mph, miles per hour]

Component	Part	NAICS code	Cost (percent)[1]	Description	Technology trends
Rotor	Blade	326199	22.2	Rotor blades convert wind energy to mechanical energy. Can have stall-regulated or variable-pitch design. Principal materials are fiberglass and reinforcing products, such as epoxy resin with steel.	Trend is toward lighter and stronger blades. Currently use fiberglass reinforced plastic. Increased use of composite materials including carbon fiber reinforced plastic, steel, and fiberglass.
	Blade extender	331511	NA	Steel components that support blades and secure them to the hub. Typically more than 1 metric ton in weight.	Mounted to ball bearing, which is mounted to the hub.
	Hub	331511	1.37	Hub serves as a base for rotor blades and blade extenders, and as a housing for pitch control systems. Attaches to the shaft by means of a shaft/bearing assembly. Material is typically cast iron.	Testing to make the cost of two-blade systems competitive with three-blade systems.
	Pitch drive	335312	2.66	Controls blade angle to achieve optimum angle for wind speed and desired rotation speed. Typically three motors, one for each blade.	Variable-pitch turbines use a drive system to adjust pitch and divert excess energy, reducing blade stress and keeping the blade speed within design specifications.
Nacelle (excluding drivetrain machinery)	Case	326199	1.35	Encloses mechanical components of the turbine. Primary materials are fiberglass and steel-reinforced plastic.	Use of rubber dampers for mounting to mainframe with steel supports.
	Frame	331511	2.8	Inner casing of the nacelle. Primarily, materials are cast iron and steel.	Holes are drilled into the nacelle for stability, maintenance entry, and to minimize vibration.
	Anemometer	334519	NA	Meteorological instrumentation to provide wind velocity data to yaw controls.	More accurate laser anemometers are in development.
	Brakes	333613	1.32	Mechanical brakes are used as auxiliary devices to stop machinery during maintenance and inclement weather. Prevents undesired rotation or turbine fatigue.	Yaw controls typically halt blade rotation by turning blade rotors perpendicular to the wind direction. Brake systems provide emergency backup.
	Controller	334418	NA	Electronic and fiber optic monitoring equipment that report performance to the central controller.	Traditionally at the top and bottom of the tower. More recently, a third controller is mounted in the hub. The three controllers communicate via fiber optics.
	Convertor	335999	5.01	Converts direct current (DC) electricity from the generator to alternating current (AC) to achieve compatibility with the electrical grid.	NA
	Cooling system	333412	NA	Axial fans convectively cool machinery and exhaust waste heat from nacelle.	Cooling and dehumidifying units maintain conditions to reduce rust and corrosion.
	Sensors	334519	NA	Instrumentation relays information to controllers, which automatically adjust components to address changing conditions.	Instrumentation includes wind vane (anemometer), cable twist counter, and thermocouples. Other sensors are added as required.
	Yaw drive	335312	1.25	Turns the turbine into the wind to generate maximum power. Typically four drives are used.	When wind speeds exceed 60 miles per hour, the mechanism turns the turbine perpendicular to the prevailing wind to reduce stress or prevent stalling.

Table 4. Principal components of a wind turbine and areas of research for each component.—Continued

[Data are from Sterzinger and Svrcek (2004), de Vries (2008), Abreu and others (2009), and Sakki (2009). NAICS, North American Industry Classification System; NA, not available; mph, miles per hour]

Component	Part	NAICS code	Cost (percent)[1]	Description	Technology trends
Drivetrain components	Shafts	333613	1.91	Low- and high-speed shafts are the mechanisms for conversion from low-speed rotation of the rotor (kinetic energy) to high-speed rotation of the gearbox (electrical energy).	Shaft sizes have decreased as component parts such as bearings have become smaller. Smaller shafts have greater fatigue, necessitating better fatigue-handling systems and more frequent maintenance.
	Bearings	332991	1.22	Bearings are required for the shafts, gearbox, yaw mechanism, generator, and other rotating parts. The nacelle and tower are connected by a contact ball bearing, allowing the nacelle to rotate.	Technological improvements allow for smaller bearings.
	Couplings	333613	0.96	The flexible coupling is attached to the high-speed shaft to dampen out oscillating loads introduced by the gearbox, improving electricity quality produced by the generator.	Increased use of composite materials for increased strength and flexibility. Use of these materials is expected to increase to lighten turbine weight.
	Gear boxes	333612	12.91	A gearbox is used to convert low-speed rotation of the input shaft from the rotor to high-speed rotation. The high speed is necessary to drive the generator.	Trend toward large turbines has led to very expensive gearboxes because torque increases more quickly than the power when increasing rotor diameter. Research is ongoing for multiple-generator drivetrain configurations while increasing energy capture and reliability.
	Generators	333611	3.44	Generator produces electrical energy by spinning the rotor around a magnetic stator using electromagnetism to produce AC electricity. Alternatively, permanent magnet materials may be used to generate electricity.	Primarily synchronous and asynchronous. Increased use of direct-drive generators to eliminate the need for a gearbox, reducing maintenance costs of a turbine.
Tower	Tower	332312	26.3	Primarily made of steel (or concrete), built in sections because of size. May use composite materials if costs can be reduced. Oversize-load issues often constrain transportation to the site.	Research is ongoing to overcome transportation problems and the high cost of erection, focusing on slip-formed concrete bases, onsite tower fabrication, truss tower sections, and self-erecting tower technologies.
	Tower flange	331511	1.04	Ductile iron fittings that join tower segments.	Bolting and welding are used to connect tower seams.
	Power electronics	335999	3.59	Transformer and other DC to AC power-conversion apparatus, except for electronic circuitry.	NA.

[1] Percentage of total capital cost for a typical turbine with blades 45.3 meters in length and a tower 100 meters in height.

industry will likely increase. One scenario for achieving the proposed goal of producing 20 percent of the projected U.S. electrical consumption from wind power by 2030 would require the installation of wind turbines capable of generating more than 16,000 MW of new capacity annually by 2018, with this generation rate continuing annually through 2030 (American Wind Energy Association, 2009c). All the wind-derived electricity produced in the United States during 2008 originated from onshore wind turbines. Under this scenario, the DOE envisioned that 82 to 92 percent (255,000 to 285,000 MW) of wind-generated electricity could come from onshore wind turbines, 7 to 17 percent (23,000 to 54,000 MW) from offshore wind turbines, and less than 1 percent from small wind turbines (U.S. Department of Energy, 2008). Because electrical production from small (capacity of less than 0.1 MW) wind turbines would likely account for less than 0.4 percent of U.S. electricity-generating capacity in 2030, small wind turbines were excluded from this analysis.

Although table 4 includes a description of principle components and parts of a typical wind turbine, material requirements of wind turbines in use today can vary from one type or manufacturer to another, and current and future research may result in the development of wind turbines with mixes of materials different from those widely used today. The following discussion outlines each major component in terms of current use of materials and possible technological improvements that could lead to changes in material use.

Nacelle

The nacelle contains much of the equipment required for energy conversion and generation and typically accounts for 25 to 40 percent of the weight of the wind turbine (Ancona and McVeigh, 2001). The nacelle case contains the drivetrain components (bearings, coupling, gears, generator, and shafts) and the analytical and auxiliary equipment (anemometer, brakes, controller, convertor, cooling system, sensors, and yaw drive system). Materials used for these components consist primarily of aluminum, cast iron, copper, plastic, stainless steel, and steel alloys.

Torque is converted to electrical power using a speed-increasing gearbox and a generator. Many utility-scale wind turbines use a three-stage gearbox to convert the low-speed, high-torque power derived from the rotor to the high-speed, low-torque power that feeds the generator. Gearboxes comprise primarily cast iron and stainless steel, with minor amounts of aluminum and copper. Utility-scale wind turbines in use or under development in 2008 included double-fed, asynchronous (induction) wound-rotor generators (used in 73 percent of the wind turbines under contract for development in 2008); asynchronous generators with a cage rotor (14 percent); direct-drive, synchronous generators (11 percent); and permanent magnet generators (2 percent) to produce electrical energy suitable for transfer to the electrical power grid (Sakki, 2009, p. 7). Electromagnets found in many generators consist of iron cores surrounded by wound copper wire; smaller turbines may utilize cage rotors in their induction generators, comprising copper or aluminum rods connected electrically by aluminum end rings mounted to an iron core.

The trend toward larger turbines has led to very expensive gearboxes because torque increases more quickly than the power when increasing rotor diameter, leading to increased stress on the gears and higher maintenance requirements for gearboxes. The increased use of multiple-generator drivetrain configurations or direct-drive generators that do not require a gearbox has led to turbines with fewer moving parts, resulting in less maintenance and lower operating costs. The use of composite materials in couplings can increase component strength and flexibility and lighten weight but may add to component cost. Technological improvements allow smaller component parts, such as bearings, to be used. Shaft sizes have decreased accordingly, but smaller shafts experience greater fatigue, necessitating improvements in shaft design and more frequent maintenance (Sterzinger and Svercek, 2004).

Since 2006, manufacturers such as GE Energy, Siemens AG, and Vestas Wind Systems A/S (Vestas) have introduced into their product lines permanent magnet generators in drivetrains for wind turbines. Permanent magnets are used in the generator's rotor instead of wound copper-coiled electromagnets, eliminating much of the weight associated with copper windings and stator coils and the energy required to power up the electromagnets. Designs with permanent magnets use a power convertor to provide flexible, variable-speed power control in case of grid power fluctuations with no additional power required to initiate the magnetic field (Shankir, 2010). Disadvantages include a higher cost for the convertor and power electronics, energy losses in the power conversion process, and the possible introduction of harmonic distortions when connecting to the electrical grid (Kusiak, 2010; Shankir, 2010). Sintered ceramic magnets and rare-earth magnets are the two types of permanent magnets used in wind turbines. Sintered ceramic magnets, comprising iron oxide (ferrite) and barium or strontium carbonate, have a lower cost but generate a lower energy product than do rare-earth permanent magnets comprising neodymium, iron, and boron (Nd-Fe-B). The energy-conversion efficiency of sintered Nd-Fe-B is roughly 10 times that of sintered ferrite, but the cost per kilogram of sintered Nd-Fe-B is 30 times that of ferrite. Sintered Nd-Fe-B is electrically conductive, causing current losses and inductive heating in the magnets, which can result in efficiency losses or performance degradation at higher wind speeds (Marcos, 2009). Availability, cost, and efficiency factors for each type of generator therefore must be considered before selection. Although use of permanent-magnet generators of both types is increasing, the higher forecast projections of cost, technical limitations, and market pricing of materials are likely to reduce the rate of market penetration considerably below levels predicted by some manufacturers (Marcos, 2009; Sakki, 2009). Permanent-magnet generators were used in about 2 percent of the wind turbines manufactured globally in 2008 (Sakki, 2009).

Rotor

The rotor typically makes up 10 to 14 percent of the weight of the wind turbine (Ancona and McVeigh, 2001). The rotor of a wind turbine consists of four principal components—the blades, the blade extender, the hub, and the pitch drive system. Rotor blades are constructed primarily of fiberglass-reinforced plastic mixed with epoxy adhesive and lightweight core materials, such as balsa wood or polymer foam. A steel blade extender is used to provide additional blade support and to attach the blade to the hub. The hub, constructed primarily of cast iron, serves as a base for the rotor blades and extenders and as a housing for pitch control systems. The pitch drive, constructed primarily of stainless and alloy steels, controls blade angle for optimum energy recovery and enables adjustment for wind speed and other weather conditions that may affect wind turbine operation.

As of 2009, the trend in blade design was toward increased use of composite materials, such as carbon-reinforced plastic, in highly stressed locations to stiffen blades and improve fatigue resistance while reducing weight. Blade design and configurations are customized because wind characteristics vary between locations. At sites with lower wind speeds, longer blades may be used to increase energy capture. Variable-pitch drive systems are used to automatically adjust turbine pitch for changing wind patterns, reduce blade stress, and keep blade speed within design specifications.

Tower

The tower provides the support system for the turbine blades and the nacelle and serves as the conduit for electrical and electronic transmission and grounding. The most widely used tower configuration in the United States comprises steel sections with a concrete foundation custom designed for local site conditions. A tower, including the concrete base, typically accounts for 30 to 65 percent of the total weight of the wind turbine. Tower height is selected to optimize wind energy capture.

Projected Use of Materials Through 2030

Although an in-depth study of materials used in the wind turbine industry is beyond the scope of this report, a careful selection of existing wind turbine data can allow for the development of simplified distribution models for materials required by representative wind turbines and allow for estimates of the total material requirements necessary for the United States to meet the goal of supplying 20 percent of its electricity demand from wind power by 2030. Estimates of materials use are compared with U.S. consumption statistics for these materials as developed by the USGS to evaluate how increased demand from this sector could affect U.S. and world markets and possibly lead to changes in the supply of these materials.

As of 2009, small wind turbines of less than 100-kW capacity accounted for 0.06 percent of the wind-generating capacity of the United States, and onshore utility-scale turbines accounted for 99.94 percent of generating capacity. There was no capacity in 2009 from offshore wind turbines; the American Wind Energy Association projected that the first domestic utility-scale production from offshore turbines would occur in 2016. Wind turbine capacity that has come online since 2000 accounted for 93 percent of the total 2008 U.S. capacity from wind turbines, more than 50 percent of which are 1.5 MW in size. Turbines produced by GE Energy and Vestas accounted for approximately 52 percent of the wind turbines placed into production in the United States from 2000 through 2008 (Wiser and Bolinger, 2009, p. 15), and wind turbines manufactured by GE Energy and Vestas were considered representative of the current generation of wind turbine used in the United States. Given that the average life of a turbine is 20 to 30 years, it is likely that the majority of these turbines will still be in operation in 2030. In addition, this analysis considered two newer, larger wind turbines developed by these manufacturers with operational parameters and material technologies consistent with the latest wind turbine trends. It is expected that these turbines would be representative of the next generation of wind turbine coming online after 2010.

Turbine data supplied by the manufacturers and published data from other sources were used by the USGS to develop estimates of the principal materials required for two classes of wind turbine, a current-generation 1.5-MW onshore wind turbine and a next-generation 3.0-MW onshore wind turbine (table 5). Requirements for small wind turbines and offshore wind turbines were not addressed in this analysis; neither were requirements for the large-scale replacement of turbine components during the operating life of a turbine. Assumptions related to the estimates for materials required for both current- and next-generation onshore wind turbines are provided in appendix 2.

As rotor blades increase in size, greater amounts of fiberglass and carbon fibers are required per blade, but improvements in blade technology are leading to the use of less material per unit of energy generated. Modern wind turbine towers still contain large quantities of steel and concrete, although advances in tower materials increase tower compartmentalization and strength while allowing for lighter and more portable tower components and more efficient tower foundation designs. This allows less steel and concrete to be used per unit of energy generated. Increased use of ferrite and rare-earth permanent magnets would reduce the number of moving parts in a turbine by simplifying or eliminating the gearbox, but the unit requirements for iron oxide and rare-earth elements in permanent magnets would increase.

Economically, permanent magnet generators have become increasingly competitive with other generator types used in wind turbines. Increased demand for rare-earth

Table 5. Estimated requirements for materials per megawatt capacity of electricity for representative wind turbine technologies.

[kg, kilogram; kg/MW, kilograms per megawatt; MW, megawatt; Nd, neodymium; Nd-Fe-B, neodymium, iron, and boron; Nd_2O_3, neodymium oxide; XX, not applicable]

Turbine	Steel, stainless (kg/MW)	Concrete (kg/MW)	Fiberglass (kg/MW)	Miscellaneous[1] (kg/MW)	Copper[2] (kg/MW)	Nd in magnet[3] (kg/MW)	Cast iron (kg/MW)	Total weight (kg/MW)
Current generation[4]	115,000	590,000	9,800	8,050	2,500	0	23,900	750,000
Next generation[5]	103,000	402,000	6,800	9,300	3,000	43.2	20,000	540,000
Average change in megawatt consumption, in percent	-10	-32	-31	+16	+20	XX	-16	-28
	(million kg)	**(million kg)**	**(million kg)**	**(million kg)**	**(million kg)**	**(million kg)**	**(million kg)**	**(million kg)**
Average for 2010–2030[6]	1,500	6,800	110	130	40	0.38	310	8,890
Total by 2030[7]	30,000	135,000	2,300	2,400	750	6	6,000	176,456

[1] Includes aluminum, plastic, epoxy resins, polymer foam, and wood.

[2] Includes copper windings, copper alloys in components, copper wire, and copper in electronics.

[3] Estimates of rare-earth element requirements were developed based on published information on rare-earth content of wind turbine generators from Hatch (2009) and Lifton (2009). Wind turbines of the current generation typically did not use permanent magnets; therefore, the rare-earth element requirement of these wind turbines was considered negligible. It was assumed that 20 percent of the next generation wind turbines would use rare-earth permanent magnets. The remaining 80 percent would either use conventional electromagnets or ferrite permanent magnets that use no rare-earth elements. A next generation wind turbine that used a rare-earth permanent magnet would require 216 kg/MW Nd or 251 kg/MW Nd_2O_3, assuming that Nd accounts for about 27 percent of the weight of a rare-earth (Nd-Fe-B) permanent magnet. The Nd content of the average next generation wind turbine was therefore estimated as [(80 percent × 0) + (20 percent × 216 kg/MW)] = 43.2 kg/MW Nd [50 kg/MW Nd_2O_3].

[4] The representative current-generation onshore wind turbine is capable of generating 1.5 MW of electricity using conventional technology that includes a three-blade rotor, steel tower, three-stage gearbox, and a wound-rotor type generator.

[5] The representative next-generation wind turbine is capable of generating 3 MW of electricity and could use more composite materials in the rotor blades, steel-concrete towers, and a mixed generator technology assuming 80 percent double-fed induction generator technology and 20 percent permanent magnet technology. The latter could use rare-earth elements.

[6] The estimate of the average amount of material that would be required annually for 2010–2030 in order to achieve the goal of wind power supplying 20 percent of the U.S. demand for electricity by 2030 based on the distribution of current and next generation wind turbines as reported in appendix 2.

[7] The estimate of the total amount of material that would be required for 2010–2030 in order to achieve the goal of having wind power supply 20 percent of the U.S. demand for electricity by 2030 based on the distribution of current and next generation wind turbines as reported in appendix 2.

elements used in some permanent magnets has contributed to renewed interest in evaluating the need to redevelop domestic sources of supply for these strategic elements; in 2009, the United States imported most of its rare-earth elements from China (Hedrick, 2010), and most rare-earth permanent magnets manufactured worldwide use rare-earth elements from China (Lifton, 2009).

As global requirements for rare-earth elements continue to grow, any sustained increase in demand for neodymium oxide from the wind resource sector would have to be met by increased supply through expansion of existing production or the development of new mines. China's own domestic use of its rare-earth resources is increasing, with domestic consumption rates reported to be about 60 percent of production (Molycorp Minerals LLC, 2010). The availability of rare-earth elements required for permanent magnets is currently being evaluated by U.S. policymakers (U.S. Government Accountability Office, 2010).

In 2008, the DOE wind study assessed the likelihood of wind energy being able to provide 20 percent of the U.S. electricity supply by 2030 (U.S. Department of Energy, 2008). Included in this analysis was a comprehensive assessment of associated material requirements to meet this goal. Table 6A summarizes the estimates for selected materials required to meet the anticipated growth of the wind turbine industry for selected years based on the raw data provided by the DOE wind study; replacement parts were not included in these estimates. The amount of material that is available for recycling, remanufacturing, or disposal was not considered by the DOE study, but estimates of the amounts of material recycled (table 6B) or disposed of in landfills (table 6C) from dismantled wind turbines have been evaluated and are included in this report. Annual estimates for the amount of material recycled or landfilled were developed using the historical turbine capacities in megawatts from 1995 through 2005, an average turbine life of 25 years, and the average unit

Table 6. Annual requirements for materials in selected years to meet projected wind turbine demand by 2030.

[Based on a mix of 1.5-megawatt onshore and 4-megawatt offshore wind turbines selected to supply 20 percent of U.S. electrical demand by 2030, and a maximum wind turbine installation rate of 7,000 wind turbines per year. Data are from U.S. Department of Energy (2008). Units are reported in thousands of metric tons. Averages and totals have been rounded to two significant digits because they reflect a combination of reported and estimated data. In part B, for example, turbines constructed in 1996 would be available for recycling in 2021 and those constructed in 1997 could be recycled in 2022. A recycling rate of 90 percent was assumed for aluminum, cast iron, concrete, copper, electronics, and steel. No recycling was assumed for adhesives, core materials, fiberglass, or plastic. Recycling of rare-earth elements from permanent magnets would likely occur but not during the period of study. Abbreviations: kWh/kg, kilowatt hours per kilogram; NA, not applicable]

Year	kWh/kg	Steel[1]	Concrete[2]	Glass fiber reinforced plastic	Carbon fiber composite	Adhesive materials	Blade core materials	Aluminum	Copper	Permanent magnet[3]
A. Total material requirements for selected years										
2006	65	110	1,614	7.1	0.2	1.4	0.4	1.2	1.6	0.03
2010	70	464	6,798	29.8	2.2	5.6	1.8	4.6	7.4	0.07
2015	75	1,188	16,150	73.8	9.0	15.0	5.0	15.4	10.2	0.96
2020	80	2,644	37,468	162.2	20.4	33.6	11.2	29.6	20.2	2.20
2025	85	2,544	35,180	156.2	19.2	31.4	10.4	27.8	19.4	2.10
2030	90	2,308	33,800	152.4	18.4	30.2	9.6	26.4	18.4	2.00
Average 2010–2030	NA	1,800	26,000	120	14	23	8	21	15	1.50
Total by 2030[4]	NA	44,000	620,000	2,700	320	550	180	490	370	34
B. Estimates of material recycled for selected years or periods, based on industry capacity and recovery estimates and 25-year turbine life.										
2006	65	0	0	0	0	0	0	0	0	0
2010	70	0	0	0	0	0	0	0	0	0
2015	75	0	0	0	0	0	0	0	0	0
2020	80	0	0	0	0	0	0	0	0	0
2021–2025	85	140	550	0	0	0	0	3	3	0
2026–2030	90	880	3,500	0	0	0	0	15	20	0
Total by 2030[4]	NA	1,000	4,000	0	0	0	0	18	23	0
C. Estimates of material landfilled for selected years or periods, based on industry capacity and recovery estimates and 25-year turbine life										
2006	65	0	0	0	0	0	0	0	0	0
2010	70	0	0	0	0	0	0	0	0	0
2015	75	0	0	0	0	0	0	0	0	0
2020	80	0	0	0	0	0	0	0	0	0
2021–2025	85	16	62	12	0	2	3	0.3	0.3	0
2026–2030	90	98	390	72	0	13	16	2	2	0
Total by 2030[4]	NA	110	450	84	0	15	19	2	2	0

[1] Steel includes iron and steel alloys, stainless steel, and cast iron.

[2] Concrete used in tower foundations may last longer than the 25 year life of a wind turbine so may not need to be recycled.

[3] The composition of the permanent magnets are not specified but assumed to include both ferrite and rare-earth permanent magnets. Permanent magnets were not used in utility-scale, onshore wind turbines before 2006 (Europe) and 2015 (projected for the United States). Assuming a service life for the magnet of 25 years, any magnets installed in U.S. turbines are assumed to be in operation in 2030.

[4] Estimated by the USGS based on available data as reported from U.S. Department of Energy (2008).

capacity estimates in kilograms per megawatt for selected materials, assuming that all wind turbines to be recycled or landfilled would be similar to the representative current generation of wind turbines used in this study.

As of 1995, the cumulative generating capacity for first-generation wind turbines was reported to be 1,416 MW, and some of that capacity has since been decommissioned or retrofitted; thus, negligible recycling of wind turbines prior to 2020, or 25 years after the start of the second-generation turbine technology, has been assumed for this study. From 1995 through 2005, 7,583 MW of capacity came into production, mostly from turbines in the 0.8- to 1.5-MW range (U.S. Department of Energy, 2008). This capacity is for new or expanded projects and does not include capacity from wind turbines that have been replaced or retrofitted. Assuming a 25-year turbine life, material from turbines that came into production in 1995 would be available for recycling, remanufacturing, or disposal by 2019 unless the turbines had since been decommissioned or retrofitted with newer technology; turbines that came into production in 2005 would be available for dismantling by 2029. Turbines that came online after 2005 would likely still be in service in 2030. Recycling rates as of 2005 were assumed.

The profile of composite materials for the current generation of wind turbines (table 5, “Miscellaneous”) was used to characterize the profile of composite materials in the wind turbines that made up the 7,583 MW of capacity that came into production from 1995 through 2005. It was assumed that a turbine using state-of-the-art technology could be erected at the site of the turbine being replaced, so only the blades, the nacelle and its components, and the tower of the outdated wind turbine would be recycled or landfilled from 2020 through 2030. No provisions for selective replacement of turbine parts, turbine retrofitting, or turbine foundation recycling were considered in these estimates.

The amount of the selected materials recycled or disposed of for specified periods was estimated based on calculated amounts of these materials that were available for recycling, estimates of anticipated recycling rates used in the Vestas life cycle studies (Elsam Engineering A/S, 2004; Vestas Wind Systems A/S 2006a,b), and assuming a wind turbine life of 25 years. These estimates suggest that recycled steel could account for up to 12 percent of the total steel requirement for wind turbine production in 2030, 22 percent of the aluminum requirement, and 39 percent of the copper requirement. These should be considered the “best case” estimates, however, as no attempt was made to account for metal recovery or processing losses. It is likely that materials recovered from recycled 25-year-old turbines would be different from materials required for new turbines because of technological improvements, so 100 percent substitution may not be possible or desirable.

Table 6A shows the material requirements as reported by the 2008 DOE wind study. These estimates represent data as of 2005 on the total material requirements to meet the goal of 20 percent wind power by 2030 using a specific mix of small wind turbines and onshore and offshore utility-scale wind turbines. Discussions with technical staff at the National Renewable Energy Laboratory (Maureen Hand, oral commun., 2010) support the assumption that the material estimates (Fingersh and others, 2006; U.S. Department of Energy, 2008) are representative of current-generation wind turbine technology.

The USGS analysis described in this report used the DOE material estimates as a baseline. The growth patterns used in the DOE wind study for onshore wind turbines were applied to this analysis. Recent technical advances in wind turbine technology were incorporated into this assessment to develop the typical next generation wind turbine. The simplified assumptions used in this analysis can be found in tables 5, 6, and A2–1 (appendix 2). Variation from the DOE estimates reported in table 6A and estimates from this study (table A2–1) can be attributed to changes in material requirements for newer technology, differences in study methodology and the projected rate of wind turbine growth, consideration of recycled material in this study, and inclusion of small wind and offshore turbines in the DOE study. The DOE study data have been provided to give readers an indication how material requirements might vary depending on base assumptions.

Table 5 shows estimates for the average change in material consumption between current- and next-generation wind turbines. The trend toward using lighter weight materials is reflected in the decrease in consumption of materials per unit for cast iron, concrete, and steel and the increase in consumption of plastic and composite materials (table 5, “Miscellaneous”). The increased use of copper in wind turbine components is attributed primarily to the more sophisticated electronic components and copper wiring used to transmit power among individual wind turbines at a wind powerplant and then to transport the electricity to the power grid.

Data from tables 5 and A2–1, were used to develop a range for the average and cumulative amount of selected resources that would be required assuming wind energy was able to supply 20 percent of the U.S. electricity supply by 2030. A brief discussion of resource requirements to meet this goal follows.

Cast Iron and Steel

Available data suggest that developing the commercial wind turbine industry to a level sufficient to meet the 2030 goal would require 36 to 44 Mt of cast iron and steel from 2010 to 2030, or an annual average of 1.8 Mt. This average annual requirement represented less than 2 percent of the U.S. apparent consumption of steel in 2008 (102 Mt) (Fenton, 2010).

Concrete

Similarly, the available data suggest that 135 to 615 Mt of concrete would be required. Between 6.8 and 26 Mt of concrete would be required annually, or less than 3 percent of the U.S. apparent consumption of concrete in 2008 as reported by the USGS, assuming portland cement is 11 percent of the concrete mix (van Oss, 2010).

Fiberglass and Composites

The data suggest that 2.3 to 2.7 Mt of fiberglass would be required. From 110,000 to 115,000 metric tons (t) of fiberglass would be required annually, and an additional 14,000 t of composite material would also be required each year. This estimate of the average annual fiberglass requirement represents about 14 percent of the U.S. consumption of fiberglass for 2008 as reported by the USGS (Dolley, 2009).

Rare Earth Elements

Permanent-magnet generators have become more economically feasible for wind turbine generators. This technology yields smaller, lighter generators by eliminating copper from the generator rotor. An assessment of available data (Hatch, 2009; Lifton, 2009) suggests that wind turbines that use rare earth permanent magnets comprising neodymium, iron, and boron require about 216 kilograms (kg) of neodymium per megawatt of capacity, or about 251 kg of neodymium oxide (Nd_2O_3) per megawatt of capacity. If the growth projections reported for the stated goal of 20 percent wind energy by 2030 are used as a basis for estimating rare earth element requirements for electricity generated by wind power, and assuming the total market penetration rate of rare earth permanent-magnet generators for wind-generation applications is 20 percent of annual installed capacity, then about 560 t of neodymium or about 650 t of additional Nd_2O_3 would be required annually to reach the 310-GW electricity-generation capacity projected for the United States in 2030. For comparison, projected world production of neodymium in 2009 was 19,096 t (Lowder, 2010), world demand for Nd_2O_3 in 2010 was estimated to be 27,000 t, and world supply was estimated to be 24,400 t (Lynas Corporation Limited, 2010), leading to a reported supply deficit of about 10 percent for 2010. China produced about 96 percent of the world's rare-earth elements in 2009 (Hedrick, 2010). Using these data, industry growth through 2030 would require an additional 380 metric tons per year of neodymium, or about 2 percent of the projected 2010 world supply. In July 2010, however, China's Ministry of Commerce reduced China's export quota for rare earth oxides by 77 percent for the second half of 2010 (Industrial Minerals, 2010). The continued restriction of Chinese rare earth exports could affect the short-term global supply of rare earth elements.

Laxson and others (2006) estimated that, if wind energy could be harnessed to supply 20 percent of the U.S. electricity demand by 2030, then the wind turbine industry would require up to 19 percent of the annual global production of neodymium and Nd_2O_3; this is based on a 1999 global production estimate for permanent magnet materials of 13 Mt increased by 28.5 percent annually to 75 Mt in 2005 and assuming all turbines have permanent-magnet generators. The DOE wind study concluded that there did not appear to be a resource limitation for permanent magnets based on the estimated U.S. rare earth reserve of 13 Mt (Hedrick, 2006). However, the DOE wind study concluded that the capacity for additional raw-material production and the capability to manufacture wind turbines would need to accommodate both the wind turbine industry and projected increases for rare-earth permanent magnets in other sectors (Laxson and others, 2006). USGS data suggest that the global mining industry is endeavoring to respond to the increase in demand for rare-earth elements by expanding or developing new capacity, but significant new production is not expected before 2015 (Lynas Corporation Limited, 2010).

Copper

The data from this study suggest that, although use of permanent magnets may reduce the copper in wind turbine generators, this decrease is offset by an increase in copper use in electronic components and the copper wiring necessary to connect wind turbines within the wind powerplant and to connect the powerplant to the utility grid. Wind powerplants are often located in areas distant from consumers, and large amounts of copper wire are necessary to provide power connections. The Sweetwater II 91.5-MW wind powerplant in Texas, for example, is reported to use more than 56 km of copper low-voltage wire and grounding cable and more than 108 km of wire containing copper in its high-voltage power cable to connect the wind turbines within the wind powerplant and to connect the wind powerplant to the power grid (Harwell and others, 2005).

The data used in this study suggest that 370,000 to 750,000 t of copper would be required for wires and cables from 2010 to 2030. Between 15,000 and 40,000 t of copper would be required annually, or less than 2 percent of the U.S. apparent consumption of refined copper in 2008 of more than 2 Mt (Edelstein, 2010).

Land Area

Wind turbines require a large land area for siting, construction, and operation. Although land is not considered a material component in wind turbines, land requirements for turbine erection and operation must be considered when assessing overall resource requirements of this growing energy sector. Estimates to reach the goal of supplying 20 percent of the U.S. demand for electricity by 2030 suggest that about 50,000 square kilometers (km^2) of land would be required for onshore wind turbines and an additional 11,000 km^2 would be required for offshore projects (U.S. Department of Energy, 2008, p. 110). However, much of this land area could be used for other purposes, such as farming or grazing, during the operational phase of the wind project. The effective footprint of land that would be occupied by turbines and related infrastructure would range from 2 to 5 percent of this amount. A 2006 estimate suggested that about 0.2 to 1.0 hectare (0.5 to 2.5 acres) per turbine is required during the construction phase and about 0.3 to 0.4 hectare (0.7 to 1 acre) per turbine is required during the operation phase (Strickland and Johnson, 2006). A second estimate attributed about 0.3 hectare per megawatt for the direct impact area that is permanently occupied and about 0.7 hectare per megawatt for the direct impact area that would be temporarily occupied during construction (Denholm and others, 2009). An estimate of the average land area leased by existing U.S. wind projects in 2008 was reported to be 34.5 hectares per megawatt (Denholm and others, 2009). Using this estimate, a wind powerplant consisting of 100 of the 1.5-MW wind turbines would occupy about 5,175 hectares, but only 150 hectares would be temporarily or permanently affected by a wind powerplant that would have the capability for supplying power to about 30,000 households, assuming an individual household uses 11,300 kWh/yr.

Conclusions

Achieving the goal of using wind energy as the source for 20 percent of the electricity-generating capacity of the United States by 2030 would require an average annual consumption of about 6.8 Mt of concrete, 1.5 Mt of steel, 310,000 t of cast iron, 40,000 t of copper, and 380 t of the rare-earth element neodymium. With the exception of neodymium, the annual material requirements represent less than 3 percent of the U.S. apparent consumption of these materials for 2008.

Dismantling of wind turbines during the 2010 to 2030 period could result in approximately 1 Mt of recycled steel, and an additional 114,000 t of steel could be sent to landfills. Recycled material could account for about 3 percent of the total steel requirement for wind turbine production from 2010 to 2030, 4 percent of the aluminum requirement, and 3 percent of the copper requirement. Approximately 4 Mt of concrete could be recycled during this period if concrete used in tower foundations is not reused for retrofitted wind turbines; an additional 450,000 t of concrete could be sent to landfills. About 23,000 t of copper and 18,000 t of aluminum could be recycled during the period covered under this study; about 84,000 t of fiberglass and 2,300 t of aluminum and copper could be sent to landfills.

The use of rare earth elements in wind turbine generators has increased with the development of permanent-magnet direct-drive generators; in selective applications, these generators appear to be competitive with conventional electromagnetic generators. Data suggest that, unless the market penetration of rare earth permanent magnets in wind-generation applications greatly exceeds the 20 percent level assumed in this study or unless China, the principal supplier of rare earth elements to the market, should restrict the supply of these materials, the current and proposed production level of rare earth elements may be sufficient to supply the wind turbine industry in the short term until new rare earth production and downstream manufacturing facilities come online. In July 2010, however, China's Ministry of Commerce reduced China's export quota for rare earth oxides by 77 percent for the second half of 2010 (Industrial Minerals, 2010). This action reduced the amount of rare earth oxide exports from China below the world consumption level for these materials. Data analyzed for this report to assess the supply of materials required for electricity generation from wind power suggest that, with the possible exception of rare-earth elements, there should not be a shortage of any of the principal materials. There may, however, be selective shortages from a manufacturing perspective if the total demand for these materials from all markets is greater than the available supply of raw materials or component manufacturing capacity. Changing economic conditions could also affect the capacity and the development schedule for meeting the anticipated capacity.

The requirements for materials reported in this study were developed using the assumption that wind energy converted to wind power would contribute 20 percent of the U.S. electricity demand and require up to 310 GW of capacity by 2030, as proposed by the DOE wind study. With the exception of the rare-earth element neodymium, these material requirements represent less than 3 percent of the U.S. apparent consumption in 2008. However, the wind energy sector must overcome many challenges to meet the goal of wind power providing 20 percent of the electricity-generating capacity for the United States by 2030. For electricity generation from wind turbines to assume a larger contribution in U.S. energy production, the wind turbine industry must resolve issues such as local opposition to site locations, the high cost of transportation for components, and U.S. power grid routing issues. This will be essential before the United States can achieve a national power supply that includes a sizeable wind power component. At the end of 2009, the wind turbine industry was growing faster than the rate projected by the 2008 DOE wind study, perhaps in part because of Federal support for the growth of this industry, as demonstrated by the renewal of the investment tax credit for renewable energy resources and additional provisions included in the American Recovery and Reinvestment Act of 2009. Information published by the U.S. Energy Information Administration (2010) projects the wind-powered generating capacity of the United States to level off at about 64 GW of capacity by 2015, well below the level proposed in the 2008 DOE wind study. The actual rate of growth will depend on future economic, political, and technological conditions. In spite of this uncertainty, it seems likely that the industry will continue to grow at some level and continue to require large amounts of steel, concrete, copper, and specialty metals and materials to support this growth.

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Appendix 1. Estimates of Wind Turbine Life Cycle Emissions, Energy Consumption, and Water Consumption

Although an analysis of the emissions from a wind turbine is not within the scope of this report, an understanding of these emissions relative to other energy sources can provide a clearer understanding of why wind energy is favored by many when compared with other sources of electrical power.

Published life cycle analyses provide information on the amount of water and embedded energy necessary for the production of wind turbines. The following estimates were developed by Vestas Wind Systems A/S for their wind turbines, but are considered representative of the industry. Estimates include the amount of energy and water required to extract raw materials, process these raw materials into usable products, manufacture components for wind turbines, transport and assemble the components of turbines, operate the turbines, and decommission the turbines at the end of the turbine's life.

Wind-generated electricity uses less water than electricity generated by fossil fuels or nuclear power. As shown in table 3 of this report, a representative utility-scale wind turbine would need about 144 to 193 liters (L) (38 to 51 gallons) of fresh water to generate 1 kWh of electricity. During an estimated 20-year life, a 1.65-MW wind turbine would consume about 780 t of water and a 3-MW wind turbine would consume about 8,000 t of water (Vestas Wind Systems A/S, 2006a). The U.S. Department of Energy has reported that each megawatthour generated by wind power has the potential to save 2,300 L (600 gallons) of water that would otherwise be used in fossil-fuel powerplants to produce electricity (U.S. Department of Energy, 2008, p. 17). Wind turbines typically consume less energy than do conventional fossil fuel-powered facilities. Vestas life cycle studies suggest that a 1.5- to 3-MW wind turbine consumes about 0.1 megajoule per kilowatthour (MJ/kWh) produced, or it consumes about 4 gigawatthours of energy during a 20-year life (Vestas Wind Systems A/S, 2006 a,b). Studies suggest that a 1.65-MW wind turbine must operate about 7.2 months before it would produce as much electricity as it consumes during its 20-year life (Vestas Wind Systems A/S, 2006a).

Wind power studies suggest that lifetime carbon dioxide emissions vary from 5.6 to 9.6 grams per kilowatthour of energy (g/kWh) for the type of utility-scale wind turbines under consideration. Methane emissions range from 11.6 to 15.4 milligrams per kilowatthour of energy (mg/kWh). Nitrogen oxide emissions range from 20 to 38.6 mg/kWh. Nonmethane volatile organic compound emission rates range from 2.2 to 8.5 mg/kWh, particulates range from 10.3 to 32.3 mg/kWh, and sulfur dioxide emissions range from 22.5 to 41.5 mg/kWh (European Wind Energy Association, 2007). For comparison, fossil fuel production in 1998 emitted an average of 689 g/kWh of carbon dioxide, 3.63 g/kWh of sulfur dioxide, and 2.22 g/kWh of nitrogen oxide (American Wind Energy Association, 1999). The U.S. Department of Energy estimated that in 2008, emissions from domestic fossil fuel and renewable energy sources amounted to an average of 601 g/kWh of carbon dioxide, 1.9 g/kWh of sulfur dioxide, and 0.81 g/kWh of nitrogen dioxide (U.S. Energy Information Administration, 2010). Carbon dioxide, sulfur dioxide, and nitrogen oxide emissions from electric power-generation facilities using other renewable sources are reported to be at comparable levels to those of wind-powered operations (National Academy of Sciences, 2010).

Life cycle studies suggest that the construction and initial transportation phases for wind turbines account for about 74 to 90 percent of total lifetime emissions. The operational phase of a wind turbine, including maintenance and replacement of materials and components, contributes 7 to 12 percent of the emissions, and transportation and decommissioning contribute the remaining 3 to 14 percent (European Wind Energy Association, 2007).

When emissions from the construction of various wind turbine components are analyzed, construction of the tower accounted for about 30 percent of carbon dioxide emissions, 20 percent of nitrogen oxide emissions, and 19 percent of particulate emissions. Construction of the nacelle accounted for about 30 percent of sulfur dioxide emissions, 29 percent of the particulate emissions, 26 percent of methane emissions, and 17 percent each of carbon dioxide, nitrogen oxide, and nonmethane volatile organic compound emissions. Rotor blade construction accounted for about 14 percent of methane emission, but contributed to less than 10 percent of all other emission categories (European Wind Energy Association, 2007).

Appendix 2. Wind Turbine Assumptions and Selection Methodology

Estimates of the materials needed by the wind turbine industry from 2010 through 2030 were developed using the growth scenario developed by the U.S. Department of Energy (2008) that used 20 percent of electric power generated from wind power by 2030 as a baseline. Representative wind turbines were selected based on the number of units in production and the availability of technical data for these turbines. GE Energy's 80-meter, 1.5-MW wind turbine has been the top selling wind turbine in the United States (from 2004 through 2009) and more than 12,000 units have been sold worldwide. More than 1,200 of the Vestas 80-meter, 1.65-MW wind turbines are operating worldwide, and turbines of this widely used class of wind turbines have been selected for a number of new U.S. wind powerplants. These two turbines were selected for this study to represent the generation of wind turbines currently in operation or planned by 2015.

GE Energy's 100-meter, 2.5-MW wind turbine is one of a new class of wind turbine using a rare-earth permanent-magnet generator instead of the wound-motor type of generator and incorporates larger rotor blades and power train features into the turbine design. More than 150 units have been installed, and more than 400 units are currently on order. The Vestas 105-meter, 3-MW wind turbine is designed for higher wind speeds than the other representative wind turbines. Other new features include a larger nacelle configuration but with about the same weight because of the increased use of lighter weight composite materials in the larger rotor blades. These wind turbines were selected to represent the next generation of onshore wind turbines planned for use from 2010 through 2030.

Data for these wind turbines were compiled from various company and public sources. Estimates of the requirements for materials for current- and next-generation wind turbines were developed by aggregating the weight and composition data for the selected wind turbines and adapting these data to meet the reported or anticipated requirements of the industry based on industry practice as of 2010. Because the requirements for materials in individual components were considered proprietary, the raw component data used to develop material estimates cannot be reported. Consequently, the reported requirements for materials for the typical wind turbines in table 5 will not precisely match the individual data for any of the representative wind turbines that were selected for use in this study.

Annual and cumulative requirements for selected materials were developed by incorporating the estimated requirements for the representative wind turbine technologies shown in table 5 with estimated growth projections for the industry for 2010 through 2030. Table A2–1 lists these estimates for 2010 through 2030. For each study year, the estimated ratio of current and next generation wind turbine technology was developed. Material requirements for a given year (expressed in thousands of metric tons) were then estimated by combining the annual growth of turbine capacity (in megawatts) estimated for that year, the requirements for materials for the representative current- and next-generation wind turbines (in kilograms per megawatt), and the estimated percentages of current and next generation wind turbines applicable for that year. Estimates reflect the contribution of onshore wind turbines, which account for most U.S. wind turbine capacity through 2015 and are expected to account for more than 80 percent of production capacity for new wind turbines until 2030. Although estimates shown in this appendix were developed using baseline growth patterns reported by the DOE wind study (U.S. Department of Energy, 2008), growth estimates were adjusted to reflect the actual 2005 to 2009 industry growth, the exclusion of small wind and offshore turbines, and material assumed to be recycled during the period. In this report, estimates of materials required were developed independently from the estimates reported in the DOE wind study, which used a different methodology, so estimates in this report should be considered complementary to the earlier estimates.

This study assumes that the principal metals used in the construction of wind turbines can be recycled at a rate of 90 percent (excluding rare earth elements); each material would have a 10 percent loss that likely would end up in a landfill. The study assumes that all plastic, core material, and fiberglass components would be disposed of in landfills after a 25-year operating life. No attempt was made to account for the recycling of defective parts before the end of turbine life. The assumptions are based on life cycle studies performed for the Vestas wind turbines considered in this study (Vestas Wind Systems A/S, 2006a,b) and do not consider improvements in the recycling rate that may have occurred after 2005.

Before 2007, landfills were the only option for the disposal of the wind turbine blades made of composite material that could not be recycled. Recent research suggests it may be possible to incinerate some blade components and reprocess the glass component from these blades. Although preliminary, the research suggests that the energy consumption is approximately 6 percent lower when recycling the materials in blades when compared with placing the rotors in landfills (Vestas Wind Systems A/S, 2006a).

Because steel is a major component in wind turbines, small changes in the amount of steel recycling affect the overall amount of waste generated during the disposal of wind turbines. The Vestas' life cycle studies found that an increase in steel recovery from 90 percent to 96 percent led to a 3 percent decrease in carbon dioxide generation (Vestas Wind Systems A/S, 2006b); a 10 percent increase in recycling would result in an 8 percent decrease in carbon dioxide emissions (Vestas Wind Systems A/S, 2006a).

Table A2–1. Estimates used in this report for the quality of selected materials required by the wind turbine industry from 2010 through 2030.

[kg, kilogram; kt, thousand metric tons; MW, megawatt; NA, not available; Nd, neodymium; Nd-Fe-B, neodymium-iron-boron; Nd_2O_3, neodymium oxide; t, metric ton; XX, not applicable]

Year	New onshore capacity (MW)	Onshore percent of total (percent)	Current-generation turbine (percent)	Next-generation turbine (percent)	Steel/ stainless steel (kt*)	Concrete (kt*)	Fiberglass (kt*)	Miscellaneous[1] (kt*)	Copper[2] (kt*)	Rare earths[3] (kt*)	Cast iron (kt*)
Prior to 2010	35,000	100	100	0	NA	NA	NA	NA	NA	NA	NA
2010	8,000	100	100	0	920	4,720	78	64	20	0.00	191
2011	10,000	100	95	5	1,144	5,806	97	81	25	0.02	237
2012	9,000	100	90	10	1,024	5,141	86	74	23	0.04	212
2013	9,600	100	85	15	1,087	5,393	90	79	25	0.06	224
2014	9,600	100	80	20	1,081	5,303	88	80	25	0.08	222
2015	13,400	100	75	25	1,501	7,276	121	112	35	0.14	307
2016	13,200	99	70	30	1,470	7,044	117	111	35	0.17	300
2017	15,600	98	65	35	1,728	8,178	137	132	42	0.24	352
2018	15,300	96	60	40	1,686	7,876	132	131	41	0.26	342
2019	15,300	96	55	45	1,677	7,733	129	132	42	0.30	339
2020	15,300	96	50	50	1,668	7,589	127	133	42	0.33	336
2021	15,800	96	45	55	1,713	7,688	129	138	44	0.38	344
2022	15,800	96	40	60	1,703	7,540	147	139	44	0.41	341
2023	15,300	96	35	65	1,640	7,157	116	136	43	0.43	327
2024	15,300	96	30	70	1,631	7,014	118	137	44	0.46	324
2025	15,200	95	25	75	1,611	6,825	115	137	44	0.49	319
2026	14,500	91	20	80	1,528	6,374	107	131	42	0.50	301
2027	13,300	86	15	85	1,394	5,722	96	121	39	0.49	274
2028	12,800	83	10	90	1,334	5,386	91	117	38	0.50	261
2029	10,400	80	5	95	1,077	4,279	72	96	31	0.43	210
2030	10,100	78	0	100	1,040	4,060	69	94	30	0.44	202
Total by 2030[4]	307,800	XX	XX	XX	29,658	134,103	2,262	2,375	753	6	5,963
Average for 2010–2030[5]	12,990	NA	NA	NA	1,500	6,800	110	130	40	0.38	310

[1] Includes aluminum, plastic, epoxy resins, polymer foam, and wood.

[2] Includes copper windings, copper alloys in components, copper wire, and copper in electronics.

[3] Published estimates suggest that a 2.5-MW turbine requires 0.6 to 1.0 t of permanent magnet material per megawatt of power or 0.2 to 0.33 t of Nd per megawatt of power. A 3.5-MW turbine would require an average of 2 t (2,000 kg) of permanent magnet material, or an average of 216 kg of Nd per megawatt produced, assuming Nd accounts for about 27 percent of the weight of a Nd-Fe-B permanent magnet. Assuming that turbines using rare-earth permanent magnets would account for 20 percent of the wind turbine market by 2030, the average rare-earth (primarily Nd) weight per megawatt of a next generation wind turbine would be 43.2 kg of Nd (50 kg of Nd_2O_3) per megawatt of power [(80 percent × 0) + (20 percent × 216 kg)].

[4] Estimate of the total amount of the specified material that would be required for 2010–2030 based on the reported annual material assumptions given.

[5] Estimate of the average values that would be required for 2010–2030.

[*] Correction posted on September 4, 2012.

Wilburn, D.R.—**Wind Energy in the United States and Materials Required for the Land-Based Turbine Industry From 2010 Through 2030**—SIR 2011–5036