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An Assessment of the Available Windy Land Area and Wind Energy Potential in the Contiguous United States

D. L. Elliott
L. L. Wendell
G. L. Gower

August 1991

Prepared for the U.S. Department of Energy
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Richland, Washington 99352

ABSTRACT

Estimates of land areas with various levels of wind energy resource and resultant wind energy potential have been developed for each state in the contiguous United States. The estimates are based on published wind resource data and account for the exclusion of some windy lands as a result of environmental and land-use considerations. Despite these exclusions, the amount of wind resource estimated over the contiguous United States is surprisingly large and has the potential to supply a substantial fraction of the nation's energy needs, even with the use of today's wind turbine technology. Although this study shows that, after exclusions, only about 0.6% of the land area in the contiguous United States is characterized by high wind resource (comparable to that found in windy areas of California where wind energy is being cost-effectively developed), the wind electric potential that could be extracted with today's technology from these areas across the United States is equivalent to about 20% of the current U.S. electric consumption.

Future advances in wind turbine technology will further enhance the potential of wind energy. As advances in turbine technology allow areas of moderate wind resource to be developed, more than a tenfold increase in the wind energy potential is possible. These areas, which cover large sections of the Great Plains and are widely distributed throughout many other sections of the country, have the potential of producing more than three times the nation's current electric consumption. Twelve states in the midsection of the country contribute over 90% of the wind electric potential in the contiguous United States and have the potential to produce several times their own electrical consumption, which puts them in a position to export electric power or use it for other applications.

SUMMARY

In support of the U.S. Department of Energy's National Energy Strategy, estimates of land areas with various levels of wind energy resource and resultant wind electric potential have been developed for each state in the contiguous United States. The estimates are based on published wind resource data and account for the exclusion of some land as a result of environmental and land-use considerations. Windy lands excluded from wind energy development (under the scenario of moderate exclusion based on land use described here) include environmentally protected lands (such as parks and wilderness areas), urban lands, wetlands, and a substantial fraction of forest and agricultural lands. Only a small fraction of range and barren lands was excluded (to account for some land occupied by roads and structures), because wind plants have been successfully located in these types of land-use areas in California. Despite these exclusions, the amount of wind resource estimated over the contiguous United States is surprisingly large, and it is not limited by the availability of windy lands. That is, the wind resource has the potential of supplying a substantial fraction of the nation's energy needs, even with the use of today's technology.

Today's technology allows the exploitation of the wind resource mainly in specific areas where the annual average wind resource is class 5 or greater, that is, where the wind power density is 400 W/m^2 or greater at 30 m (100 ft) above the ground. Areas of class 5 and greater wind resource have annual average wind speeds of approximately 7 m/s (16 mph) and higher at heights of 30 m (100 ft). To date, development of these areas has occurred primarily in California, where class 5 areas are being cost-effectively developed. Although this study shows that, after exclusions, only about 0.6% of the land area in the contiguous United States is characterized by class 5 or greater wind resource, the wind electric potential that could be extracted with today's technology from these areas across the United States is equivalent to about 20% of the current U.S. electric consumption. Three states--North Dakota, Wyoming, and Montana--could contribute about 80% of the U.S. wind electric potential from class 5 or greater wind resource areas. The wind electric potential in North Dakota, Wyoming, and Montana exceeds the electric

consumption in these states by factors of 25.6, 14.8, and 7.4, respectively. Although California is the world leader in wind power generation (with over 80% of the world's capacity), the wind electric potential from class 5 lands in California contributes less than 3% of the wind potential possible from all class 5 lands in the contiguous United States. However, only about 20% of California's class 5 wind potential has been developed, according to our estimates of the land area potentially available after environmental and land-use exclusions.

Future advances in wind turbine technology will further enhance the potential of wind energy in the United States. These advances include improvements in airfoil designs and optimized controls that increase the energy-capture efficiency of wind turbines and improvements in structures and materials that allow taller and larger-diameter wind turbines to be developed, which in turn can reach more available wind energy more economically. As advances in turbine technology allow areas with lower wind resource to be developed, such as class 3 areas (where the annual average wind power density is 300 to 400 W/m^2 at 50-m heights), more than a tenfold increase in the wind energy potential is possible. Areas with class 3 and greater wind resource, where annual average wind speeds at 50 m generally exceed 6.4 m/s or about 14 mph, represent approximately 13% of the contiguous U.S. land area. These areas, which cover large sections of the Great Plains stretching from Texas to the Dakotas, but which are also widely distributed throughout many other sections of the country, have the potential of displacing over 100 Quads (fossil-fuel equivalent) of electric energy annually. (A Quad is one quadrillion Btus.) Compare that with the total energy use of approximately 80 Quads in the contiguous United States in 1988, with 36% of that total having been devoted to the production of electricity. Twelve states in the midsection of the country contribute over 90% of the wind electric potential in the contiguous United States. They are, in order of greatest potential, North Dakota, Texas, Kansas, South Dakota, Montana, Nebraska, Wyoming, Oklahoma, Minnesota, Iowa, Colorado, and New Mexico. These states also have the potential to produce several times their own electrical consumption, which puts them in a position to export electric power or use it for other possible applications. Other states in the West, the Northeast, and in the vicinity of the Great Lakes have the potential to provide a substantial fraction of their own electrical consumption or, in some states with relatively low consumption levels, even more than their own consumption.

Under the most severe land-use restriction, where essentially all lands except for range lands and barren lands in the West are excluded from wind energy development, the U.S. wind electric potential (with advanced technology) from lands with class 3 or greater resource would be approximately 47 Quads (fossil-fuel equivalent) annually, which still exceeds the amount of energy currently consumed for electrical generation (about 30 Quads) in the United States. Although this scenario severely reduces the amount of windy land area and wind electric potential in many of the midwestern and eastern states, wind electric potentials in many of the western states survive this scenario quite well, because large fractions of their windy lands are classified as range or barren lands. For example, Wyoming loses only 30% of its wind electric potential under the most restrictive scenario.

Although this study provides quantitative estimates of the annual average wind electric potential, three qualifications must be emphasized. First, the results presented here must be regarded as estimates only because they would change with the use of different assumptions and specifications. Second, this study does not diminish the need for careful siting and array design before the actual installation of a wind plant. Third, wind is an intermittent resource, and wind technology must therefore be integrated with other baseload power sources to provide a stable utility system. Seasonal analyses of the wind electric potential, like those reported in this study for the annual average data, would be a refinement that would make the results more valuable to utilities and energy planners. Other important factors not addressed in this study that influence the area available and total wind electric potential include remoteness of the resource (transmission, access), match between production and demand (seasonal and daily, storage), utility and public acceptance, local ordinances, and other technological and institutional factors. (These factors and their implications on the development and deployment of wind-energy technologies are discussed in a DOE Interlaboratory White Paper, "The Potential of Renewable Energy".)

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1.0 INTRODUCTION

A wind energy resource atlas of the United States (Elliott et al. 1987) shows that areas potentially suitable for wind energy applications are dispersed throughout much of the United States. Major wind resource areas in the contiguous United States include much of the Great Plains from northwestern Texas and eastern New Mexico northward to the Dakotas and western Minnesota, the high plains of Wyoming and Montana, the Atlantic coast from North Carolina to Maine, the Great Lakes, the Pacific coast from central California to Washington, the Texas Gulf coast, exposed ridge crests in the Appalachians as well as the mountains of the West, and windy corridors that occur in many of the western states, such as the passes in California where thousands of wind turbines are currently operating.

Although the U.S. wind atlas contains maps showing the geographical distribution of the wind resource, the atlas provides neither quantitative estimates of the available windy land area nor the wind electric potential possible from the development of these land areas. The actual installation of wind turbines requires consideration of the availability of land on which to site the turbines. Land availability may be constrained by land-use considerations; for example, land may be unavailable for development because of environmental restrictions or economically valuable agricultural or urban activities.

In support of the preparation of the U.S. Department of Energy's National Energy Strategy, Pacific Northwest Laboratory (PNL) estimated the land area available for wind energy development under various scenarios of land-use restriction and several levels of wind energy resource. This report presents the estimates of land area and resultant wind electric potential developed for four scenarios of land exclusion and describes the data bases and methods used to make the estimates. Estimates of windy land area and wind electric potential were developed not only for the contiguous United States as a whole but also for each of the 48 states in the contiguous United States.

Chapter 2.0 describes the wind resource data used in the study. Gridded map data of the wind resource from the Wind Energy Resource Atlas of the United States (Elliott et al. 1987) were used in developing estimates of total windy land area for the base-case scenario with no exclusions. Chapter 3.0 describes the methods used to develop a data base of approximate areas where wind energy developments would be restricted by environmental considerations. Environmental exclusion areas include parks, monuments, wilderness areas, ecological preserves, wildlife refuges, and other types of protected natural areas. Chapter 4.0 describes the land-use data that were used in estimating land-use restrictions for various types of land (e.g., forest, agricultural, range, and urban lands). As might be expected, the estimates of land area excluded from wind energy development by certain types of land use are subject to uncertainty (for example, the extent to which agricultural and forest lands could be developed is uncertain). To deal with this uncertainty, we developed estimates of the land area that would be excluded under a "moderate" and a "severe" land-use restriction. Chapter 5.0 describes the effects of the environmental and land-use restrictions on the available windy land area. Estimates of the land area in the contiguous United States with various levels of wind resource are presented for four land exclusion scenarios: 1) no exclusions, 2) environmental exclusions only, 3) moderate land-use exclusions, and 4) severe land-use exclusions. Although maps of the available windy land area in each state are shown for only the scenario with moderate land-use exclusions, tables provide data on each state's land area with various levels of wind resource for each of the four land exclusion scenarios.

Chapter 6.0 presents the results of the wind electric potential estimates developed for the four scenarios of land exclusion. To convert the areal estimates of wind resource to estimates of potential electricity production, it was necessary to specify the wind turbine hub height, spacing, efficiency, and power losses. (Appendix A provides a discussion of the turbine spacing, power loss, and efficiency assumptions used.) The wind electric potential that could be achieved using today's turbine technology (which would be cost-effective only in areas with high wind resource, comparable to levels being tapped in California today) is compared to that projected to be available using advanced technology (which would be cost-effective even in areas of moderate wind resource). The wind electric potential is also presented for each state relative to recent estimates of total electric and total energy consumption.

Appendix B provides estimates of the windy land area and wind energy potential, by state, for a scenario of advanced wind turbine technology (utilizing areas of class 3 or greater wind resource where the annual average wind power density is greater than 300 W/m^2 at 50-m heights) and moderate land-use restrictions.

2.0 WIND RESOURCE DATA

The wind resource data base used here was published in a national wind resource atlas (Elliott et al. 1987). Estimates of the wind resource are expressed in wind power classes, defined in Table 1, ranging from class 1 (the lowest) to class 7 (the highest). A gridded map of the annual average wind energy resource for the contiguous United States is shown in Figure 1.

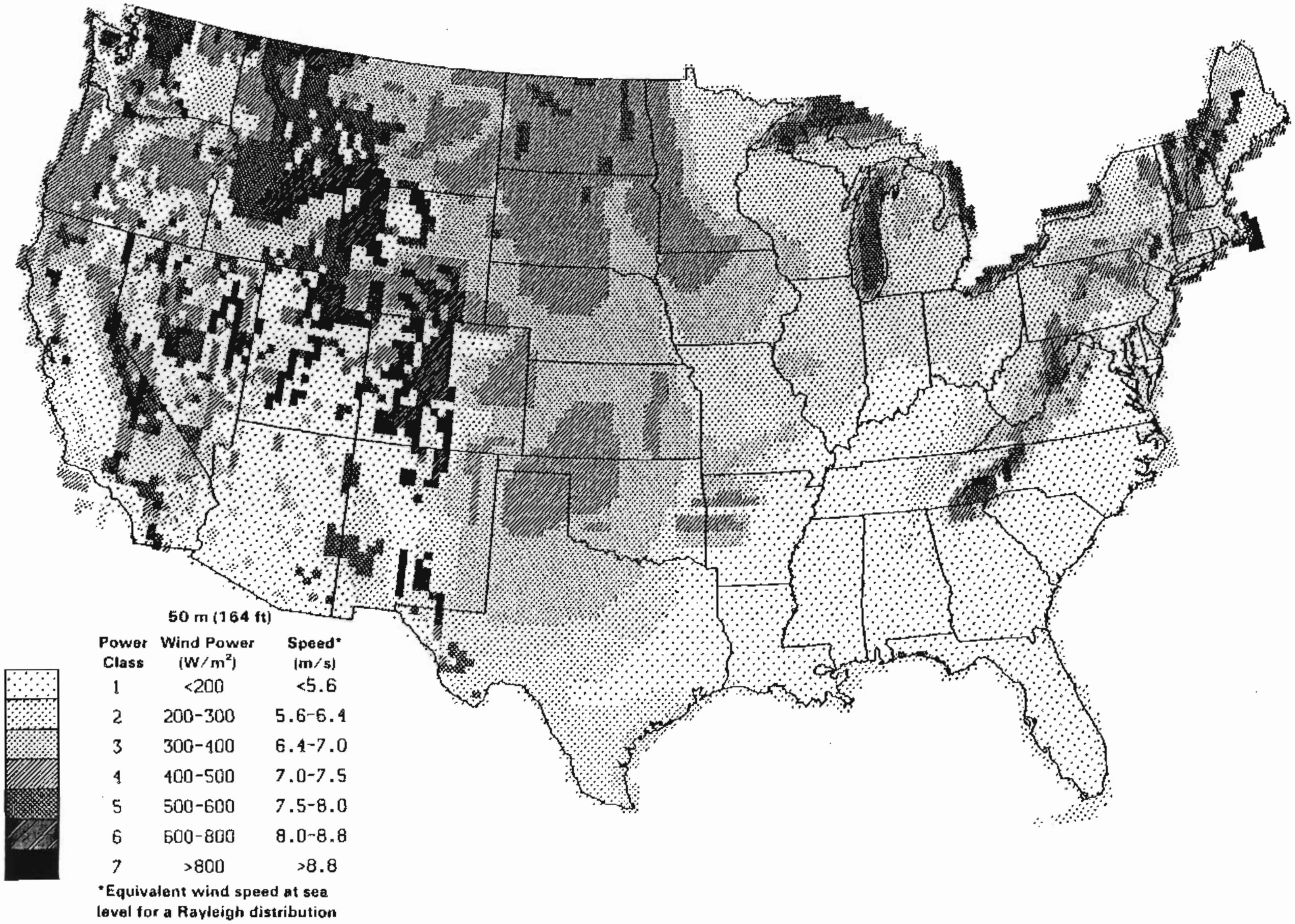
In the atlas, the annual and seasonal average wind power maps appear in both analyzed and gridded versions. To prepare the gridded maps, the analyzed wind resource maps were divided into grid cells of 1/3° longitude by 1/4° latitude over the contiguous United States. The gridded maps were used to assess the certainty of the wind resource estimates and the areal distribution of the wind resources.

TABLE 1. Classes of Wind Power Density

	10 m (33 ft)[a]		30 m (98 ft)[a]		50 m (164 ft)[a]	
Wind Power Class	Wind Power Density, W/m²	Speed[b], m/s (mph)	Wind Power Density, W/m²	Speed[b], m/s (mph)	Wind Power Density, W/m²	Speed[b], m/s (mph)
	0	0	0	0	0	0
1						
	100	4.4 (9.8)	160	5.1 (11.4)	200	5.6 (12.5)
2						
	150	5.1 (11.5)	240	5.9 (13.2)	300	6.4 (14.3)
3						
	200	5.6 (12.5)	320	6.5 (14.6)	400	7.0 (15.7)
4						
	250	6.0 (13.4)	400	7.0 (15.7)	500	7.5 (16.8)
5						
	300	6.4 (14.3)	480	7.4 (16.6)	600	8.0 (17.9)
6						
	400	7.0 (15.7)	640	8.2 (18.3)	800	8.8 (19.7)
7						
	1000	9.4 (21.1)	1600	11.0 (24.7)	2000	11.9 (26.6)

(a) Vertical extrapolation of wind power density and wind speed are based on the 1/7 power law.

(b) Mean wind speed is estimated assuming a Rayleigh distribution of wind speeds and standard sea-level air density. The actual mean wind speed may differ from these estimated values by as much as 20%, depending on the actual wind speed distribution and elevation above sea level.



50 m (164 ft)

Power Class	Wind Power (W/m²)	Speed* (m/s)
1	<200	<5.6
2	200-300	5.6-6.4
3	300-400	6.4-7.0
4	400-500	7.0-7.5
5	500-600	7.5-8.0
6	600-800	8.0-8.8
7	>800	>8.8

*Equivalent wind speed at sea level for a Rayleigh distribution

FIGURE 1. Gridded Map of Annual Average Wind Energy Resource Estimates in the Contiguous United States. Grid cells are 1/4° latitude by 1/3° longitude.

The gridded maps of the wind resource, such as the one in Figure 1, do not show some of the smaller-scale features that are apparent on the analyzed maps. For this reason, the analyzed wind resource maps show greater detail than the gridded maps, especially in mountainous or coastal areas. However, the gridded maps of the wind resource allow the user to associate the wind power classes for specific grid cells with the certainty rating, percentage of land area estimated to have a given wind power class, and other relevant quantities for those grid cells.

Each wind power class represents a range of mean wind power densities (in units of W/m^2) at specified heights above ground. The wind power density incorporates in a single number the combined effect of the frequency distribution of wind speeds and the dependence of the wind power on air density and on the cube of the wind speed. The estimated mean wind speeds shown with each power class correspond to a Rayleigh distribution of wind speeds at standard sea-level air density. Although the Rayleigh distribution approximates observed wind speed distributions reasonably well in many areas of the contiguous United States, there are many exceptions. The actual mean wind speed may differ from the estimated values in Table 1 by as much as 20%, depending on the actual wind speed distribution and elevation above sea level.

Table 2 shows why the annual average wind speed alone may not be a reliable indicator of the annual average wind power density. Data from the three locations listed indicate that the locations have identical mean wind speeds at 10 m (33 ft). However, the wind power density, which is based on the frequency distribution of the wind speeds, is substantially different for the three locations, such that each location has a different wind power class. The wind speed distribution for the location in New York is approximated well by a Rayleigh wind speed distribution. The wind speed distributions of the other two locations are not.

Vertical extrapolation of wind speed and wind power density in Table 1 is based on a power law exponent, α, of 1/7 using the following equations:

$$\frac{V_2}{V_1} = \left(\frac{Z_2}{Z_1}\right)^{\alpha} \quad \text{or} \quad \frac{P_2}{P_1} = \left(\frac{Z_2}{Z_1}\right)^{3\alpha}$$

TABLE 2. Comparison of Annual Average Wind Power at Three Sites With Identical Annual Average Wind Speeds at 10 m

Site	Annual Average Wind Speed, m/s (mph)	Annual Average Wind Power Density, W/m^2	Wind Power Class
Culebra, Puerto Rico	6.3 (14)	220	4
Tiana Beach, New York	6.3 (14)	285	5
San Gorgonio, California	6.3 (14)	365	6

where $V_{1,2}$ and $P_{1,2}$ equal the mean wind speed and wind power density at heights $Z_{1,2}$.

The increase of the mean wind power density with height is reasonably well approximated by the 1/7 power law at many sites (in areas of low roughness and relatively flat terrain), but there are numerous exceptions. In areas of complex terrain and/or high roughness, the wind shear is difficult to estimate with any reasonable degree of certainty. Therefore, it is extremely important to measure the wind resource at heights comparable to wind turbine hub heights, because large errors in a site's estimated wind resource at turbine hub height can occur if the wind resource is extrapolated up from lower heights, such as 10 m. (Hub heights of most existing commercial wind turbines are largely in the range of 18 to 30 m (60 to 100 ft) above ground.)

The wind power estimates apply to areas free of local obstructions to the wind and to terrain features that are well exposed to the wind, such as open plains, tablelands, and hilltops. Within mountainous areas, wind resource estimates apply to exposed ridge crests and mountain summits.

Today's technology allows the exploitation of the wind resource in certain areas with resource class 5 or greater. Most of the successful wind plants in California that are currently being effectively utilized to produce power in a utility grid are located in areas of class 5 or greater wind resource.

In many areas of the United States where wind power increases significantly with height (that is, an increase equal to or greater than that of the 1/7 power, as shown in Table 1), raising the hub height to 50 m could result in at least a 25% increase in energy capture for an additional cost of only about 8% (Hock et al. 1990). Data on wind power variation with height collected at 38 sites in windy areas throughout the contiguous United States indicate that the mean wind power density at the majority (79%) of these sites increases with height at a rate equal to or greater than that estimated using the 1/7 power law (Elliott et al. 1987). In areas where the 1/7 power law applies, a class 3 site with a wind turbine at 50 m would produce approximately the same wind power as a class 4 site with a wind turbine at 28 m or a class 5 site with a wind turbine at 18 m.

With projected improvements in the efficiency of advanced wind turbines (from improved airfoils, power electronics, control systems, and so on) and the use of taller towers raising hub heights to 50 m or higher, class 3 sites could become suitable for wind energy development in the near future. Based on these projections, we have used those grid cells with class 3 or greater resource in Figure 1 in further analyses involving the areal distribution (percentage of land area) and wind electric potential. Grid cells with class 1 or 2 resource are considered unsuitable for wind energy exploitation, at least for commercial-scale utility power generation in the near future, and have been excluded from further analysis.

Because the values for wind power classes shown on the wind resource map in Figure 1 apply only to areas well exposed to the wind, the map area does not indicate the true land area experiencing this power. The fraction of the land area represented by the wind power class shown on the map depends on the physical characteristics of the land-surface form. On a flat open plain, for example, close to 100% of the area will be in the same wind power class, but in hilly and mountainous areas, the wind power class assigned will only apply to that small proportion of the area that is well exposed. A map of classes of land-surface form by Hammond (1964) provided information on the distribution of plains, tablelands, hills, and mountains in the United States. For each class of land-surface form, the percentage of land area that is representative of the area well exposed to the wind has been estimated. These percentages were determined subjectively as a function of the slope, local relief, and profile type specified by Hammond.

Figure 2 shows the areal distribution (expressed as a percentage of a grid cell's total land area) in the contiguous United States for grid cells in which the annual average wind power is class 3 or greater. Grid cells where

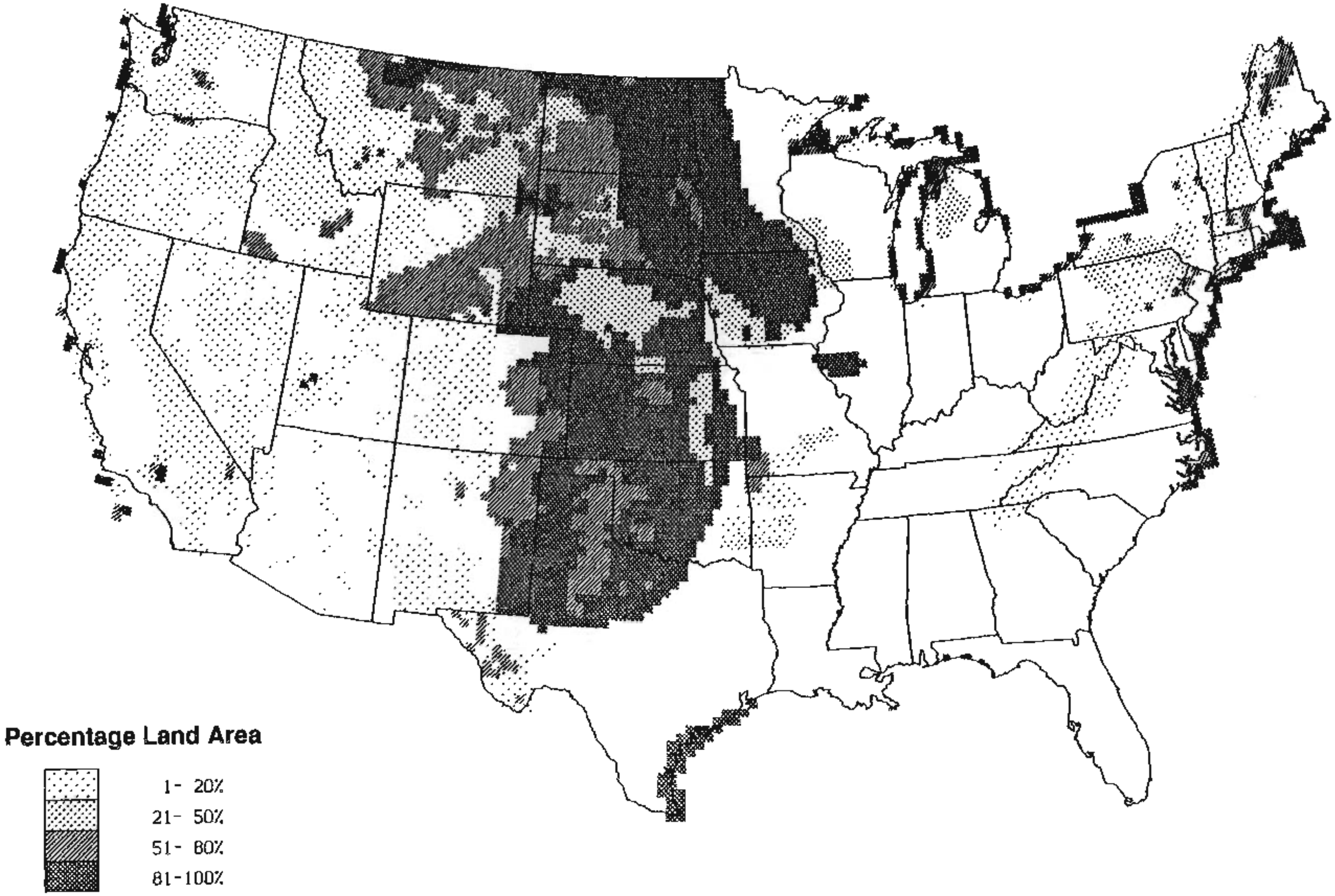


FIGURE 2. Percentage of the Land Area Estimated to Have Class 3 or Higher Wind Power in the Contiguous United States

80% or more of the total land area has class 3 or greater power are mostly located in areas of relatively flat terrain, such as much of the southern and northern Great Plains, coastal areas of Texas, and areas along the Northeast coast and Great Lakes. Hilly areas within the Great Plains, such as the Sand Hills in Nebraska and the Flint Hills in Kansas, are apparent in Figure 2 as areas where generally only 21 to 50% of the land area is well exposed to the wind. Throughout the Appalachians and mountainous areas in the West, suitable wind resource only exists on a small fraction (1 to 20%) of the land area. In many mountainous areas, only about 2 to 5% of the total land area is estimated to be well exposed. The isolated grid cells scattered in California, Oregon, Washington, and Montana that have class 3 or greater power for more than 20% of the land area in the cell represent windy coastal strips or islands in the coastal areas and wind corridors in the inland areas (such as San Gorgonio Pass in California, the Columbia River and Ellensburg corridors in Oregon and Washington, and the Whitehall and Livingston corridors in Montana). Over 50% of the land area in much of southern and central Wyoming and the plains in northwestern Montana has class 3 or greater annual average wind power.

The areal distribution data do not account for environmental or land-use restrictions; that is, any reduction in the fraction of a grid cell's land available for wind energy development was solely a result of terrain interfering with the exposure of potential turbine installations. This areal distribution data base was used as a starting point (base case) for calculating the land areas that would be affected by the environmental and land-use exclusions.

The data on environmental and land-use restrictions were obtained from several sources and in some cases required modification to mesh with the wind energy resource data. We chose several scenarios for estimating the effects of differing levels of land exclusion. Exclusions under these scenarios are discussed in Chapters 3.0 and 4.0 on environmental and land-use restrictions, respectively.

3.0 ENVIRONMENTAL EXCLUSIONS

Environmental exclusion areas, as defined here, largely represent natural areas including parks, monuments, wilderness areas, ecological preserves, and wildlife refuges (as well as some other type of natural areas) where industrial, commercial, and residential developments are restricted or very limited. Although no suitable data base with these environmental areas was available in digital form, national maps were obtained that depicted the locations of federally administered environmental areas. Additional environmental areas are administered by state and private agencies. In examining maps showing the geographical distribution of environmental areas, we recognized that these areas are most concentrated in mountainous and coastal regions. In mountainous regions, the amount of land area occupied by environmental areas generally increases with the ruggedness of the terrain and the local relief. We observed that the distribution and extent of environmental areas are generally correlated with the classes of land-surface form that were already in our gridded data base. For each class of land-surface form, a rough estimate of the percentage of land area to be excluded for environmental reasons was inferred from a comparison of the maps of the federally administered environmental areas with the maps of land-surface form. The exclusion values assigned to each land-surface form are shown for noncoastal areas in Figure 3.

On average, the percentage of area occupied by federally administered environmental lands is probably somewhat less than the exclusion percentages assigned. However, we tried to be conservative in our exclusion estimates to account for other lands that might be excluded for environmental reasons, such as environmental lands administered by state and private agencies, and proposed environmental lands.

A minimum exclusion of 10% was assigned to land-surface forms that, on average, contain only a small fraction of environmentally designated lands. We realize that in a few specific regions, such as flatter regions that contain some large environmentally designated land areas, our estimate of the environmental land exclusion area may be significantly less than the actual; however, in most regions our estimate of the environmental exclusion area is probably much greater than the actual.

Percent Excluded	Land-Surface Form	
	PLAINS	
10%	A1	FLAT PLAINS
10%	A2	SMOOTH PLAINS
10%	B1	IRREGULAR PLAINS, SLIGHT RELIEF
10%	B2	IRREGULAR PLAINS
	PLAINS WITH HILLS OR MOUNTAINS	
10%	A,B3a,b	PLAINS WITH HILLS
10%	B4,a,b	PLAINS WITH HIGH HILLS
20%	B5a,b	PLAINS WITH LOW MOUNTAINS
40%	B6a,b	PLAINS WITH HIGH MOUNTAINS
	OPEN HILLS AND MOUNTAINS	
10%	C2	OPEN LOW HILLS
10%	C3	OPEN HILLS
20%	C4	OPEN HIGH HILLS
40%	C5	OPEN LOW MOUNTAINS
70%	C6	OPEN HIGH MOUNTAINS
	HILLS AND MOUNTAINS	
10%	D3	HILLS
30%	D4	HIGH HILLS
50%	D5	LOW MOUNTAINS
90%	D6	HIGH MOUNTAINS
	TABLELANDS	
10%	B3c,d	TABLELANDS, MODERATE RELIEF
10%	B4c,d	TABLELANDS, CONSIDERABLE RELIEF
30%	B5c,d	TABLELANDS, HIGH RELIEF
70%	B6c,d	TABLELANDS, VERY HIGH RELIEF

SCHEME OF CLASSIFICATION

SLOPE (1st LETTER)

A	>80% OF AREA GENTLY SLOPING
B	50-80% OF AREA GENTLY SLOPING
C	20-50% OF AREA GENTLY SLOPING
D	<20% OF AREA GENTLY SLOPING

LOCAL RELIEF (2nd LETTER)

1	0 TO 30m (1 TO 100 ft)
2	30 TO 90m (100 TO 300 ft)
3	90 TO 150m (300 TO 500 ft)
4	150 TO 300m (500 TO 1000 ft)
5	300 TO 900m (1000 TO 3000 ft)
6	900 TO 1500m (3000 TO 5000 ft)

PROFILE TYPE (3rd LETTER)

a	>75% OF GENTLE SLOPE IS IN LOWLAND
b	50-75% OF GENTLE SLOPE IS IN LOWLAND
c	50-75% OF GENTLE SLOPE IS ON UPLAND
d	>75% OF GENTLE SLOPE IS ON UPLAND

FIGURE 3. Percentages of Land Area Excluded by Environmental Considerations for Each Class of Land-Surface Form (noncoastal areas)

In all coastal areas, at least 50% of the land area was excluded (as opposed to 10% for inland areas) because it was recognized that coastal areas generally have a higher concentration of environmental areas (e.g., national wildlife refuges, national seashores, and state parks) and recreation areas (e.g., beach resorts) where industrial development would be restricted. These coastal areas include the coasts and coastal islands of the Atlantic and Pacific Oceans, the Gulf of Mexico, the Great Lakes, and seven other large lakes. The 50% exclusion was applied to grid cells in which coastal water was at least 1% of the grid cell's total area.

A map of the approximated environmental exclusion areas is shown in Figure 4. The 90% exclusion areas are the most rugged mountainous regions of the West, where local relief exceeds 3000 ft. The large exclusion in the high mountains of the West accounts not only for environmentally designated areas but also for the inaccessibility of the high mountains because of the steep terrain and heavy snow in the winter season. The mountains throughout the Great Basin Plateau, such those in Nevada where 30 to 40% of the land area was excluded, have fewer environmental areas and are more accessible than the more rugged mountains of the Rockies, Cascades, and Sierras. In the Appalachians, the exclusion areas range from 20% in the hilly areas to 50% in the most mountainous areas. Deep canyons, as well as mountains, are also accounted for in the environmental exclusion areas. The Grand Canyon is largely included in the 70% exclusion area in northwestern Arizona. The 10% exclusion areas represent flatter regions where, for the most part, environmental areas occupy only a small fraction of the total land area.

Special care was taken not to exclude known wind corridors that exist at relatively low elevations within the mountainous regions, such as the wind corridors in California, Montana, and Washington. The wind corridor areas were identified and assigned the minimal 10% exclusion.

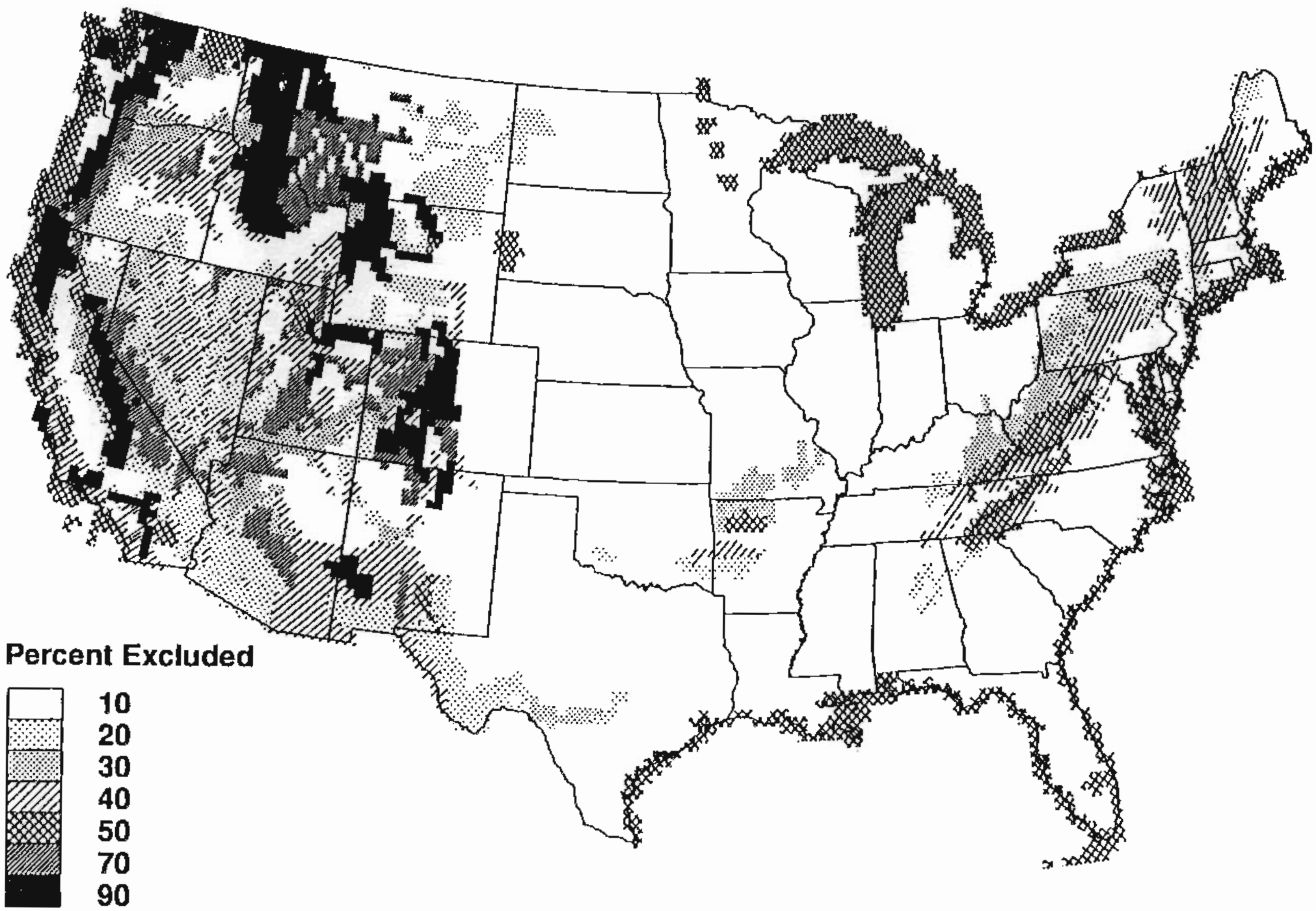


FIGURE 4. Percentage of Each Grid Cell Excluded by Environmental Considerations

4.0 LAND-USE EXCLUSIONS

For estimating land-use exclusion areas, we obtained a suitable land-use data base in digital form that was developed by the U.S. Environmental Protection Agency (EPA), Las Vegas. This land-use data base included the percentage of each grid element associated with each of the 11 land-use types: 1) agricultural land; 2) range land; 3) mixed agricultural and range land; 4) deciduous forest; 5) coniferous forest; 6) mixed forest; 7) urban land; 8) barren land; 9) nonforested wetland, 10) water; and 11) open, low scrub land. The land-use data were for grid cells of 1/6° latitude by 1/4° longitude, whereas PNL's wind resource grid cells were for 1/4° latitude by 1/3° longitude. We converted the land-use data base to the PNL grid cell format.

Maps showing the geographical distribution of each land-use type are shown in Figure 5. Forest, agricultural, and range lands combined account for the vast majority of the land area in the contiguous United States. Moreover, in any given state, at least one of these three major land-use types--forest, agricultural, or range--accounts for the majority of the state's land area. The other land-use types (excluding water) account for only a small fraction of the total land area of the United States.

Major areas occupied by water were excluded from the wind energy base case even before environmental and land-use restrictions are taken into account. For example, the map of class 3 and higher wind power areas in Figure 2 excludes major water bodies, such as coastal waters (i.e., bays, inlets, harbors, and sounds, as well as offshore areas) and major lakes (i.e., the Great Lakes and seven other large lakes). One element in our wind resource data base specified the percentage of each grid cell's area that is land, for grid cells over these coastal areas or major lakes.

To identify areas of water to be excluded, we initially attempted to use the water data derived from the EPA-developed land-use data base, which included inland water areas not in the PNL-developed data base. However, we found that some grid cells containing major coastal lands and islands (e.g., Block Island, Rhode Island; Nantucket Island, Martha's Vineyard, and a large fraction of Cape Cod, Massachusetts, as well as some significant land areas in other coastal regions of the United States) were classified as water.

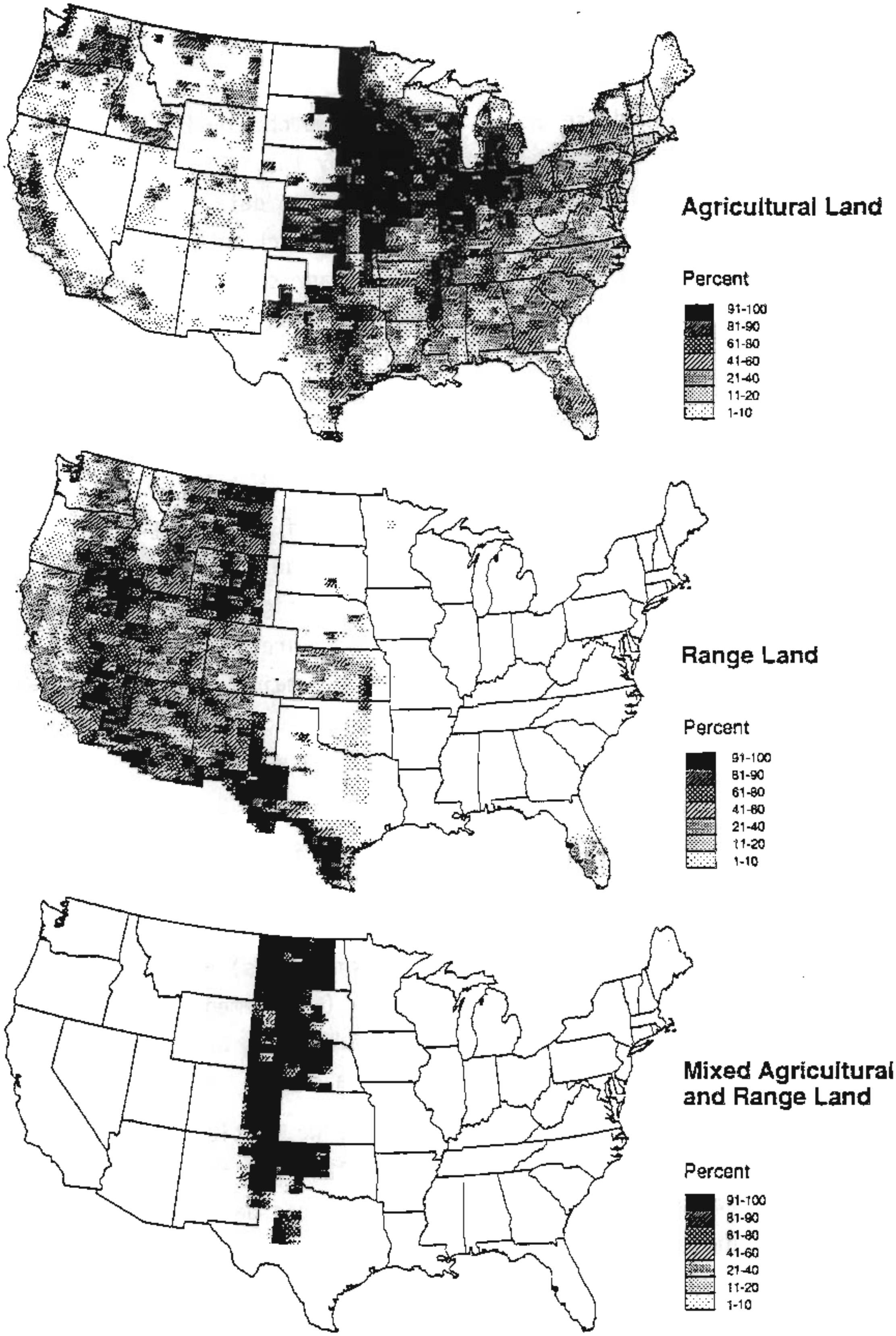


FIGURE 5. Maps of Land-Use Type from the Gridded Data Base

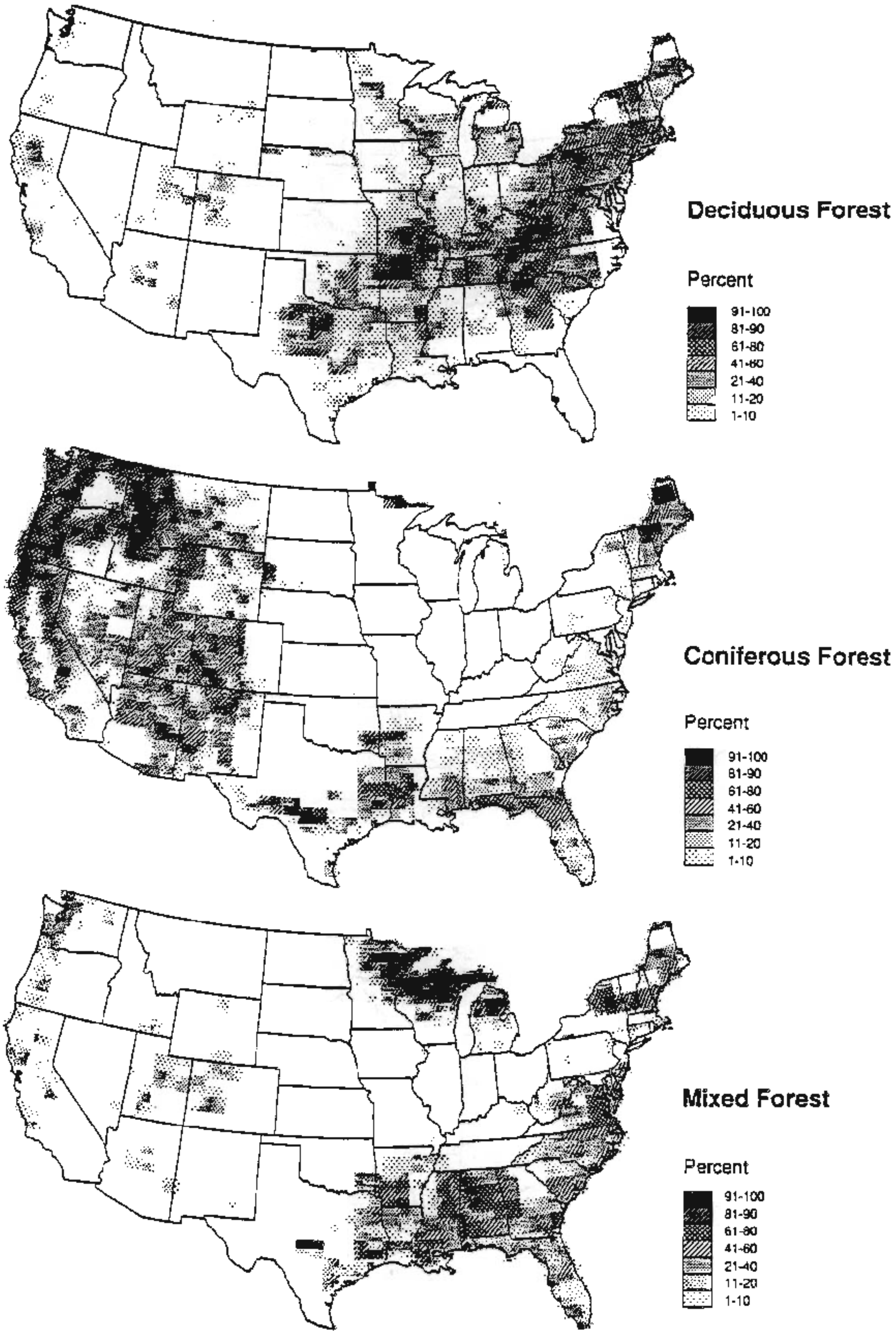


FIGURE 5. (contd)

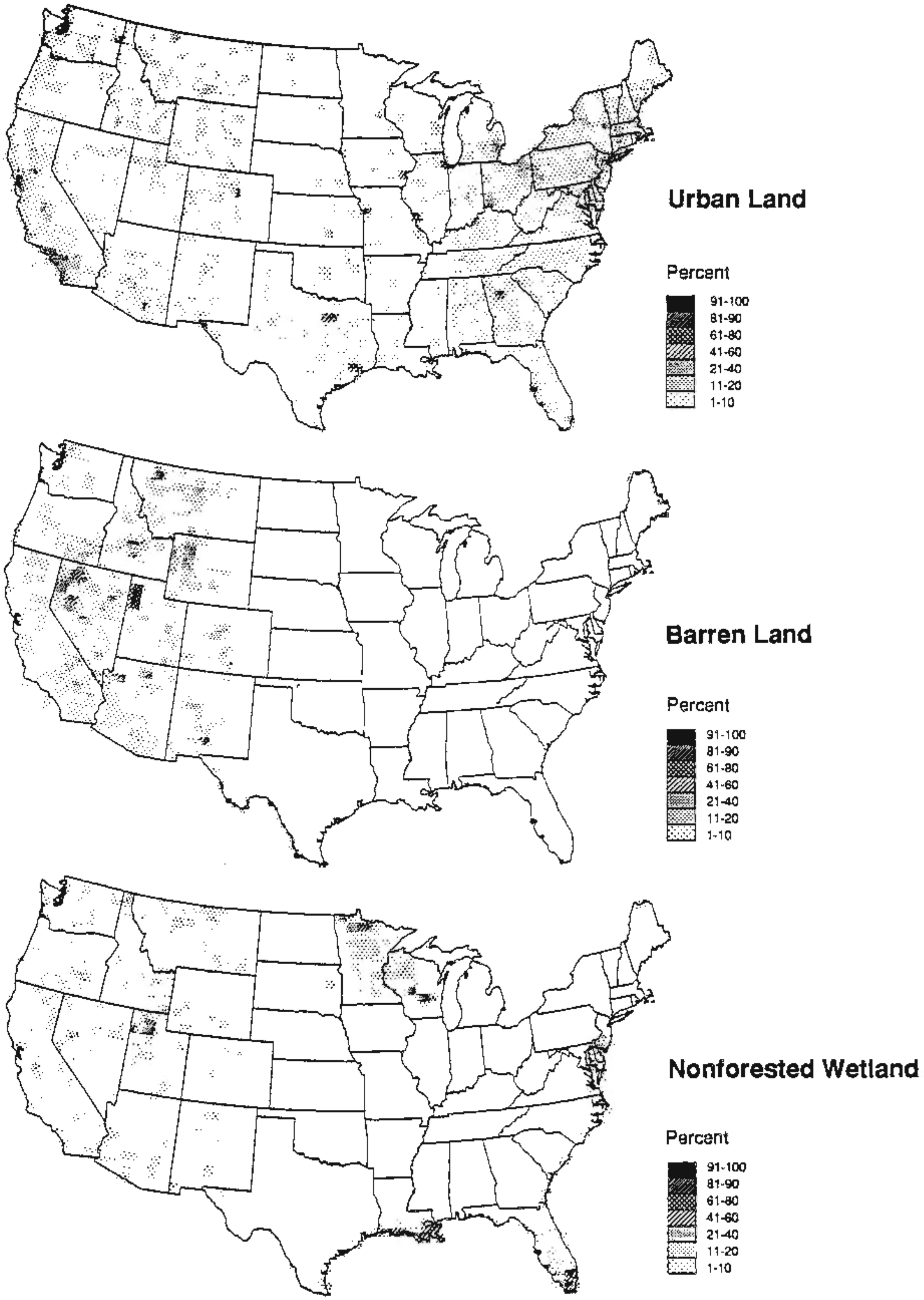


FIGURE 5. (contd)

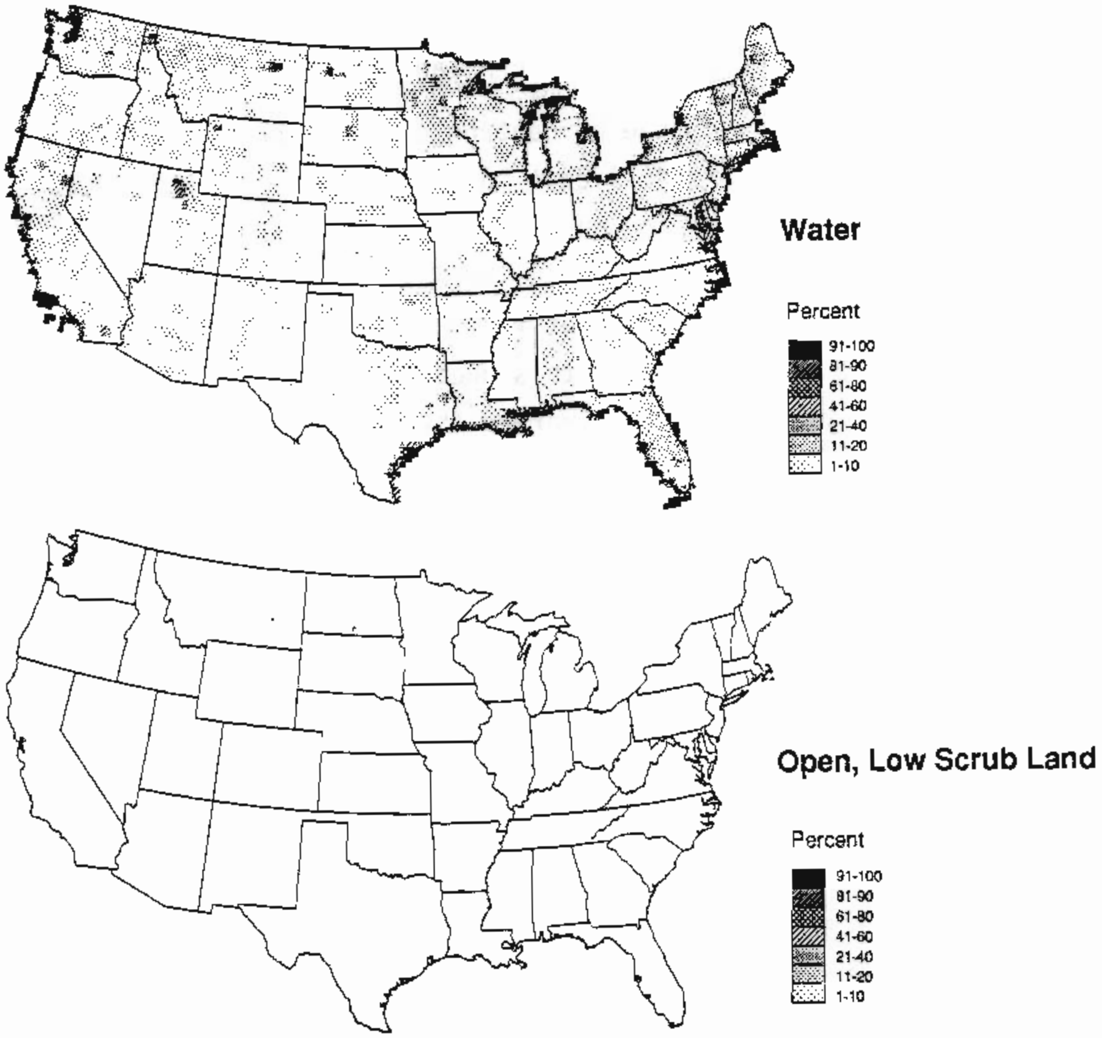


FIGURE 5. (contd)

To exclude these coastal land areas would have a substantial impact on the areal wind resource estimates, especially for states where a large fraction of the wind resource potential is from coastal lands. For this reason, we did not use the water data from the EPA land-use data base.

As might be expected, the percentage of the land area to be excluded from wind energy development is difficult to estimate for certain types of land use and vary widely, depending on the assumptions made. The greatest uncertainty concerned how to treat forest, agricultural, and mixed agricultural/range lands, which together account for a large fraction of the land area in the United States. To deal with this uncertainty, we created several land-use exclusion scenarios, in which we varied the percentage of the land area excluded for these three land-use types, to evaluate what effect the different exclusions would have on the areal estimates for a given state or the United States. For this report, we will describe two of these scenarios--a "moderate" and a "severe" land-use restriction.

Table 3 shows, for each land-use type, the percentage of land area excluded under the moderate and severe land-use restrictions. The only differences between the moderate and severe land-use restrictions occur with the forest, agricultural, and mixed agricultural/range lands. For simplicity, we have combined the three original forest land-use types (deciduous, coniferous, and mixed) into a single category called "forest". The low, open scrub land-use type has been omitted from Table 3, because no lands were classified as this type in the contiguous United States (see Figure 5). Lands that could possibly have been classified as low, open scrub land were apparently classified as range or barren land. For example, the desert scrub land in southeastern California, including the Mojave Desert, is largely classified as range land.

The land-use types in Table 3 are listed in approximate order by total land area in the contiguous United States, with forest lands occupying the largest area and urban lands the smallest area. The first four land-use types combined represent more than 90% of the total land area of the contiguous United States. Therefore, specification of the percentage of land area excluded for these four land-use types has the greatest impact on the areal wind resource estimates. The other three land-use types (barren, wetland,

TABLE 3. Percentage of Land Area Excluded Under Moderate and Severe Land-Use Restrictions for Each Land-Use Type

Land-Use Type	Percentage of Land Excluded	
	Moderate	Severe
Forest	50	100
Agriculture	30	100
Range	10	10
Mixed Ag./Range	20	55
Barren	10	10
Wetland	100	100
Urban	100	100

and urban) account for only a relatively small percentage of the contiguous U.S. land area, so that varying the exclusion percentages for these lands has only a relatively minor impact on the areal wind resource estimates.

For urban land and wetland, 100% of the land area was excluded under both moderate and severe land-use restrictions, because we believe that wind energy development in these areas is unlikely.

For range land and barren land, we do not see any conflicts with wind energy development, given that wind farms have successfully been located in these types of land-use areas in California. However, we have excluded 10% of these land areas to account for land that may be occupied by roads and structures.

For agricultural lands, we have excluded 30% of the land area under the moderate land-use restriction and 100% of the land area under the severe land-use restriction. A 30% exclusion was considered to be realistic under the moderate land-use restriction for the following reasons:

1. Wind energy development would occupy no more than about 10% of the available land area, so that most of the land area would still be available for agricultural uses.

2. The exclusion issue could depend more on economics than on anything else in the agricultural areas; if farmers receive compensation for the use of their land to the extent that their earnings are significantly greater for energy production than for crop production, then they may be more than willing to give up some land for energy production while still retaining much of it for crop production.

3. With this optimistic scenario, we have assumed that 80% of all agricultural land (in windy areas) will be available, but that about 10% of the available land is excluded to allow for existing structures and roads.

Under the severe land-use restriction, where 100% of the agricultural land would be excluded from wind energy development, the wind resource potential would be drastically reduced in many states in the Midwest and Great Plains agricultural belts. For example, Iowa would lose more than 90% of its wind resource potential, because agricultural lands make up over 90% of the state's windy land area.

For the mixed agricultural and range land-use type, we have assumed that these lands are 50% agricultural and 50% range lands. Therefore, we took the average of the percentage of land area excluded for the separate agricultural and range lands, resulting in a 20% exclusion under the moderate land-use restriction and a 55% exclusion under the severe land-use restriction. The mixed agricultural and range lands include much of the Great Plains region that extends from northwestern Texas northward to North Dakota.

For forest lands, we have excluded 50% and 100% of the land area under the moderate and severe land-use restrictions, respectively. We selected a 50% exclusion under the moderate land-use restriction for several reasons. First, although forest lands cover much of the eastern United States, in nonmountainous terrain they are predominantly in low wind resource areas (class 1 and 2). Because we are only concerned with areal estimates for areas of class 3 and higher, our focus is primarily on the forested mountain regions, where the highest wind resources are located on the ridge crests. Trees on exposed ridge crests are quite often smaller and more scattered than those on the slopes and in the valleys. In fact, well-exposed ridge crests in some forested regions are nearly devoid of trees. On ridges where the trees are relatively small (i.e., no taller than about 10 m), it may not be necessary to remove many trees if relatively tall towers (e.g., 50-m towers) are used, such that the wind turbine rotor disks are substantially above the trees. Thus, from this perspective, it appears reasonable to include much of the land area associated with windy ridge crests in forested lands that could be utilized for wind energy development without significant removal of existing trees. (We emphasize that, in mountainous terrain, the land area represented by ridge crests is typically only about 5% of the total land area.)

However, some forests are located in nonmountainous terrain (e.g., in areas of hills or tablelands) that is still estimated to have a class 3 or higher resource, such as forested areas in western Texas, central Oklahoma, southwestern Wisconsin, northern Michigan, and the northeastern states. In these areas, hilltops and uplands with good exposure to winds are likely to have good wind resource, but the wind resource is diminished significantly near or downwind from groves of trees unless the trees are relatively small in comparison to the turbine height. To exclude a larger fraction of the forest land that is located on exposed terrain in nonmountainous areas is impractical because of geographical variations in the height and density of the trees (e.g., the trees in western Texas are substantially smaller and more scattered than those in northern Michigan).

To more adequately address the exclusion of forested areas, data on the height and density of the trees would be useful, but this information is not available in our current data base. Therefore, after considering all types of terrain and the variability of the height and density of trees in the different regions and at different elevations, we have elected to exclude 50% of the forest lands under the moderate land-use restriction and 100% under the severe land-use restriction.

We performed an analysis to examine what happens to the areal estimates of wind resource for three different exclusions of forest lands: 0%, 50%, and 100%. When the forest exclusion is increased from 0% to 50% or 100%, the U.S. land area with class 3 and greater is reduced by about 8% or 14%. This small reduction in land area occurs because only a small fraction of the windy land area of the United States is forest land, since most of the forest land is located in areas of low wind resource (class 1 and 2). However, if we exclude 100% of the forest land, the windy land area is severely reduced in many of the eastern states, where large parts of the high wind resource areas are ridge crests in the Appalachians. For example, excluding all forest land eliminates about 90% of the windy land in West Virginia, where the high wind resource areas are ridge crests located in mountainous terrain that is largely forested. Under the moderate land-use restriction, where 50% of forest land is excluded, West Virginia would lose approximately half its windy land area. (This exclusion does not account for the additional land area that would be excluded by environmental considerations.)

5.0 ESTIMATES OF WINDY LAND AREA

The environmental exclusions and land-use exclusion categories were applied in a number of combinations to evaluate the effect on the amount of available land in the contiguous United States at each power class level. For a given wind power class, the available windy land area in a grid cell may be calculated by

$$A_W = A_T\, f_p(1-f_E)\ (1-f_L)$$

where A_T = total land area in the grid cell

f_p = fraction of the grid cell area in the specified wind power class

f_E = fraction of the grid cell area excluded by environmental considerations

f_L = fraction of the grid cell area excluded by land-use considerations.

The value of A_T depends on the latitude and the percentage of the grid cell that is land and within the state boundary. The value of f_p depends on the wind power class and the land-surface form. The environmental exclusion, f_E, was approximated using data on land-surface form. The value of f_L depends on the land-use types and the exclusion scenario that is specified (for example, moderate or severe land-use restrictions).

The windy land area in a state is calculated by summing A_W for all grid cells in the state, for each designated power class.

For the purpose of this report, we have chosen four land exclusion scenarios for comparison and summarize the results for the contiguous United States in Figure 6 and Table 4. The land area estimates by power class are given for each state in Tables 5 through 8 for the four land exclusion scenarios. The values of wind power density in W/m^2 that are given for each wind power class in Figure 6 represent the median values for the 30- and 50-m heights (see Table 1 for the range of wind power density values in each power class). To put the areas into perspective, we have included a representation of equivalent state land areas in Figure 6, as well as the percentage of the contiguous U.S. land area.

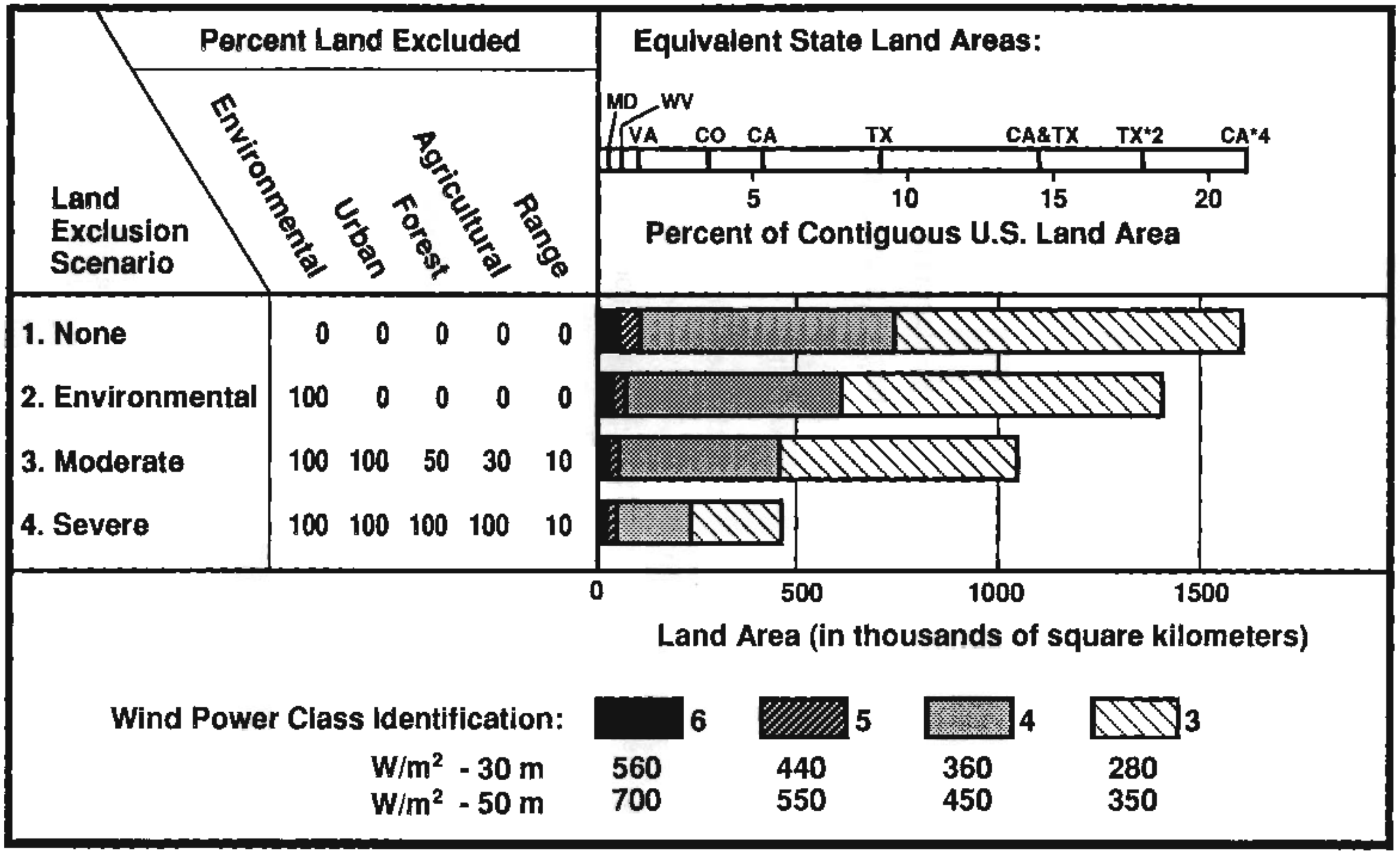


FIGURE 6. Windy Land Area in the Contiguous United States for Four Land Exclusion Scenarios

TABLE 4. Windy Land Area in the Contiguous United States for Four Land Exclusion Scenarios in Units of a) Square Kilometers, b) Percentage of U.S. Land Area, and c) Ratio to the Base Case (Scenario 1)

a) Windy Land Area in Square Kilometers

	Land Exclusion Scenario*					Square Kilometers (in Thousands) Per Power Class							
	E	U	F	A	R	3	4	5	6	7	≥ 3	≥ 4	≥ 5
1	0	0	0	0	0	903.2	614.4	53.0	35.6	1.5	1607.7	704.6	90.1
2	100	0	0	0	0	787.3	537.5	36.6	21.2	0.4	1383.0	595.7	58.2
3	100	100	50	30	10	579.4	415.1	27.9	17.2	0.3	1040.0	460.5	45.4
4	100	100	100	100	10	216.6	188.0	15.3	14.5	0.2	434.7	218.0	30.0

b) Windy Land Area in Percent of Contiguous U.S. Land Area

						Percentage of U.S. Land Area Per Power Class							
1	0	0	0	0	0	11.77	8.01	0.69	0.46	0.02	20.95	9.18	1.17
2	100	0	0	0	0	10.26	7.00	0.48	0.28	<0.01	18.02	7.76	0.76
3	100	100	50	30	10	7.55	5.41	0.36	0.22	<0.01	13.55	6.00	0.58
4	100	100	100	100	10	2.82	2.45	0.20	0.19	<0.01	5.66	2.84	0.39

c) Windy Land Area as a Ratio to the Base Case (Scenario 1)

						Land Area Ratio (Scenario X/Scenario 1) Per Power Class							
1	0	0	0	0	0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2	100	0	0	0	0	0.87	0.87	0.69	0.60	0.25	0.86	0.85	0.65
3	100	100	50	30	10	0.64	0.68	0.53	0.48	0.18	0.65	0.65	0.50
4	100	100	100	100	10	0.24	0.31	0.29	0.41	0.12	0.27	0.31	0.33

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* Land-Use Types: E - Environmental; U - Urban; F - Forest; A - Agriculture; R - Range. Values are the percentage of windy land area excluded from wind power plant development by land types.

TABLE 5. State Land Area by Power Class for Land Exclusion Scenario 1 (No Exclusions)

State	Square Kilometers per Power Class					Percentage of Land per Power Class					Total Land, km^2
	3	4	5	6	7	3	4	5	6	7	
Alabama	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	131,487
Arizona	1,119	311	571	57	0	0.4	0.1	0.2	0.0	0.0	293,986
Arkansas	4,807	642	62	0	0	3.6	0.5	0.1	0.0	0.0	134,883
California	6,670	3,752	1,777	2,145	104	1.6	0.9	0.4	0.5	0.0	404,815
Colorado	28,472	34,853	178	3,408	376	10.6	13.0	0.1	1.3	0.1	268,311
Connecticut	1,035	99	8	0	0	8.2	0.8	0.1	0.0	0.0	12,618
Delaware	657	32	0	0	0	13.1	0.7	0.0	0.0	0.0	5,005
Florida	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	140,365
Georgia	168	253	22	0	0	0.1	0.2	0.0	0.0	0.0	150,365
Idaho	7,284	2,061	3,375	1,259	100	3.4	1.0	1.6	0.6	0.1	213,449
Illinois	11,296	22	0	0	0	7.8	0.0	0.0	0.0	0.0	144,120
Indiana	0	70	0	0	0	0.0	0.1	0.0	0.0	0.0	93,064
Iowa	66,520	23,808	0	0	0	45.9	16.4	0.0	0.0	0.0	144,950
Kansas	113,949	49,506	0	0	0	53.8	23.4	0.0	0.0	0.0	211,814
Kentucky	111	12	0	0	0	0.1	0.0	0.0	0.0	0.0	102,743
Louisiana	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	115,310
Maine	10,655	1,172	472	175	13	13.3	1.5	0.6	0.2	0.0	80,277
Maryland	894	129	11	0	0	3.5	0.5	0.1	0.0	0.0	25,477
Massachusetts	4,732	339	634	265	0	23.4	1.7	3.1	1.3	0.0	20,265
Michigan	13,900	1,407	567	0	0	9.4	0.9	0.4	0.0	0.0	147,511
Minnesota	34,962	63,775	0	0	0	17.0	31.0	0.0	0.0	0.0	206,030
Mississippi	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	122,333
Missouri	10,707	0	0	0	0	6.0	0.0	0.0	0.0	0.0	178,568
Montana	74,795	46,719	11,376	4,529	164	19.9	12.4	3.0	1.2	0.0	376,564
Nebraska	101,771	29,585	0	0	0	51.3	14.9	0.0	0.0	0.0	198,508
Nevada	1,877	2,379	2,017	1,432	137	0.7	0.8	0.7	0.5	0.1	284,624
New Hampshire	341	342	305	89	6	1.5	1.5	1.3	0.4	0.0	23,292
New Jersey	2,461	237	0	0	0	12.7	1.2	0.0	0.0	0.0	19,342
New Mexico	56,965	5,733	738	1,312	132	18.1	1.8	0.2	0.4	0.0	314,256
New York	13,298	2,182	174	14	0	10.8	1.8	0.1	0.0	0.0	122,707
North Carolina	1,061	236	460	132	9	0.9	0.2	0.4	0.1	0.0	126,504
North Dakota	880	120,255	22,479	0	0	0.5	65.7	12.3	0.0	0.0	183,113
Ohio	843	278	0	0	0	0.8	0.3	0.0	0.0	0.0	106,210
Oklahoma	77,127	36,015	10	0	0	43.4	20.2	0.0	0.0	0.0	177,817
Oregon	1,090	7,842	949	83	5	0.4	3.2	0.4	0.0	0.0	249,117
Pennsylvania	7,001	3,368	88	0	0	6.0	2.9	0.1	0.0	0.0	116,260
Rhode Island	204	31	0	0	0	7.5	1.2	0.0	0.0	0.0	2,732
South Carolina	98	40	4	0	0	0.1	0.1	0.0	0.0	0.0	78,227
South Dakota	39,848	97,004	1,366	3	0	20.3	49.3	0.7	0.0	0.0	196,715
Tennessee	223	199	60	30	2	0.2	0.2	0.1	0.0	0.0	106,591
Texas	151,216	39,652	413	116	8	22.3	5.8	0.1	0.0	0.0	678,623
Utah	1,639	645	567	2,120	181	0.8	0.3	0.3	1.0	0.1	212,569
Vermont	244	438	413	40	0	1.0	1.8	1.7	0.2	0.0	24,017
Virginia	2,810	562	105	6	0	2.7	0.6	0.1	0.0	0.0	102,832
Washington	1,586	3,048	2,814	276	8	0.9	1.8	1.6	0.2	0.0	172,264
West Virginia	840	523	236	20	0	1.4	0.8	0.4	0.0	0.0	62,468
Wisconsin	11,153	850	127	0	0	7.9	0.6	0.1	0.0	0.0	140,964
Wyoming	35,844	34,015	646	18,105	253	14.3	13.5	0.3	7.2	0.1	251,201
Total	903,175	614,419	53,024	35,616	1,498	11.8	8.0	0.7	0.5	0.0	7,675,265

TABLE 6. State Land Area by Power Class for Land Exclusion Scenario 2 (Environmental Exclusions)

State	Square Kilometers per Power Class					Percentage of Land per Power Class					Total Land, km2
	3	4	5	6	7	3	4	5	6	7	
Alabama	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	131,487
Arizona	667	186	304	28	0	0.2	0.1	0.1	0.0	0.0	293,986
Arkansas	3,819	369	34	0	0	2.8	0.3	0.0	0.0	0.0	134,883
California	3,866	1,596	409	1,073	31	1.0	0.4	0.1	0.3	0.0	404,815
Colorado	25,560	31,210	51	561	61	9.5	11.6	0.0	0.2	0.0	268,311
Connecticut	874	64	5	0	0	6.9	0.5	0.0	0.0	0.0	12,618
Delaware	295	14	0	0	0	5.9	0.3	0.0	0.0	0.0	5,005
Florida	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	140,365
Georgia	118	141	11	0	0	0.1	0.1	0.0	0.0	0.0	150,365
Idaho	6,532	815	956	304	22	3.1	0.4	0.4	0.1	0.0	213,449
Illinois	9,947	10	0	0	0	6.9	0.0	0.0	0.0	0.0	144,120
Indiana	0	31	0	0	0	0.0	0.0	0.0	0.0	0.0	93,064
Iowa	59,868	21,427	0	0	0	41.3	14.8	0.0	0.0	0.0	144,950
Kansas	102,554	44,556	0	0	0	48.4	21.0	0.0	0.0	0.0	211,814
Kentucky	56	8	0	0	0	0.1	0.0	0.0	0.0	0.0	102,743
Louisiana	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	115,310
Maine	9,335	560	275	104	8	11.6	0.7	0.3	0.1	0.0	80,277
Maryland	416	74	7	0	0	1.6	0.3	0.0	0.0	0.0	25,477
Massachusetts	3,610	186	288	119	0	17.8	0.9	1.4	0.6	0.0	20,265
Michigan	9,153	648	255	0	0	6.2	0.4	0.2	0.0	0.0	147,511
Minnesota	31,005	57,384	0	0	0	15.1	27.9	0.0	0.0	0.0	206,030
Mississippi	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	122,333
Missouri	9,335	0	0	0	0	5.2	0.0	0.0	0.0	0.0	178,568
Montana	66,185	40,573	7,668	2,769	33	17.6	10.8	2.0	0.7	0.0	376,564
Nebraska	91,594	26,626	0	0	0	46.1	13.4	0.0	0.0	0.0	198,508
Nevada	1,281	1,389	1,111	819	79	0.4	0.5	0.4	0.3	0.0	284,624
New Hampshire	271	205	177	47	3	1.2	0.9	0.8	0.2	0.0	23,292
New Jersey	1,650	106	0	0	0	8.5	0.6	0.0	0.0	0.0	19,342
New Mexico	50,854	5,079	222	428	41	16.2	1.6	0.1	0.1	0.0	314,258
New York	9,116	1,344	92	7	0	7.4	1.1	0.1	0.0	0.0	122,707
North Carolina	490	126	238	67	4	0.4	0.1	0.2	0.1	0.0	126,504
North Dakota	710	107,792	20,231	0	0	0.4	58.9	11.1	0.0	0.0	183,113
Ohio	379	124	0	0	0	0.4	0.1	0.0	0.0	0.0	106,210
Oklahoma	69,188	32,278	6	0	0	38.9	18.1	0.0	0.0	0.0	177,817
Oregon	704	4,173	432	28	1	0.3	1.7	0.2	0.0	0.0	249,117
Pennsylvania	5,383	2,487	52	0	0	4.6	2.1	0.0	0.0	0.0	116,260
Rhode Island	98	14	0	0	0	3.6	0.5	0.0	0.0	0.0	2,732
South Carolina	77	20	2	0	0	0.1	0.0	0.0	0.0	0.0	78,227
South Dakota	35,813	87,216	1,208	1	0	18.2	44.3	0.6	0.0	0.0	196,715
Tennessee	118	102	30	15	1	0.1	0.1	0.0	0.0	0.0	106,591
Texas	131,820	35,649	328	92	6	19.4	5.2	0.1	0.0	0.0	678,623
Utah	1,305	335	221	790	42	0.6	0.2	0.1	0.4	0.0	212,569
Vermont	189	262	236	23	0	0.8	1.1	1.0	0.1	0.0	24,017
Virginia	1,533	321	56	3	0	1.5	0.3	0.1	0.0	0.0	102,832
Washington	911	1,575	1,287	86	3	0.5	0.9	0.8	0.1	0.0	172,264
West Virginia	469	292	129	11	0	0.8	0.5	0.2	0.0	0.0	62,468
Wisconsin	8,631	382	57	0	0	6.1	0.3	0.0	0.0	0.0	140,964
Wyoming	31,513	29,746	228	13,860	46	12.6	11.8	0.1	5.5	0.0	251,201
Total	787,292	537,493	36,604	21,236	381	10.3	7.0	0.5	0.3	0.0	7,675,265

TABLE 7. State Land Area by Power Class for Land Exclusion Scenario 3 (Environmental and Moderate Land-Use Exclusions)

State	Square Kilometers per Power Class					Percentage of Land per Power Class					Total Land, km^2
	3	4	5	6	7	3	4	5	6	7	
Alabama	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	131,487
Arizona	499	142	211	19	0	0.2	0.1	0.1	0.0	0.0	293,986
Arkansas	2,109	195	18	0	0	1.6	0.1	0.0	0.0	0.0	134,883
California	2,992	1,168	301	768	23	0.7	0.3	0.1	0.2	0.0	404,815
Colorado	20,330	24,899	29	352	38	7.6	9.3	0.0	0.1	0.0	268,311
Connecticut	507	33	2	0	0	4.0	0.3	0.0	0.0	0.0	12,618
Delaware	179	8	0	0	0	3.6	0.2	0.0	0.0	0.0	5,005
Florida	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	140,365
Georgia	61	73	5	0	0	0.0	0.1	0.0	0.0	0.0	150,365
Idaho	5,741	613	648	224	17	2.7	0.3	0.3	0.1	0.0	213,449
Illinois	6,786	6	0	0	0	4.7	0.0	0.0	0.0	0.0	144,120
Indiana	0	22	0	0	0	0.0	0.0	0.0	0.0	0.0	93,064
Iowa	41,695	15,007	0	0	0	28.8	10.4	0.0	0.0	0.0	144,950
Kansas	75,386	33,284	0	0	0	35.6	15.7	0.0	0.0	0.0	211,814
Kentucky	29	3	0	0	0	0.0	0.0	0.0	0.0	0.0	102,743
Louisiana	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	115,310
Maine	5,287	435	148	57	4	6.6	0.5	0.2	0.1	0.0	80,277
Maryland	268	41	3	0	0	1.0	0.2	0.0	0.0	0.0	25,477
Massachusetts	2,009	121	246	119	0	9.9	0.6	1.2	0.6	0.0	20,265
Michigan	6,141	558	240	0	0	4.2	0.4	0.2	0.0	0.0	147,511
Minnesota	20,875	40,214	0	0	0	10.1	19.5	0.0	0.0	0.0	206,030
Mississippi	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	122,333
Missouri	5,786	0	0	0	0	3.2	0.0	0.0	0.0	0.0	178,568
Montana	55,797	33,528	5,864	2,110	24	14.8	8.9	1.6	0.6	0.0	376,564
Nebraska	69,093	21,051	0	0	0	34.8	10.6	0.0	0.0	0.0	198,508
Nevada	1,110	1,152	925	675	65	0.4	0.4	0.3	0.2	0.0	284,624
New Hampshire	141	109	95	25	1	0.6	0.5	0.4	0.1	0.0	23,292
New Jersey	1,044	90	0	0	0	5.4	0.5	0.0	0.0	0.0	19,342
New Mexico	42,148	3,989	150	303	29	13.4	1.3	0.1	0.1	0.0	314,258
New York	5,599	918	51	4	0	4.6	0.8	0.0	0.0	0.0	122,707
North Carolina	444	68	128	35	2	0.3	0.1	0.1	0.0	0.0	126,504
North Dakota	569	84,255	15,893	0	0	0.3	46.0	8.7	0.0	0.0	183,113
Ohio	255	110	0	0	0	0.2	0.1	0.0	0.0	0.0	106,210
Oklahoma	47,371	25,517	3	0	0	26.6	14.4	0.0	0.0	0.0	177,817
Oregon	559	2,850	285	17	0	0.2	1.1	0.1	0.0	0.0	249,117
Pennsylvania	3,150	1,372	28	0	0	2.7	1.2	0.0	0.0	0.0	116,260
Rhode Island	86	14	0	0	0	3.2	0.5	0.0	0.0	0.0	2,732
South Carolina	41	10	1	0	0	0.1	0.0	0.0	0.0	0.0	78,227
South Dakota	25,628	67,257	841	0	0	13.0	34.2	0.4	0.0	0.0	196,716
Tennessee	83	56	17	7	0	0.1	0.1	0.0	0.0	0.0	106,591
Texas	94,918	28,396	285	82	6	14.0	4.2	0.0	0.0	0.0	678,623
Utah	1,000	241	154	532	28	0.5	0.1	0.1	0.2	0.0	212,569
Vermont	111	142	128	12	0	0.5	0.6	0.5	0.1	0.0	24,017
Virginia	1,051	184	30	1	0	1.0	0.2	0.0	0.0	0.0	102,832
Washington	593	1,148	913	55	2	0.3	0.7	0.5	0.0	0.0	172,264
West Virginia	255	158	68	5	0	0.4	0.2	0.1	0.0	0.0	62,468
Wisconsin	5,762	312	56	0	0	4.1	0.2	0.0	0.0	0.0	140,984
Wyoming	26,003	25,390	178	11,801	34	10.4	10.1	0.1	4.7	0.0	251,201
Total	579,449	415,117	27,944	17,203	273	7.5	5.4	0.4	0.2	0.0	7,675,265

TABLE 8. State Land Area by Power Class for Land Exclusion Scenario 4 (Environmental and Severe Land-Use Exclusions)

State	Square Kilometers per Power Class					Percentage of Land per Power Class					Total Land, km^2
	3	4	5	6	7	3	4	5	6	7	
Alabama	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	131,487
Arizona	367	106	130	11	0	0.1	0.0	0.0	0.0	0.0	293,986
Arkansas	12	0	0	0	0	0.0	0.0	0.0	0.0	0.0	134,883
California	2,256	728	217	489	15	0.6	0.2	0.1	0.1	0.0	404,815
Colorado	11,397	13,962	7	148	16	4.2	5.2	0.0	0.1	0.0	268,311
Connecticut	107	4	0	0	0	0.9	0.0	0.0	0.0	0.0	12,618
Delaware	45	1	0	0	0	0.9	0.0	0.0	0.0	0.0	5,005
Florida	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	140,365
Georgia	0	1	0	0	0	0.0	0.0	0.0	0.0	0.0	150,365
Idaho	5,485	417	324	152	13	2.6	0.2	0.2	0.1	0.0	213,449
Illinois	261	6	0	0	0	0.2	0.0	0.0	0.0	0.0	144,120
Indiana	0	14	0	0	0	0.0	0.0	0.0	0.0	0.0	93,064
Iowa	196	12	0	0	0	0.1	0.0	0.0	0.0	0.0	144,950
Kansas	16,702	9,119	0	0	0	7.9	4.3	0.0	0.0	0.0	211,814
Kentucky	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	102,743
Louisiana	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	115,310
Maine	1,076	314	18	9	0	1.3	0.4	0.0	0.0	0.0	80,277
Maryland	91	4	0	0	0	0.4	0.0	0.0	0.0	0.0	25,477
Massachusetts	590	65	208	119	0	2.9	0.3	1.0	0.6	0.0	20,265
Michigan	2,078	459	219	0	0	1.4	0.3	0.2	0.0	0.0	147,511
Minnesota	784	730	0	0	0	0.4	0.3	0.0	0.0	0.0	206,030
Mississippi	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	122,333
Missouri	32	0	0	0	0	0.0	0.0	0.0	0.0	0.0	178,568
Montana	45,127	25,087	4,025	1,581	17	12.0	6.7	1.1	0.4	0.0	376,564
Nebraska	23,036	11,424	0	0	0	11.6	5.8	0.0	0.0	0.0	198,508
Nevada	1,060	1,016	815	587	56	0.4	0.4	0.3	0.2	0.0	284,624
New Hampshire	20	12	10	1	0	0.1	0.1	0.0	0.0	0.0	23,292
New Jersey	329	77	0	0	0	1.7	0.4	0.0	0.0	0.0	19,342
New Mexico	31,800	2,207	87	197	18	10.1	0.7	0.0	0.1	0.0	314,256
New York	1,329	402	5	0	0	1.1	0.3	0.0	0.0	0.0	122,707
North Carolina	388	3	4	0	0	0.3	0.0	0.0	0.0	0.0	126,504
North Dakota	321	39,513	8,007	0	0	0.2	21.6	4.4	0.0	0.0	183,113
Ohio	120	98	0	0	0	0.1	0.1	0.0	0.0	0.0	106,210
Oklahoma	8,365	13,730	0	0	0	4.7	7.7	0.0	0.0	0.0	177,817
Oregon	439	1,371	143	7	0	0.2	0.6	0.1	0.0	0.0	249,117
Pennsylvania	244	81	0	0	0	0.2	0.1	0.0	0.0	0.0	116,260
Rhode Island	77	14	0	0	0	2.8	0.5	0.0	0.0	0.0	2,732
South Carolina	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	78,227
South Dakota	2,618	27,821	2	0	0	1.3	14.1	0.0	0.0	0.0	196,715
Tennessee	1	2	0	0	0	0.0	0.0	0.0	0.0	0.0	106,591
Texas	37,520	15,931	272	81	6	5.5	2.3	0.0	0.0	0.0	678,623
Utah	738	160	95	293	14	0.3	0.1	0.0	0.1	0.0	212,569
Vermont	20	17	14	1	0	0.1	0.1	0.1	0.0	0.0	24,017
Virginia	455	14	0	0	0	0.4	0.0	0.0	0.0	0.0	102,832
Washington	243	676	504	21	0	0.1	0.4	0.3	0.0	0.0	172,264
West Virginia	4	4	1	0	0	0.0	0.0	0.0	0.0	0.0	62,468
Wisconsin	991	237	56	0	0	0.7	0.2	0.0	0.0	0.0	140,964
Wyoming	19,930	22,193	142	10,835	24	7.9	8.8	0.1	4.3	0.0	251,201
Total	216,644	188,032	15,305	14,532	179	2.8	2.4	0.2	0.2	0.0	7,875,265

5.1 SCENARIO 1 - NO EXCLUSIONS

Scenario 1 represents the base case, drawn from areal estimates produced in the resource assessment analyses, with no environmental or land-use exclusions. For the no-exclusion scenario, the area for class 5 and above (i.e., the power class levels of the California passes that are currently supporting successful wind plants) is equivalent to an area approximately the size of Virginia. Similarly, the area for power classes 4 and greater is equivalent to an area approximately the size of Texas, and that for power class 3 and greater is equivalent to one four times the size of California.

The estimate of land area with class 3 and higher wind resource represents the summation of the grid cell land areas shown in Figure 2. In that figure, the percentage of a grid cell's land area with class 3 and higher resource is a function of the land-surface form and is shown by the four categories of percentage of land area: 1-20%, 21-50%, 51-80%, and 81-100%.

The 1-20% category is largely mountainous terrain, where only a small fraction of the land area in a grid cell (e.g., the ridge crests and mountain summits) is windy. Although the actual area of windy land in mountainous areas may vary considerably, depending on the spatial distribution of the mountains and ridges, we have determined that, on the average, roughly 5% of land area is well-exposed terrain features such as ridge crests and mountain summits, whereas 95% of the land area is sheltered terrain such as valleys and hillsides. To account for local areas of acceleration in mountainous terrain, in which the wind resource may be higher than the average (assigned) wind power class for ridge crests, we assume that 10% of the land area represented by ridge crests (i.e., 10% of 5%, or 0.5% of the grid cell's total area) is one wind power class higher than the assigned value. For example, although the U.S. annual average wind power map in Figure 1 does not have any grid cells with class 7 average (assigned) wind power, data included in the U.S. atlas (Elliott et al. 1987) show that class 7 sites exist where the terrain causes a local acceleration of the winds. Therefore, in mountainous terrain represented by the 1-20% category in Figure 2, we assume that 4.5% (i.e., 0.9 times 5%) of the grid cell's land area is represented by the assigned wind power class and that 0.5% (i.e., 0.1 times 5%) of the land area is one power class higher than the assigned power class. As a result of this assumption, we have estimated that there is about 1,500 km^2 of land area with class 7 wind resource in the contiguous United States before environmental and land-use restrictions are applied (see Table 4). To put this area of 1,500 km^2 into perspective, one grid cell (at say 40° N) is approximately 800 km^2, so all of the class 7 land area combined is still slightly smaller than the area of two grid cells in Figure 1.

For the other three categories of percentage of land area shown in Figure 2 (i.e., 21-50%, 51-80%, and 81-100%), we have used the approximate midpoint of each interval (35%, 65%, and 90%) in computing the areal estimates shown in Figure 6 and Table 4. Considering the large uncertainties in the subjective assignment of percentage of land area that is exposed for the various land-surface forms, we did not feel that any greater precision in our specification of the values of percentage of land area with a given wind power class was justified. For each grid cell, the land area that is represented by the assigned power class in Figure 1 is computed by multiplying the grid cell's total land area by the percentage of land area of the grid cell in Figure 2 (using the percentages given above for the four categories). In our areal estimates, we have not accounted for any of the remaining land area that is less than the assigned power class in Figure 1 (i.e., all of the remaining land area is excluded and could be considered to have class 1 or 2 wind resource). For example, in much of the Sand Hills of Nebraska and Flint Hills of Kansas, where 35% of the land area was estimated to have wind power class 4, the remaining 65% of the land area in each grid cell was excluded or considered to have low wind resource. However, some of the land area in those grid cells assigned power class 4 may actually have class 3 or possibly class 5 resource, or even lower wind resources (class 1 or 2). In flatter areas such as southwestern Kansas, where 90% of the land area was estimated to have wind power class 4, the remaining 10% of the land area was excluded. In reality, the wind resource could be distributed over more power classes (for example, although most of the land area is estimated to be class 4, there may be some class 3 and possibly class 5 areas, as well as some low resource areas). Local variability of the wind resource in a region of relatively flat terrain in the Great Plains has been described by Kessler and Eyster (1987).

5.2 SCENARIO 2 - ENVIRONMENTAL EXCLUSIONS

Scenario 2, in which we exclude all of the environmental land area (as approximated in Figure 4), shows a 35% decrease from the base case in the area having class 5 and greater but only a 14% decrease in the area having class 3 and greater. In general, the estimates of land excluded by environmental considerations probably exceed the exclusions that would be calculated if actual (rather than approximated) areas were used.

Areas of class 7 are most affected by the environmental exclusions: 75% of the class 7 area is eliminated when environmental restrictions are applied, because most of the class 7 areas are ridge crest sites in the high mountains of the West, where environmental exclusions are greatest. For example, in Colorado (the state with the largest amount of class 7 land area before environmental exclusions), the class 7 land area decreases from 376 km^2 in the base case to 61 km^2 after environmental exclusions. All of Colorado's class 7 lands are high ridge crests in the Rocky Mountains, where most of the land is excluded by environmental considerations. On the other hand, Nevada (which ranked fifth in class 7 land area in the base case, with 137 km^2) ranked first in class 7 land area after environmental exclusions, with an estimated 79 km^2. Although all of Nevada's class 7 lands are also ridge crests, the mountains of the Great Basin Plateau in Nevada (where roughly 40% of the land area was excluded based on environmental considerations) have fewer designated natural areas and are generally more accessible than the more rugged Rocky Mountains in Colorado.

The percent reduction in class 6 land area from environmental exclusions is 40% for the contiguous United States. Wyoming (which has considerably more class 6 area than any other state) has 65% of the class 6 area in the contiguous United States after environmental exclusions, compared to 51% of the class 6 area before environmental exclusions. In Wyoming, where much of the class 6 area is in the high plains of the south, the percent reduction in class 6 area from environmental exclusions is only 24%. The class 6 plains of southern Wyoming represent the largest class 6 area in the contiguous United States. Most of the remaining class 6 lands in the contiguous United States are high ridge crests in mountainous terrain where accessibility and siting may be difficult. If we exclude Wyoming, the percent reduction in class 6 for the rest of the contiguous United States from environmental exclusions is 68%. Although most of the class 6 lands (excluding those in Wyoming) are high ridge crests in mountainous terrain, there are some notable areas that are not high ridge crests. For example, a significant fraction of the class 6 lands in California and Montana are relatively low-elevation wind corridors (e.g., passes or valleys) more conducive to wind turbine siting than high ridge crests in mountainous terrain. In Massachusetts, the eastern state with the largest class 6 area after environmental exclusions (with 119 km^2), the class 6 lands are exposed coastal areas and islands, where 50% of the land area was excluded by environmental restrictions.

The percent reduction in class 5 land area from environmental exclusions is 31% for the contiguous United States. Most of the class 5 land area is located in North Dakota and Montana, which together account for 76% of the class 5 area in the contiguous United States after environmental exclusions. The percent reductions in class 5 land area from environmental exclusions in North Dakota and Montana are 10% and 32%, respectively.

The percent reduction in land area for classes 3 and 4 is 13% each for the contiguous United States. Most of the class 3 and 4 areas are located in flatter regions, where only 10% of the land was excluded by environmental restrictions. Class 3 and 4 lands account for about 10.3% and 7.0%, respectively, of the total U.S. land area. North Dakota and South Dakota, the two states with the largest class 4 land area, together account for 36% of the class 4 land area in the contiguous United States. Eleven states in the central United States--Colorado, Iowa, Kansas, Minnesota, Montana, North Dakota, Nebraska, Oklahoma, South Dakota, Texas, and Wyoming--have more than 95% of the class 4 land area in the contiguous United States. The state with the most class 3 land area is Texas, although percentages of land in class 3 in four states (Iowa, Kansas, Nebraska, and Oklahoma) are higher than in Texas.

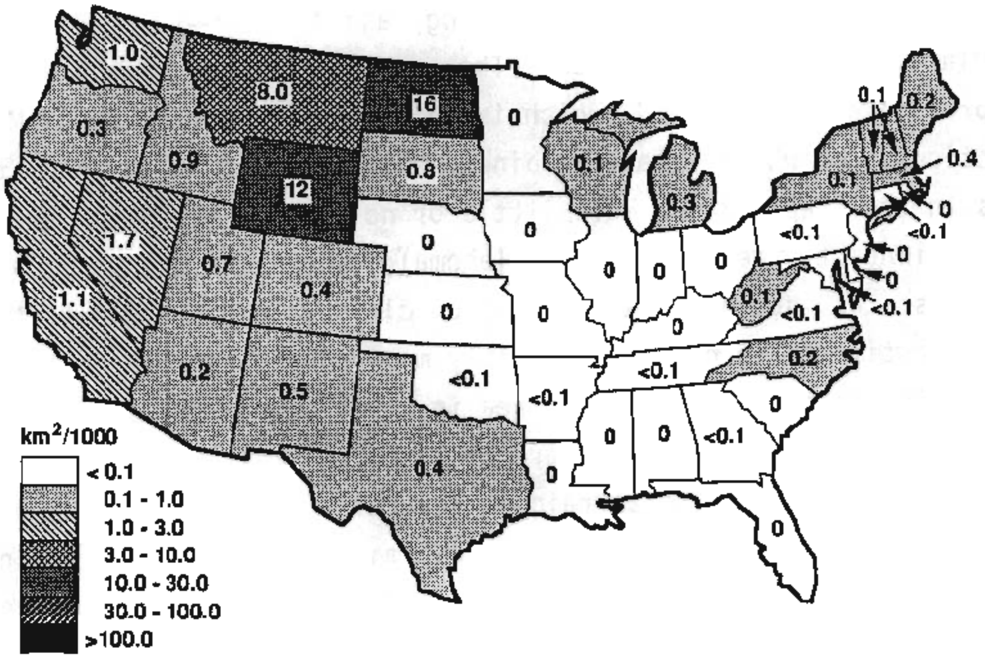
5.3 SCENARIO 3 - ENVIRONMENTAL AND MODERATE LAND-USE EXCLUSIONS

In Scenario 3, we excluded all the environmental and urban land, 50% of the forest land, 30% of the agricultural land, and 10% of the range land. Exclusions for the other land-use types are listed in Table 3 under "Moderate". For this scenario, the U.S. land area with class 3 or greater is 65% of that with no exclusions (Scenario 1), as shown in Table 4c. The area with class 3 and higher resource is equivalent to an area approximately the size of California and Texas combined, whereas the area with class 4 and higher resource is equivalent to an area approximately the size of California (see Figure 6). The area with class 5 and higher resource is equivalent to an area larger than Maryland but smaller than West Virginia. The area with class 6 is equivalent to an area slightly smaller than New Jersey; most of the class 6 lands are located in Wyoming, where their area is equivalent to an area approximately the size of Connecticut. There are about 270 km^2 of class 7 resource, an area equivalent to 10% of the size of Rhode Island. The class 7 lands are exposed ridge crests, mostly located in the mountainous areas of the West.

The moderate land-use exclusions alone had a greater effect on the areal estimates for class 3 and above than did the environmental exclusions. For example, about 225,000 km^2 (equivalent to an area slightly larger than Kansas) were excluded under environmental restrictions, whereas about 343,000 km^2 (equivalent to an area slightly smaller than Montana) were excluded under the moderate land-use restrictions. The percent reductions in lands with class 3 and higher resource under environmental and moderate land-use restrictions were 14% and 22%, respectively, resulting in a combined reduction of 36%. The percent reductions were largest for power classes 5, 6, and 7, which were 47%, 52%, and 82%, respectively. For these higher classes, more land was excluded by environmental restrictions than by moderate land-use restrictions. In contrast, for classes 3 and 4, more land was excluded under moderate land-use restrictions than under environmental restrictions. A large fraction of the class 3 and 4 areas is agricultural land, 30% of which was excluded under the moderate land-use restriction, whereas only about 13% of the class 3 and 4 areas is environmental land.

The distribution of windy land on a state-by-state basis for Scenario 3 is shown in Figure 7a for class 5 and greater and in Figure 7b for class 3 and greater. A comparison of these two figures shows that the great majority of the power class 3 and 4 areas that appear in Figure 6 for the contiguous United States are concentrated in the Great Plains states. However, there are also some respectable amounts of windy land in the states of the Northeast.

a) Wind Resource ≥ Class 5



b) Wind Resource ≥ Class 3

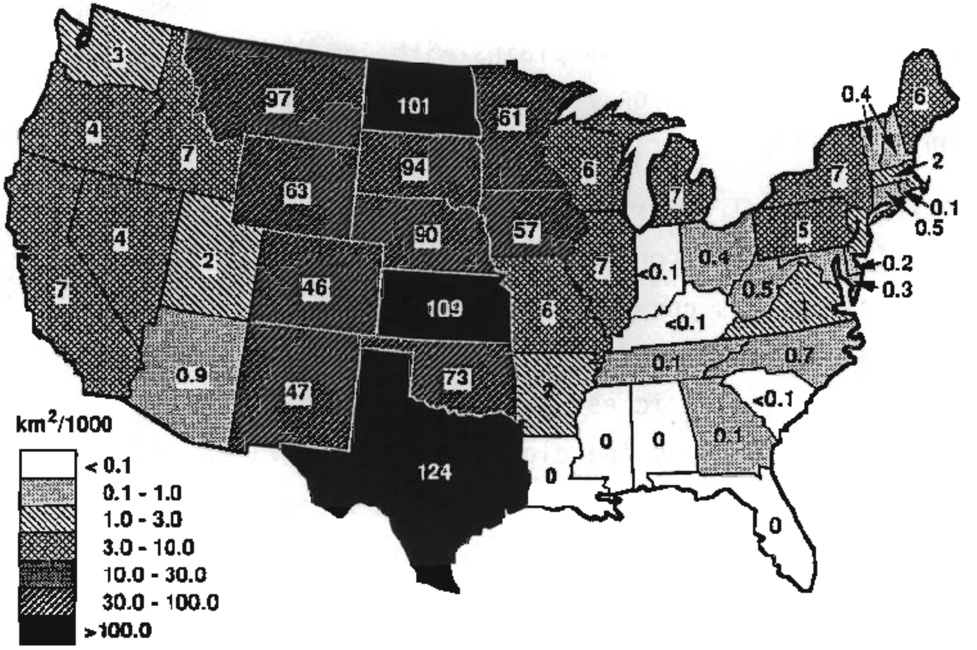


FIGURE 7. Available Windy Land (in Thousands of Square Kilometers) for Land Exclusion Scenario 3 and for a Wind Resource Specification of a) ≥ Class 5 and b) ≥ Class 3

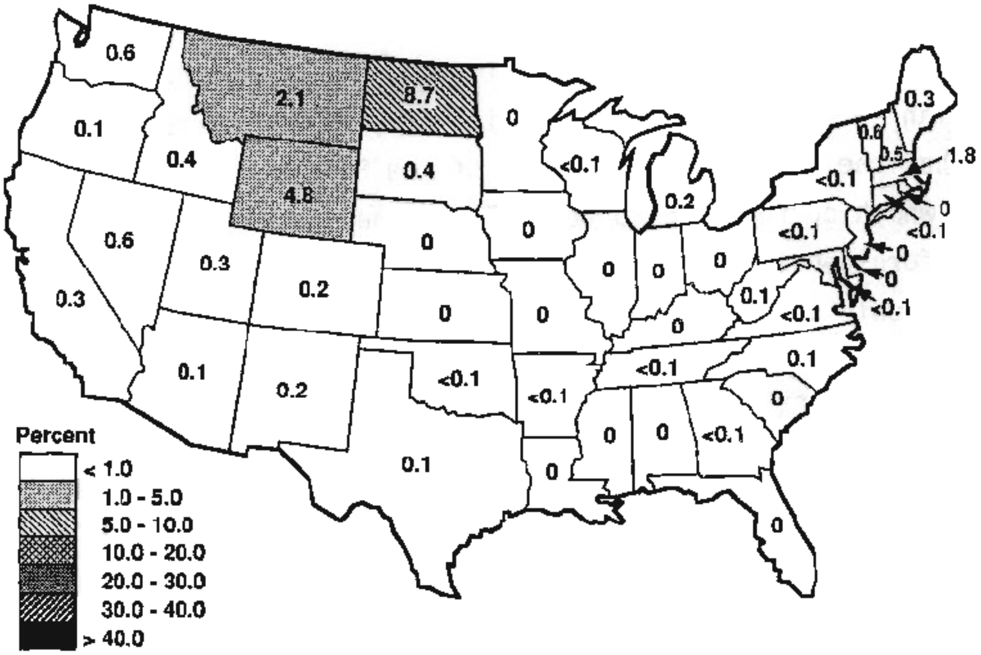
Windy land is shown as a percentage of a state's total area in Figure 8a for class 5 and greater and in Figure 8b for class 3 and greater.

Three states--North Dakota, Wyoming, and Montana--have 79% of the land with class 5 or greater resource. The combined class 5 area in these states is approximately 36,000 km^2, which is equivalent to the sizes of Massachusetts, Connecticut, and Rhode Island combined. Although Figure 7a shows that other states in the Great Plains have little or no class 5 area (for example, Iowa, Kansas, Minnesota, Nebraska, and Oklahoma), significant class 5 lands may exist in states that have large areas of class 4 land. While North Dakota has been estimated to have considerably more class 5 land area than other Great Plains states, the class 5 area in North Dakota could in fact be substantially less than estimated here because the class 5 sites appear to be located on relatively high terrain in generally flat areas of minor relief. The greatest uncertainty in the areal estimates for the Great Plains is in the specification of the percentage of land area that is represented by the assigned power class. This specification was dependent on the land-surface form classification. Thus our method assumed that 90% of the land area in the grid cells in eastern North Dakota had class 5 resource, because the land-surface form classification was plains with low relief. However, the class 5 sites are actually located on relatively high terrain, which may represent a significantly smaller fraction of the land area than 90%.

Data from several areas of the Great Plains show that minor relief can have a significant effect on the wind resource and that the spatial variation of the wind resource is considerably greater than is indicated by the existing wind resource maps or implied by the land-surface form classifications. In the future, a more realistic estimate of the windy land area in the Great Plains may be achieved by using digital terrain data to identify minor relief features, such as normally imperceptible hills and ridges as well as slightly sheltered areas.

Twelve states in the midsection of the country (Texas, Kansas, North Dakota, Montana, South Dakota, Nebraska, Oklahoma, Wyoming, Minnesota, Iowa, New Mexico, and Colorado--listed in order by amount of the windy land area) have 92% of the U.S. land area with class 3 or greater. With 124,000 km^2, Texas has the most windy land area, but this represents only 18% of the

a) Wind Resource ≥ Class 5



b) Wind Resource ≥ Class 3

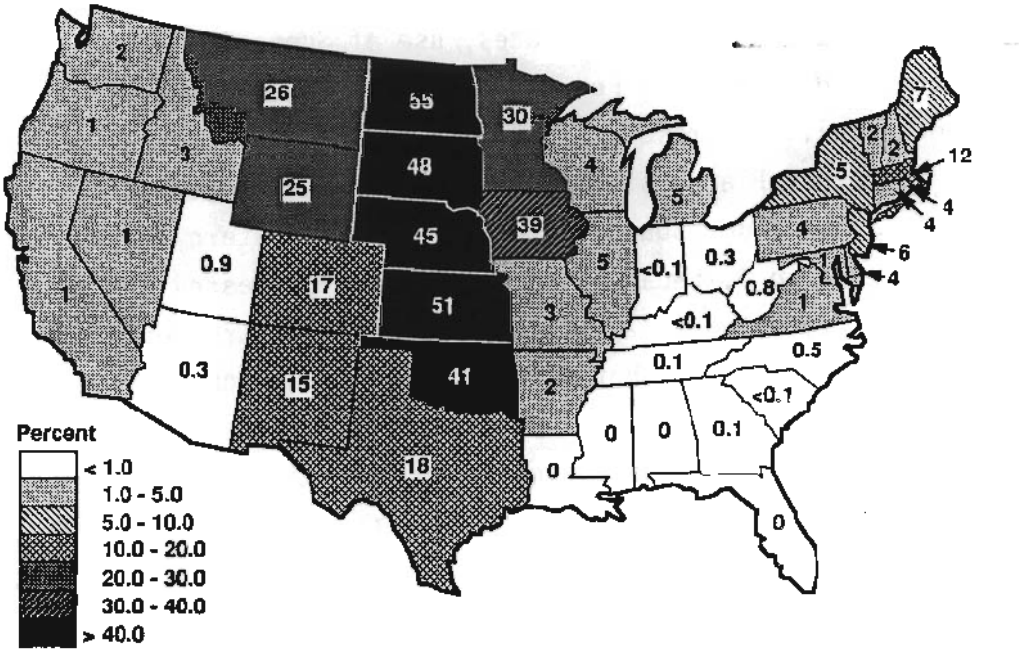


FIGURE 8. Available Windy Land as a Percentage of Each State's Total Area for Land Exclusion Scenario 3 and for a Wind Resource Specification of a) ≥ Class 5 and b) ≥ Class 3

state's total land area. North Dakota may be considered the windiest state, with 55% of its land area estimated to have class 3 or higher resource, but Kansas is only slightly less windy with 51% of its land in class 3 or higher. In five states, more than 40% of the total land area has class 3 or higher resource (see Figure 8b). In the East, the state with the highest percentage of windy land area is Massachusetts with 12%, which represents about 2500 km^2. New York has the most windy land area of the East Coast states, with about 6600 km^2, which corresponds to about 5% of the state's land area. For comparison, California has about 5200 km^2 of land with class 3 or higher resource, but that is only slightly more than 1% of the state's total land area.

5.4 SCENARIO 4 - ENVIRONMENTAL AND SEVERE LAND-USE EXCLUSIONS

Scenario 4 (in which all environmental, agricultural, forest, and urban lands are excluded) severely reduces the resource. The factor in Scenario 4 that most reduces the land area is the 100% agricultural exclusion. For this scenario, the percentage of U.S. land area with class 3 or greater is only 27% of that in Scenario 1, which had no exclusions. The majority of this remaining 27% is range lands in the West.

In some areas of the United States, use of Scenario 4 would practically eliminate the wind resource. For example, Iowa would lose 99% of its wind resource potential. The resource potential would also be considerably reduced in many of the other Plains states, where a large fraction of the land is agricultural. The wind resource potential in the eastern states is drastically reduced with Scenario 4, because they are largely forested and much of the land that is not forested is agricultural. Thus, the resource potential in those eastern states that do not have good coastal resources is essentially eliminated using Scenario 4. On the other hand, the resource in many of the western states survives Scenario 4 quite well, because a large fraction of their wind resource areas is classified as range land. Thus Wyoming, under Scenario 4, loses only about 30% of its resource potential, because most of the wind resource is located in range land.

6.0 ESTIMATES OF WIND ENERGY POTENTIAL

To calculate the contribution that could be made by wind energy as an alternative or a supplement to conventional energy sources, the estimates of the windy land area must be converted to estimates of electric power production that can be related to current and projected levels of energy consumption. This conversion can be accomplished with the gridded areal resource data, the gridded exclusion data, and specifications of turbine hub height, spacing, efficiency, and losses.

The total power intercepted over a given land area is a function of the number of wind turbines, the rotor-swept area of the wind turbine, and the total available power in the wind. This can be expressed as

$$P_I = P_c A_t N_t \tag{1}$$

where P_I = power intercepted

P_c = average wind power density in a vertical plane perpendicular to the wind

A_t = rotor-swept area of the wind turbine

N_t = number of wind turbines.

N_t depends on the total land area and the wind turbine spacing:

$$N_t = \frac{A_L}{(S_r D)\ (S_l D)} \tag{2}$$

where A_L = land area

S_r = spacing between turbine rows (in rotor diameters)

S_l = lateral spacing between the turbines (in rotor diameters)

D = turbine rotor diameter.

By substitution of Eq. (2) into Eq. (1), the average power intercepted (in MW) per square kilometer of land area can be calculated using

$$P_I/A_L = (\pi/4)\ P_c/S_r S_l \qquad (3)$$

The average power intercepted per square kilometer, for each wind power class 3 through 7, is given in Table 9 for a 50-m hub height and a spacing with $S_r = 10$ and $S_l = 5$. The average power output per square kilometer (P_O/A_L), also shown in Table 9 for each power class, was calculated using

$$P_O/A_L = (P_I/A_L)E_s(1-L) \qquad (4)$$

where E_s is the estimated system efficiency and L represents the estimated power losses; both were specified as 0.25 in this case. A discussion of the turbine spacing, power losses, and efficiency assumptions is given in Appendix A.

Because the average power density values used for this report represent mean annual values, annual electric energy production potential (in MWh) per square kilometer can be calculated by multiplying the average power output values in Table 9 by 8760 (the number of hours in a year); dividing this number by 1000 yields the annual electric energy production potential in millions of kWh/km^2, also shown in Table 9.

To obtain the average power output for each grid cell over the contiguous United States, the value of the average power output per square kilometer for each power class in the grid cell is multiplied by the area of the land with

TABLE 9. Average Power Intercepted, Average Power Output, and Annual Energy Production per Square Kilometer of Land Area for Wind Resource $\geq$ Class 3, 50-m Hub Height, 10D by 5D Spacing, 25% Efficiency, and 25% Power Losses

Power Class	Wind Power Density, W/m^2	Average Power Intercepted, MW/km^2	Average Power Output, MW/km^2	Annual Energy Production, million kWh/km^2
3	350	5.50	1.03	9.02
4	450	7.07	1.33	11.65
5	550	8.64	1.62	14.19
6	700	11.00	2.06	18.04
7	900	14.14	2.65	23.21

the corresponding power class in the grid cell. These values are then summed for all the grid cells in each state; then, a total for the 48 states is computed to determine the wind electric potential for the contiguous United States. The results of this computation are shown in Table 10 and Figure 9, for the same set of land exclusion scenarios as in Table 4 and Figure 6.

The annual wind electric potential (in kWh) was converted to primary energy equivalent (in Btus) using a thermal conversion factor of 10,235 Btu/kWh. This thermal conversion factor was the average for electricity generated in 1988 at U.S. fossil fuel steam-electric power plants (Energy Information Administration 1990). This is the factor used by the Energy Information Administration (EIA) to convert hydroelectricity and electricity generated from wood, waste, wind, photovoltaic, and solar thermal energy to primary energy equivalents. In Table 10 and Figure 9, the annual wind energy potential (fossil-fuel equivalent) is given in units of Quads (quadrillion Btus).

Table 11 gives the wind potential as a percentage of 1990 electric consumption (Energy Information Administration 1991), 1988 total energy consumption (Energy Information Administration 1990), and projected energy consumption in the year 2030 (Solar Energy Research Institute 1990). Total electricity consumed in 1990, based on the EIA's data on reported sales by electric utilities to ultimate consumers, was 2705.5 billion kWh. Total energy consumption, based on the EIA's 1988 data (the latest available at the time of this writing), was 80.2 Quads. These totals for electricity and energy consumption were for all 50 states. In Table 11, we use the totals for just the 48 contiguous states, which were 2692.7 billion kWh for 1990 electric consumption and 79.4 Quads for 1988 total energy consumption.

The EIA noted that, because of the lack of consistent historical data, their energy consumption statistics exclude wood, waste, geothermal, wind, photovoltaic, and solar thermal energy (except for small amounts used by electric utilities to generate electricity for distribution). Rader et al. (1990) estimated that, when the amount of renewable energy unaccounted for by the EIA is added, the United States actually consumed closer to 83 Quads in 1988.

TABLE 10. Wind Potential in the Contiguous United States for Four Land Exclusion Scenarios in Units of a) Average Wind Power Potential in Thousands of Megawatts, b) Annual Wind Electric Potential in Billions of kWh, and c) Annual Wind Energy Potential (Fossil-Fuel Equivalent) in Quads. Assumptions: 50-m hub height, 10D by 5D spacing, 25% efficiency, and 25% power losses.

a) Average Wind Power Potential in Thousands of Megawatts

	Land Exclusion Scenario*					Thousands of MW Per Power Class							
	E	U	F	A	R	3	4	5	6	7	≥ 3	≥ 4	≥ 5
1	0	0	0	0	0	930.3	817.2	85.9	73.4	4.0	1910.8	980.5	163.3
2	100	0	0	0	0	810.9	714.9	59.3	43.7	1.0	1629.8	818.9	104.0
3	100	100	50	30	10	596.8	552.1	45.3	35.4	0.7	1230.3	633.5	81.4
4	100	100	100	100	10	223.1	250.0	24.8	29.9	0.5	528.3	305.2	55.2

b) Annual Wind Electric Potential in Billions of kWh

						Billions of kWh Per Power Class							
1	0	0	0	0	0	8147	7158	752	643	35	16,735	8588	1430
2	100	0	0	0	0	7101	6262	519	383	9	14,274	7173	911
3	100	100	50	30	10	5226	4836	396	310	6	10,777	5549	713
4	100	100	100	100	10	1954	2190	217	262	4	4,628	2674	484

c) Annual Wind Energy Potential (Fossil-Fuel Equivalent) in Quads**

						Quads Per Power Class							
1	0	0	0	0	0	83.4	73.3	7.7	6.6	0.4	171.3	87.9	14.6
2	100	0	0	0	0	72.7	64.1	5.3	3.9	0.1	146.1	73.4	9.3
3	100	100	50	30	10	53.5	49.5	4.1	3.2	<0.1	110.3	56.8	7.3
4	100	100	100	100	10	20.0	22.4	2.2	2.7	<0.1	47.4	27.4	5.0

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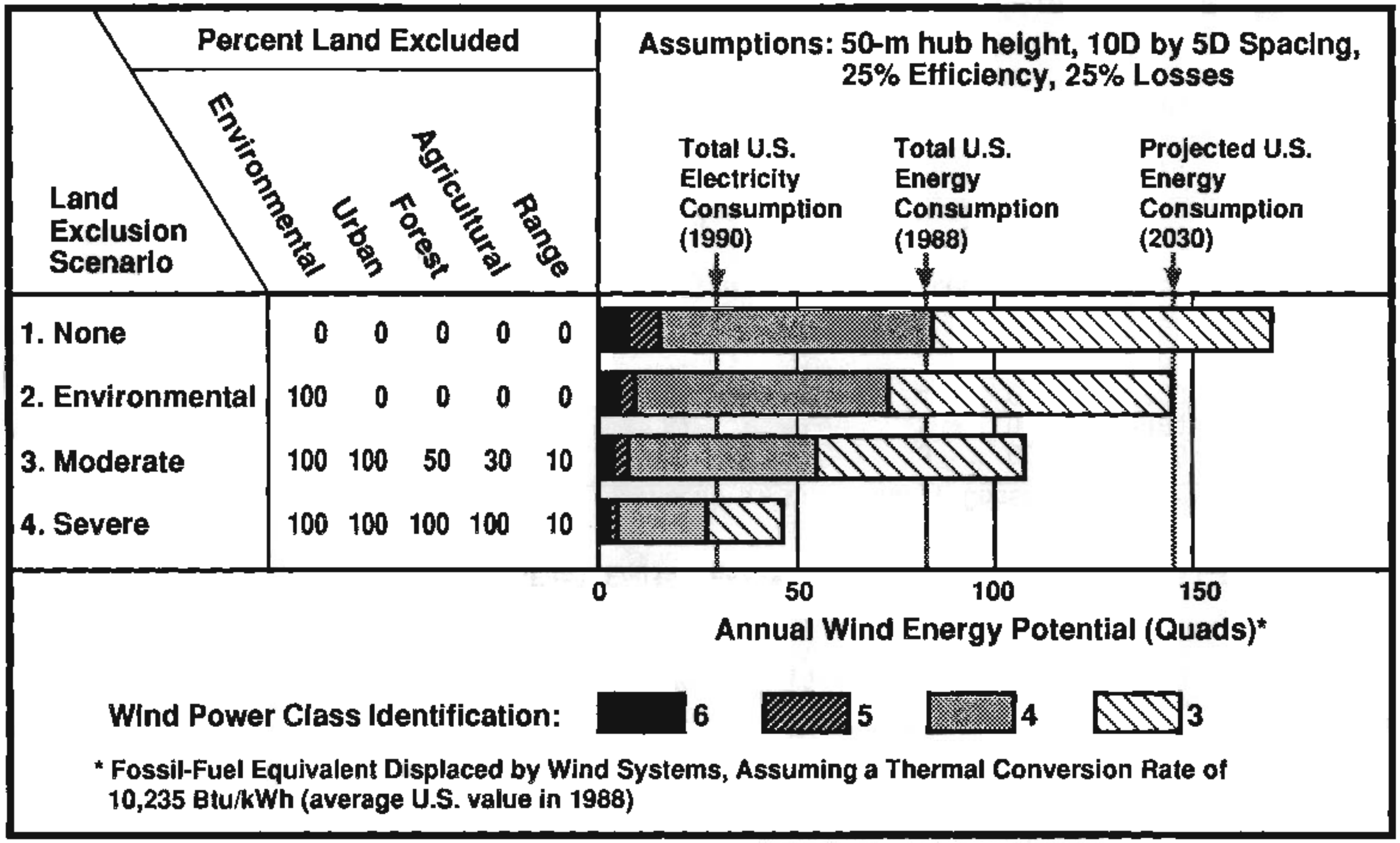
* Land-Use Types: E - Environmental; U - Urban; F - Forest; A - Agriculture; R - Range
Values are the percent of windy land area excluded from wind power plant development by land types.

** Assumes a thermal conversion rate of 10,235 Btu/kWh (average U.S. value in 1988).



Land Exclusion Scenario	Percent Land Excluded: Environmental	Urban	Forest	Agricultural	Range
1. None	0	0	0	0	0
2. Environmental	100	0	0	0	0
3. Moderate	100	100	50	30	10
4. Severe	100	100	100	100	10

* Fossil-Fuel Equivalent Displaced by Wind Systems, Assuming a Thermal Conversion Rate of 10,235 Btu/kWh (average U.S. value in 1988)

FIGURE 9. Wind Energy Potential of the Contiguous United States for Four Land Exclusion Scenarios

TABLE 11. Wind Potential in the Contiguous United States for Four Land Exclusion Scenarios as a Percentage of U.S. a) 1990 Total Electric Consumption, b) 1988 Total Energy Consumption, and c) Projected Total Energy Consumption in the Year 2030. Assumptions: 50-m hub height, 10D by 5D spacing, 25% efficiency, and 25% power losses.

a) Annual Wind Electric Potential as a Percent of U.S. Total Electric Consumption in 1990 (2692.7 Billion kWh)

	Land Exclusion Scenario*					Percent of U.S. Electric Consumption Per Power Class							
	E	U	F	A	R	3	4	5	6	7	≥ 3	≥ 4	≥ 5
1	0	0	0	0	0	303	266	28	24	1.3	622	319	53
2	100	0	0	0	0	264	233	19	14	0.3	530	266	34
3	100	100	50	30	10	194	180	15	12	0.2	400	206	27
4	100	100	100	100	10	73	81	8	10	0.1	172	99	18

b) Annual Wind Energy Potential (Fossil-Fuel Equivalent) as a Percent of U.S. Total Energy Consumption in 1988 (79.4 Quads)**

						Percent of U.S. Energy Consumption Per Power Class							
1	0	0	0	0	0	105	92	10	8	0.5	216	111	18
2	100	0	0	0	0	93	81	7	5	0.1	184	92	12
3	100	100	50	30	10	67	62	5	4	<0.1	139	72	9
4	100	100	100	100	10	25	28	3	3	<0.1	60	35	6

c) Annual Wind Energy Potential (Fossil-Fuel Equivalent) as a Percent of Projected Energy Consumption in 2030 (144.2 Quads)**

						Percent of Projected 2030 Energy Consumption Per Power Class							
1	0	0	0	0	0	58	51	5	4	0.3	119	61	10
2	100	0	0	0	0	50	44	4	3	<0.1	101	51	6
3	100	100	50	30	10	37	34	3	2	<0.1	76	39	5
4	100	100	100	100	10	14	16	2	2	<0.1	33	19	3

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* Land-Use Types: E - Environmental; U - Urban; F - Forest; A - Agriculture; R - Range
Values are the percent of windy land area excluded from wind power plant development by land types.

** Assumes a thermal conversion rate of 10,235 Btu/kWh (average U.S. value in 1988).

Our assumptions about the turbine were intended to include some features of an advanced design. For instance, the 50-m hub height is not typical of most of today's operational turbines. However, this hub height takes advantage of the increase of wind power with height that is common over much of the central United States. As can be seen from the 30- and 50-m power density values shown in Figure 6, the resulting increase in power is 25%. If other assumptions about turbine spacing, efficiency, or power losses are made, the wind energy potential shown in Table 10 and Figure 9 can be easily adjusted using ratios of the preferred assumptions to the ones used here. To determine the wind electric potential for a different spacing, multiply the values for the 10D by 5D spacing in Table 10 by the ratio $50/S_rS_l$. For example, the ratio would be 0.5 for a 10D by 10D spacing [i.e., 50/(10*10)]. Table 12 gives ratios for various turbine spacings. Although we have assumed a power loss of 25% (of which about 10 to 15% may be attributed to array losses caused by wind turbine wake effects) for the 10D by 5D spacing used in the calculations, the power ratios in Table 12 do not account for the effects of wind turbine spacing on array losses. At tighter spacings than 10D by 5D, actual power ratios may be significantly less than indicated here because wake effects are greater with tighter spacings. Conversely, at wider spacings than 10D by 5D, actual power ratios may be less than indicated here because wake effects are lower with wider spacings. The optimum turbine spacing depends on many factors, as discussed in Appendix A.

The striking feature of Figure 9 is that the wind energy resource for Scenario 3, even at the levels being tapped in California today (class 5 and above), has the potential to make a substantial contribution to meeting the nation's electrical and total energy needs. As shown in Table 11 for Scenario 3, the wind potential from class 5 and above is equivalent to about 27% (or 20% for a 30-m hub height) of electrical consumption in the contiguous United States and about 9% (or 7% for a 30-m hub height) of the total energy consumption. In kilowatt-hours (kWh), the annual wind electric potential from all class 5 and higher resource areas is about 570 billion kWh (for a 30-m hub height). Assuming a 25% average capacity factor, the potential installed capacity would be about 260,000 MW (the average power production over one year would be about 65,000 MW). California's installed wind

TABLE 12. Power Ratios for Various Turbine Spacings in Comparison to That of the 10D by 5D Spacing Used in the Estimates of Wind Electric Potential

Turbine Spacing		Power Ratio(a)
7D by 2D	(b)	3.57
8D by 2D		3.12
10D by 2D		2.50
8D by 3D		2.08
10D by 3D		1.67
12D by 3D		1.39
8D by 6D	(c)	1.04
10D by 5D		1.00
8D by 8D		0.78
12D by 6D		0.70
15D by 5D		0.67
10D by 8D		0.62
12D by 8D		0.52
10D by 10D		0.50
12D by 12D		0.35
16D by 16D		0.20

(a) These ratios do not account for effects of wind turbine wake interference on array losses, which are greater at tighter spacings.
(b) Typical spacing of many arrays in California.
(c) Typical spacing of arrays in Denmark.

capacity in 1990 was 1468 MW, which generated 2.42 billion kWh, according to S. Rashkin, California Energy Commission (phone conversation July 19, 1991). Thus, the wind electric generation in California today is only about 0.5% of the total possible from all class 5 and higher wind resource areas in the contiguous United States.

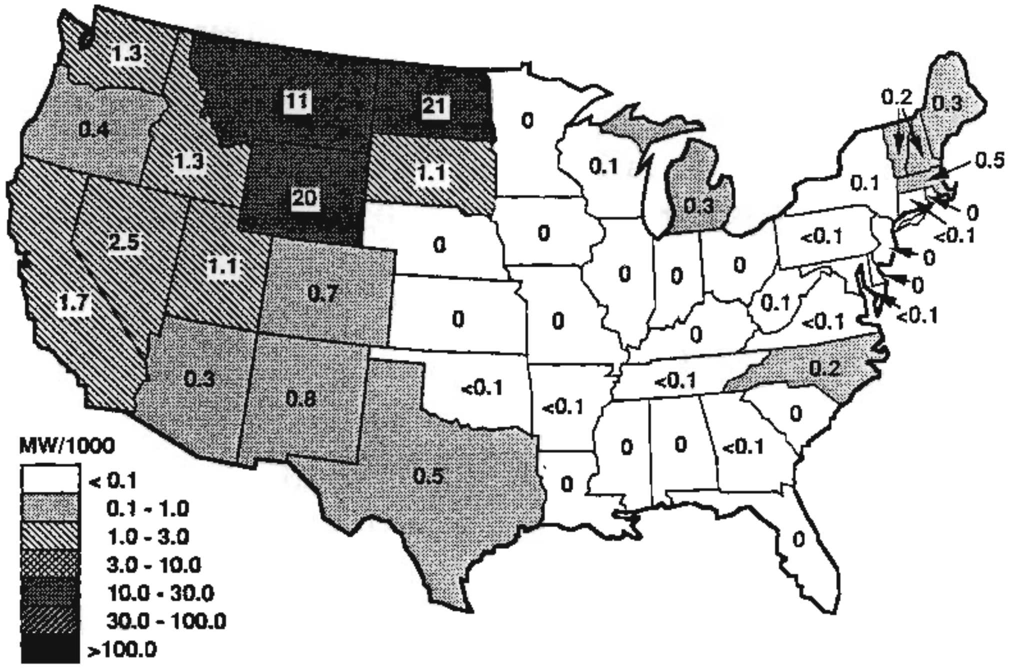
When the technology has advanced to the point where power classes 3 and 4 can be tapped cost-effectively, the total wind potential for Scenario 3 will increase more than tenfold, to about 110 Quads fossil-fuel equivalent of electricity production annually (see Table 10c). The total annual wind electric potential from class 3 and above resource areas is equivalent to four times the electricity consumed in the contiguous United States in 1990 (see Table 11a). Even under the most severe land-use restriction (Scenario 4), in which virtually all but range and barren lands are excluded, the total annual wind electric potential is still about 1.7 times the current electric consumption. If wind resource areas of class 4 and higher are considered, the wind electric potential is approximately 200% and 100% of the contiguous U.S. electric consumption for the moderate and severe land-use exclusions, respectively.

Comparing the wind potential (fossil-fuel equivalent) to the total energy consumption in the contiguous United States, wind potential from class 3 and higher resource areas and under Scenario 3 is equivalent to almost 140% of the 1988 total energy consumption and about 75% of the energy consumption projected for the year 2030. Even under a severe land-use restriction (Scenario 4), these percentages reduce only to about 60% and 30%, respectively.

To show the wind resource distribution over the country, wind electric potential by state is shown for Scenario 3 in Figure 10. The wind electric potential estimates in Figure 10 are shown in units of thousands of MW_{avg}, which represent average power potential. The MW_{avg} can be multiplied by 8.76×10^{-3} to get annual wind electric potential in billions of kWh (for example, 100,000 MW_{avg} = 876 billion kWh per year) or divided by a capacity factor to estimate installed capacity. A large fossil-fueled steam or nuclear power plant typically produces around 1000 MW_{avg}. Because the wind electric potential estimates in Figure 10 are given in thousands of MW_{avg}, the wind electric potential can easily be related to an equivalent number of large power plants. For example, the wind electric potential for Wyoming shown in Figure 10a (20,000 MW_{avg}) is equivalent to that produced by about 20 large power plants.

Figure 10a, which shows the wind electric potential for a 30-m hub height and wind resource of class 5 and above, is intended to represent the contribution possible with today's technology in areas that have wind resources comparable to the California passes currently supporting successful wind plants. Table 13 gives the average power output per square kilometer of land area in

a) 30-m Hub Height, Wind Resource ≥ Class 5 at 30 m



b) 50-m Hub Height, Wind Resource ≥ Class 3 at 50 m

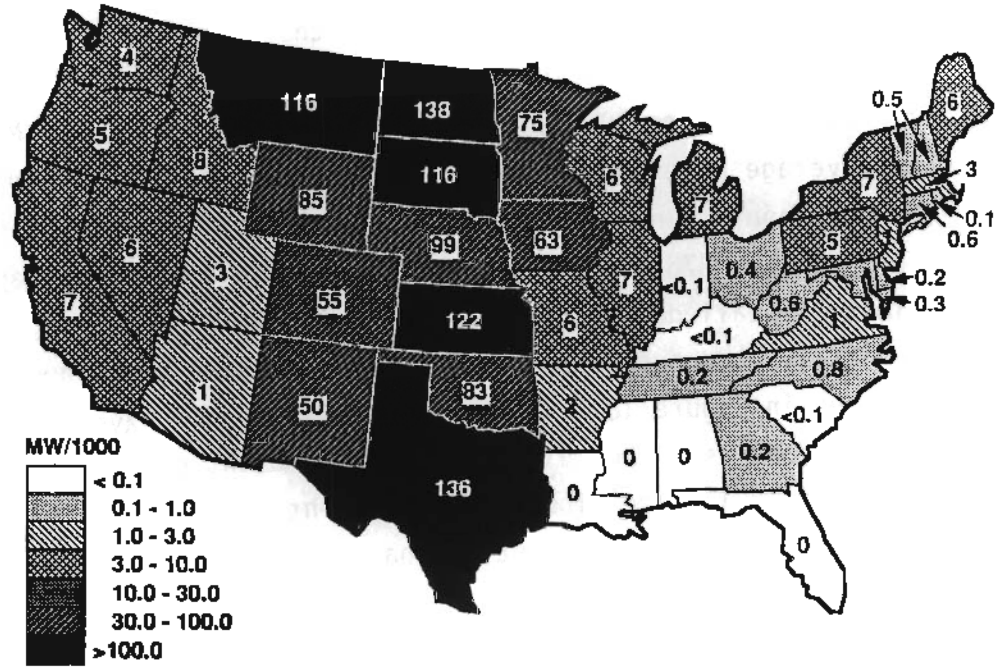


FIGURE 10. Wind Electric Potential (in Thousands of MW_{avg}) for a) 30-m Hub Height and Wind Resource ≥ Class 5 at 30 m, and b) 50-m Hub Height and Wind Resource ≥ Class 3 at 50 m. Other specifications are 10D by 5D spacing, 25% efficiency, 25% losses, and land exclusion Scenario 3.

TABLE 13. Average Power Intercepted, Average Power Output, and Annual Energy Production per Square Kilometer of Land Area for Wind Resource $\geq$ Class 5, 30-m Hub Height, 10D by 5D Spacing, 25% Efficiency, and 25% Power Losses

Power Class	Wind Power Density, W/m^2	Average Power Intercepted, MW/km^2	Average Power Output, MW/km^2	Annual Energy Production, million kWh/km^2
5	440	6.91	1.30	11.39
6	560	8.80	1.65	14.45
7	720	11.31	2.12	18.57

power classes 5 and above for a 30-m hub height. This average was used in determining the wind electric potential estimates in Figure 10a. Note that the average power output values in Table 13 for a 30-m hub height are 20% less than those in Table 9 for a 50-m hub height. Figure 10b, which shows the wind electric potential for a 50-m hub height and wind resource of class 3 and above, is intended to represent the contribution possible with advanced technology that allows areas with power classes 3 and 4 to be developed.

Probably the most dramatic change in the potential for individual states associated with technological advances occurs in several states in the central portion of the country (Iowa, Kansas, Minnesota, Nebraska, and Oklahoma, for example). These states go from having virtually no potential with current technology (Figure 10a) to being among the top 12 states with advanced technology (Figure 10b). Some of those states that were estimated to have substantial areas of class 4 wind resource, but essentially no class 5 areas based on the available data, may in fact have significant areas of class 5 resource that have not yet been identified. For example, since the completion of U.S. Wind Resource Atlas (Elliott et al. 1987), an extensive area of about 2640 km^2 estimated to have class 5 wind resource potential has been identified in Minnesota (Geisen 1990). The wind electric potential of this class 5 area in Minnesota is about 30 billion kWh (using our assumptions in converting the land area to wind electric potential), which is equivalent to about 63% of the state's 1990 electric consumption. More detailed wind resource assessment studies are needed to determine whether significant class 5 areas also exist in the other states that are shown in the U.S. Wind Resource Atlas as having large areas of class 4 resource.

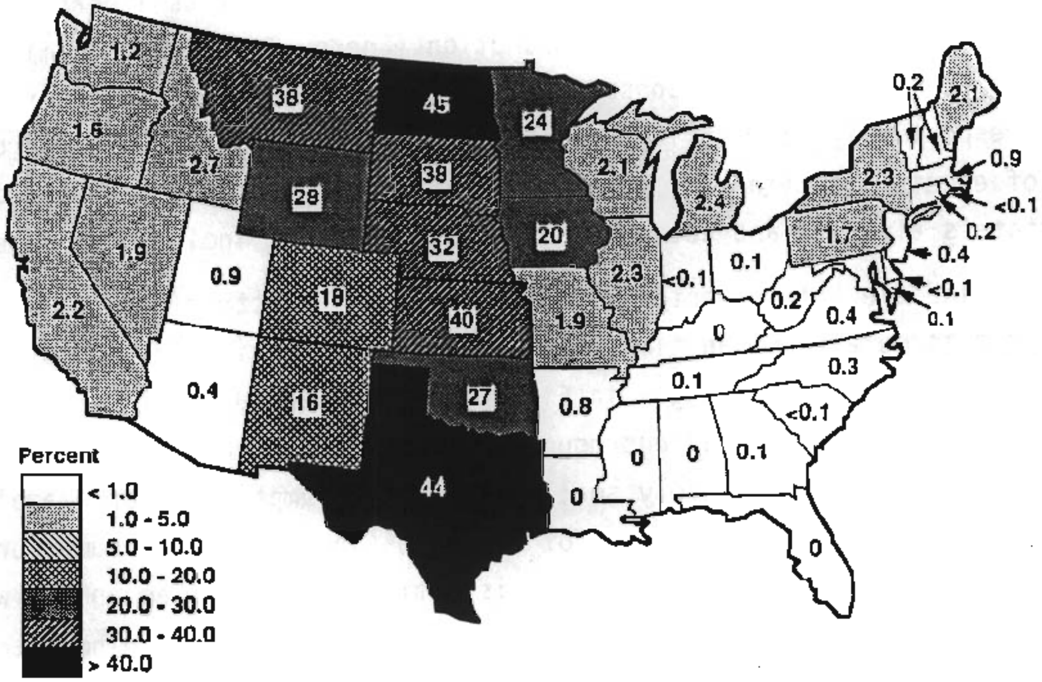
The enormous contrast between the wind electric potentials shown to be available in Figures 10a and 10b tends to take attention away from the fact that some contributions within particular states are notable, even for wind potential of class 5 and above. For example, although the wind electric potential for the contiguous 48 states shown in Figure 10a is less than 8% of that shown in Figure 10b, the wind electric potential from class 5 or greater wind resource areas in North Dakota, Wyoming, and Montana contributes about 80% of the U.S. wind electric potential from class 5 or higher resource areas. The wind electric potentials from areas of class 5 and higher resource in North Dakota, Wyoming, and Montana exceed the 1990 electric consumption in these states by factors of 25.6, 14.8, and 7.4, respectively.

To put the wind electric potential available with advanced turbine technology into perspective with recent electric (1990) and total energy (1988) consumption, we computed each state's wind potential as a percentage of the entire U.S. current electric and total energy consumption. These percentages were calculated from the wind electric potential values shown in Figure 10b. The results are shown in Figures 11a and 11b for electric and total energy consumption, respectively.

In Figures 11a and 11b, 12 contiguous states in the midsection of the country contribute over 90% of the wind energy potential of all 48 states. In order of greatest potential, these states are North Dakota, Texas, Kansas, South Dakota, Montana, Nebraska, Wyoming, Oklahoma, Minnesota, Iowa, Colorado, and New Mexico. In addition to the fact that the wind energy potential in these states is such a high percentage of the U.S. electric consumption and total energy consumption, each of these states also has the potential to produce several times its own consumption. This would put them in a position to export electric power or use it for other purposes.

Another feature that appears in Figure 11a is that, in addition to the 12 states that are the major contributors to wind electric potential, five states in the West, four states in the Midwest, and three states in the Northeast regions show a wind electric potential of meeting 1% to 3% of the total electric needs for the contiguous United States.

a) Total Electric Consumption



b) Total Energy Consumption

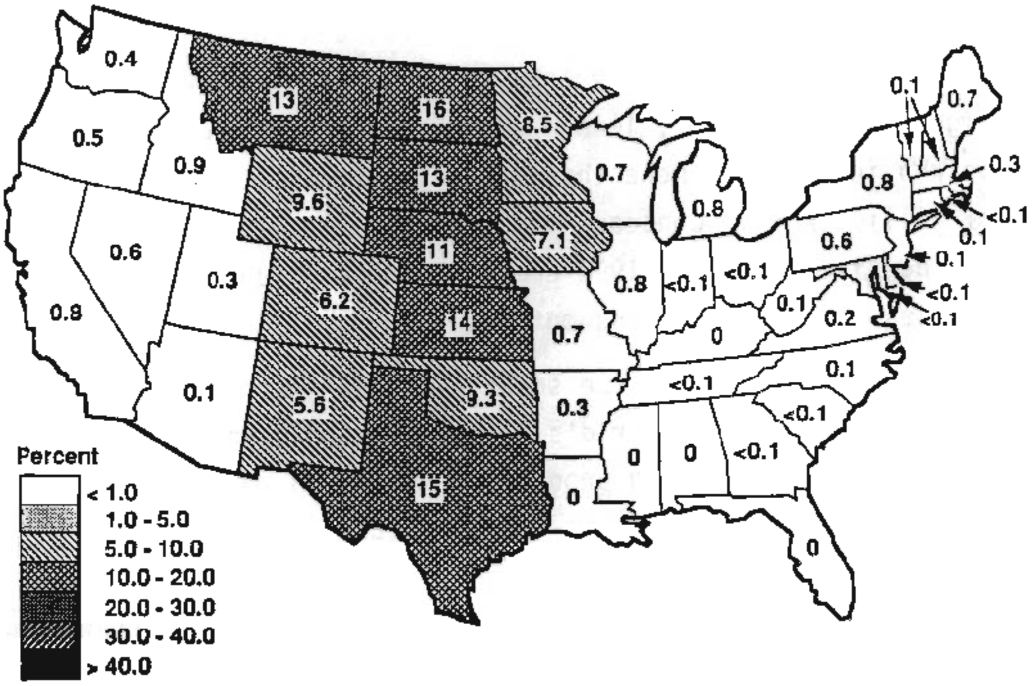


FIGURE 11. Wind Electric Potential as a Percentage of Contiguous U.S. a) 1990 Total Electric Consumption and b) 1988 Total Energy Consumption. Specifications: 50-m hub height and wind resource ≥ Class 3 at 50 m, 10D by 5D spacing, 25% efficiency, 25% losses, and land exclusion Scenario 3.

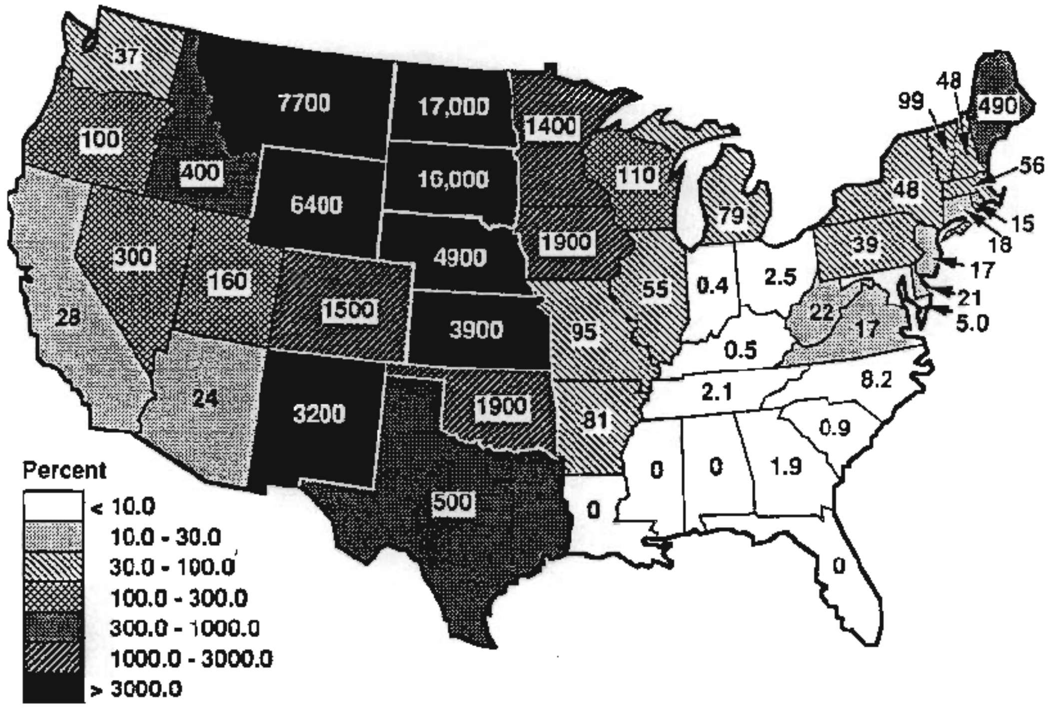
Figures 12a and 12b show the wind electric potential as a percentage of each state's 1990 total electric consumption (Energy Information Administration 1991) and 1988 total energy consumption (Energy Information Administration 1990), respectively. Electric consumption as reported by the EIA represents sales of electricity (in kWh) to ultimate consumers within a state. Data for each state's electric and total energy consumption are included in Appendix B.

The wind electric potential exceeds the total electric consumption in 17 states and is more than ten times the electric consumption in 11 states. The extremely large percentages in Figure 12 for the states of North Dakota and South Dakota reflect the enormous wind resource potential in these states in comparison to the relatively small electric consumption. For example, North Dakota, which ranks 45th out of 48 states in electric consumption with only 7.1 billion kWh consumed in 1990, is estimated to have an annual wind electric potential of 1210 billion kWh. Thus, North Dakota's wind electric potential is estimated to be approximately 170 times (or 17,000% of) its total electric consumption.

Texas, the state with the greatest electric and total energy consumption, is estimated to have only slightly less wind potential than North Dakota, as shown in Figure 10b. However, Texas' electric consumption of almost 238 billion kWh in 1990 was more than 33 times greater than that of North Dakota (7.1 billion kWh). Consequently, Texas' wind electric potential is estimated to be five times its 1990 electric consumption and only slightly greater than its total energy consumption.

California, the state with the second largest electric and total energy consumption, is currently the world's leader in wind generation (with over 80% of the world's capacity) and produced 2.4 billion kWh in 1990 from 1468 MW of installed capacity. According to our estimates, the total wind potential in California from class 3 and higher wind resource areas is equivalent to about 28% of its current electric consumption, which was 211 billion kWh in 1990.

a) Total Electric Consumption



b) Total Energy Consumption

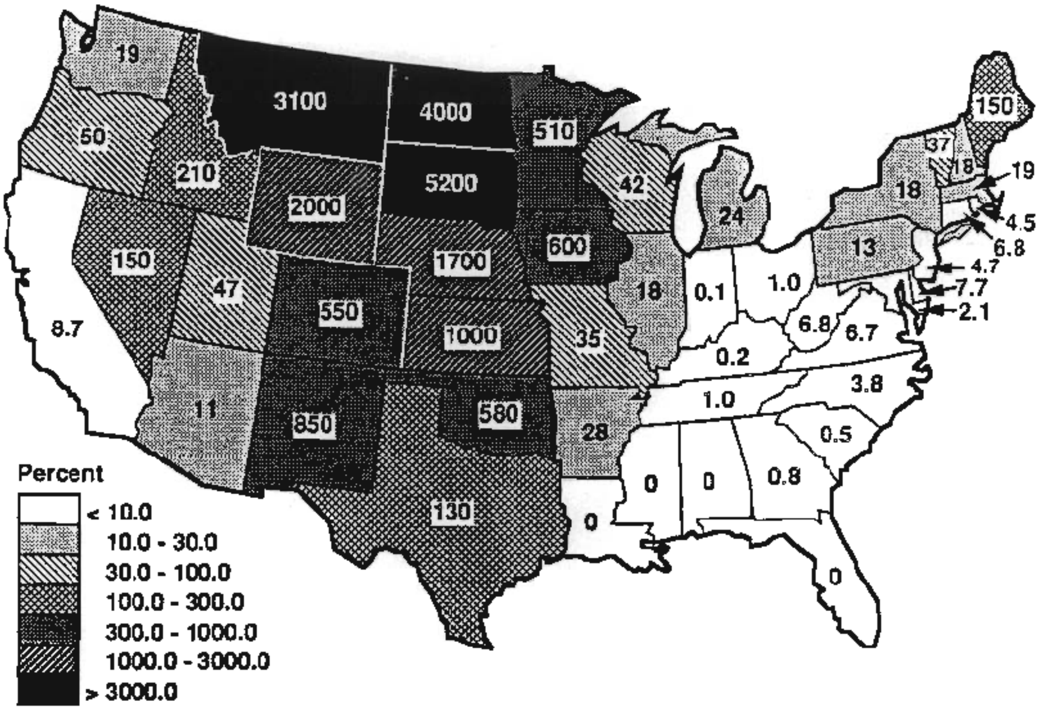


FIGURE 12. Wind Electric Potential as a Percentage of Each State's a) 1990 Total Electric Consumption and b) 1988 Total Energy Consumption. Specifications: 50-m hub height and wind resource Class 3 at 50 m, 10D by 5D spacing, 25% efficiency, 25% losses, and land exclusion Scenario 3.

7.0 CONCLUSIONS AND RECOMMENDATIONS

The primary conclusion to be drawn from this analysis is that wind energy over the contiguous United States is not limited by the availability of windy lands. That is, the wind resource has the potential of supplying a substantial fraction of the nation's energy needs, even with the use of today's technology.

Today's technology allows the exploitation of the wind resource mainly in specific areas where the annual average wind resource is class 5 or greater. To date, development of these areas has occurred primarily in California, where class 5 areas are being developed cost-effectively. Although this study shows that, after exclusions, only about 0.6% of the contiguous U.S. land area is characterized by class 5 or greater wind resource, the wind electric potential that could be extracted from these areas across the United States with today's technology is equivalent to about 20% of the current U.S. electric consumption. Three states--North Dakota, Wyoming, and Montana--could contribute about 80% of the U.S. wind electric potential from class 5 or greater wind resource areas.

Future advances in wind turbine technology will further enhance the potential of wind energy in the United States. As advances in turbine technology allow development of lower wind resource areas, such as class 3 areas, more than a tenfold increase in the wind energy potential is possible. Areas with class 3 and higher wind resource represent approximately 13% of the contiguous U.S. land area. These areas, which cover large sections of the Great Plains stretching from Texas to the Dakotas but are also distributed throughout many other sections of the country, have the potential of displacing over 100 Quads (fossil-fuel equivalent) of electric energy annually. Compare that with the total energy use of approximately 80 Quads in the contiguous United States in 1988, with 36% of that consumption being devoted to the production of electricity. Twelve states in the midsection of the country contribute over 90% of the wind electric potential in the contiguous United States. They are, in order of greatest potential, North Dakota, Texas, Kansas, South Dakota, Montana, Nebraska, Wyoming, Oklahoma, Minnesota, Iowa, Colorado, and New Mexico. These states have the potential to produce several times their own electrical consumption, which puts them in a position to export electric power or use it for other possible applications.

This study has provided a quantitative estimate of the overall resource. However, we need to emphasize three qualifications concerning this study. First, the results presented herein must be regarded as estimates only and they would change with the use of different assumptions and specifications. Second, this study does not diminish the need for careful siting and array design before the actual installation of a wind plant. Third, wind is an intermittent resource, and wind technology must therefore be integrated with other baseload power sources to provide a stable utility system. Important factors not addressed in this study that do influence the area available and total wind electric potential include resource remoteness (transmission, access), production/demand match (seasonal and daily, storage), utility and public acceptance, local ordinances, and other technological and institutional factors.

There are two levels of refinement between this study and a detailed site evaluation that would be worthwhile to pursue. One is to perform seasonal analyses. The national wind energy resource data base contains gridded maps of seasonally averaged wind power density. Analyses by season, like those reported here for the annual averaged data, could be valuable to utility companies, especially if the analyses were done for their service areas.

The second level of refinement is to improve the terrain resolution and is particularly appropriate for the scale of a utility service area. This would involve replacing the gridded landform classification data with digital terrain data now available from the U.S. Geological Survey to develop a much finer resolution of the spatial distribution of the wind resource. This much-improved spatial resolution in the analyses would bridge the gap that now exists between the gridded resource assessment results and the information required for detailed siting and array design efforts.

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APPENDIX A

WIND TURBINE SPACINGS, ENERGY LOSSES, AND EFFICIENCY

APPENDIX A

WIND TURBINE SPACINGS, ENERGY LOSSES, AND EFFICIENCY

This appendix discusses the assumptions used for wind turbine spacing, power losses, and efficiency in developing the estimates of wind electric potential.

WIND TURBINE SPACINGS AND ENERGY LOSSES

A wind turbine spacing of 10D (row spacing) by 5D (lateral spacing within a row), where D is the rotor diameter, has been assumed. This spacing is more open than that of existing arrays of wind turbines in California and Hawaii, where typical spacings are about 10D by 2D. Winds at the California and Hawaii sites are quite unidirectional, which permits tighter lateral spacing than in areas with winds whose direction is more variable. Lateral spacing typically ranges from about 1.5D to 3D, and row spacing from about 7D to 12D. The terrain features and wind flow variability often dictate the wind turbine layout, such that spacing within an array may vary considerably, especially in hilly areas such as Altamont Pass and Tehachapi in California. In some hilly areas, "stacking" of wind turbines at different heights (sometimes referred to as a "wind wall") along a ridge has been used to substantially increase the number of turbines and the net energy production without utilizing additional land area. In Denmark, where wind directions are more variable than in California and Hawaii, more open spacings, such as 8D by 6D, have been used.

The degree of array energy losses caused by wind turbine wakes has been difficult to determine with much accuracy because the ambient flow varies throughout many of the existing wind turbine arrays. The relatively shallow depth of the wind resource in Altamont Pass (where many array energy loss studies have been performed), in comparison to other regions, is another factor that brings into question the applicability of the Altamont Pass array energy loss data to other regions.

Array loss data from arrays in California and Hawaii indicate energy losses are in the range of 5 to 25%. Published data on energy losses in large arrays are scarce. Most of the published data on array losses are for four or fewer rows of wind turbines. One set of data from a level site with an array of seven rows of wind turbines, with about a 9D by 2D spacing, indicates annual average array losses of about 15% (Lynette 1986). Data collected downwind of large arrays indicate energy deficits on the order of 20 to 30% immediately downwind from the array (Nierenberg 1989). The problem of "wind rights" has now developed as a major issue in the siting of wind turbines in California and could possibly affect the geographical layout of arrays in the future.

Existing data show that array losses are a function of not only the turbine spacing, but also the turbine's thrust and power coefficients (which vary with the ambient wind speed) and the turbulence intensity of the wind (Liu 1988; Kelley 1989; Elliott and Barnard 1989; Nierenberg 1990). Wake deficits (as a percent of the ambient power, not an absolute value) are greatest at low wind speeds and low turbulence intensities. Wake and array loss models have been developed and verified with existing data (Veenhuizen et al. 1989; Lissaman et al. 1990); however, model results have not been verified for large arrays (the arrays modeled for verification had four or fewer rows of turbines).

The optimum spacing for arrays of wind turbines depends on the terrain, meteorological conditions, and turbine characteristics. In general, array losses may be reduced substantially by using more open spacings, such as 10D by 10D, 12D by 8D, or 20D by 5D. It is possible that very open spacings, such as 16D by 16D, may drastically reduce array losses. However, the cost savings achieved by reducing the array losses with more open spacings must be weighed against the cost increases caused by spreading the array over a larger land area. All of these costs could vary from region to region and from site to site within a region. At many sites, the optimum spacing could ultimately be determined more by economic issues than by purely technical considerations. From a technical standpoint, both the key and the challenge are to accurately predict the optimal array layout, which will achieve the maximum energy output while keeping the array losses below an acceptable limit.

Data from numerous arrays of wind turbines in California and Hawaii indicate that typical energy losses from all causes were about 25% (Lynette 1989). Of this amount, about 10% was attributed to array losses caused by wake interference and about 15% was attributed to other causes, such as soiled blades, downtime, and wire losses. Improved airfoils have been designed to minimize losses from soiled blades, such as that caused by soiling from insects (Tangler et al. 1990).

We have assumed a 10D by 5D spacing and have allowed for energy losses of 25%. The same spacing (10D by 5D) is used for all types of terrain, although in reality spacing will be altered substantially by the terrain features. For example, in complex terrain consisting of narrow ridges perpendicular to the prevailing wind directions, where wind turbines are sited only on the ridge crests, the spacing between rows would depend on the separation distance between ridges. On ridges where winds are unidirectional, close lateral spacings, such as 1.5D, may be suitable, and even "stacking" of wind turbines at different hub heights may be considered.

Although a significant fraction of the windy land area of the United States is ridge crest, much of the windy land area is relatively flat terrain (such as the Great Plains), where a spacing of 10D by 5D is assumed to be generally applicable. Closer spacings than this are currently used in flat terrain areas in California, such as San Gorgonio Pass, but the wind directions in these California passes are mostly unidirectional. In Denmark, where wind directions are more variable than in the California passes, a spacing of approximately 8D by 6D was used in a wind farm of 42 300-kW machines located in flat coastal terrain (Taylor 1990); array loss data are not yet available for this wind farm.

If the wind directions are widely distributed, then a more open spacing, such as 10D by 10D, may be required. However, in many flat, windy regions of the United States, the primary directions of prevailing strong winds are not as widely distributed as might be expected. For example, in much of the Great Plains, the prevailing power-producing winds (on an annual basis) are mostly from opposite direction sectors (e.g., northerly and southerly sectors with only a small percentage from easterly and westerly sectors). This type of wind regime may permit closer lateral spacings, in contrast to a wind regime with wind directions that are widely distributed. On the other hand, at sites with relatively low turbulence, greater downwind spacing (e.g., 15D) may be necessary.

WIND TURBINE EFFICIENCY

The wind turbine efficiency, which is the ratio of the net energy capture to the total available energy in the wind, is typically about 25 to 30% for current technology (on an annual average basis). The system efficiency is a function of a wind turbine's power coefficient, which varies with wind speed. For the advanced wind turbines, system efficiencies are projected to be 30 to 35%. We have conservatively assumed a system efficiency of 25% in developing the estimates of wind electric potential.

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APPENDIX B

ESTIMATES OF WINDY LAND AREA AND WIND ENERGY POTENTIAL, BY STATE

APPENDIX B

ESTIMATES OF WINDY LAND AREA AND WIND ENERGY POTENTIAL, BY STATE

Table B.1 provides estimates of windy land area and wind energy potential for each state in the contiguous United States. The windy land area and wind energy potential are calculated for an advanced wind turbine technology scenario that would allow areas with class 3 or higher wind resource to be developed. These areas have an annual average wind power density of at least 300 W/m^2 at heights of 50 m. The windy land area is calculated by the method described in Chapter 5.0. Estimates are given for the total windy land area (prior to exclusions), the windy land area excluded from wind energy development, and the potentially available windy land area (after exclusions). Windy lands excluded were 100% of the environmental and urban lands, 50% of the forest lands, 30% of the agricultural lands, and 10% of the range lands. (This exclusion was Scenario 3, the moderate land exclusion, described in Chapter 5.0).

The wind energy potential is calculated by the method described in Chapter 6.0. We have assumed a 10D by 5D spacing, 50-m hub height, 25% efficiency, and 25% losses. (These are the same assumptions as used for the advanced wind turbine technology scenario described in Chapter 6.0). The wind energy potential is expressed in units of 1) annual average power in MW, 2) annual energy production in billions of kWh, and 3) annual fossil-fuel equivalent, in trillions of Btu, displaced by wind systems assuming a thermal conversion rate of 10,235 Btu/kWh (average U.S. value in 1988). One Quad (or one quadrillion Btu) equals 1000 trillion Btu. The annual energy production potential is also expressed as a percent of the current (1990) electricity consumed in the state and in the contiguous United States. The electricity consumption totals for 1990, which are given in column three of Table B.1, are based on the Energy Information Administration's (EIA's) data on reported sales of electricity to ultimate consumers within the state. The annual fossil-fuel equivalent of the wind energy potential is also expressed as a

TABLE B.1. Estimates of Windy Land Area and Wind Energy Potential, by State

State	Area, km^2	Electricity Consumed (1990), Billion kWh	Total Energy Consumed (1988), Trillion Btu	Windy Land Area(a)				Wind Energy Potential(c)						
				Total, km^2	Excluded, km^2 (b)	Available		Average Power, MW	Annual Energy, Billion kWh	% of 1990 Electricity		Annual FF Equiv, Trillion Btu (d)	% of 1988 Total Energy	
						km^2	% of State			In State	In U.S. (e)		In State	In U.S. (e)
Alabama	131,487	59.7	1,614	0	0	0	0.0	0	0	0	0.0	0	0	0.0
Arizona	293,986	40.4	898	2,060	1,187	873	0.3	1,090	10	24	0.4	97	11	0.1
Arkansas	134,883	26.7	790	6,510	3,190	2,320	1.7	2,460	22	81	0.8	221	28	0.3
California	404,816	211.4	6,970	14,500	9,250	5,250	1.3	6,770	59	28	2.2	607	9	0.6
Colorado	268,311	31.2	902	67,300	21,600	45,700	17.0	54,900	481	1,540	17.9	4,920	546	6.2
Connecticut	12,618	27.2	757	1,140	597	543	4.3	571	5	18	0.2	51	7	0.1
Delaware	5,005	8.3	230	691	503	188	3.8	197	2	21	0.1	18	8	0.0
Florida	140,365	143.1	2,929	0	0	0	0.0	0	0	0	0.0	0	0	0.0
Georgia	150,365	80.3	2,038	445	304	141	0.1	171	1	2	0.1	15	1	0.0
Idaho	213,449	16.0	355	14,100	6,850	7,250	3.4	8,290	73	402	2.7	743	209	0.9
Illinois	144,120	112.2	3,677	11,300	4,530	6,770	4.7	6,980	61	55	2.3	626	18	0.8
Indiana	93,064	73.6	2,478	71	49	22	0.0	30	0	0	0.0	3	0	0.0
Iowa	144,950	29.1	942	90,300	33,600	56,700	39.1	62,900	551	1,900	20.5	5,640	599	7.1
Kansas	211,814	27.1	1,057	163,500	54,800	108,700	51.3	121,900	1,070	3,940	39.6	10,900	1,030	13.8
Kentucky	102,743	62.3	1,401	124	91	33	0.0	34	0	1	0.0	3	0	0.0
Louisiana	115,310	62.9	3,450	0	0	0	0.0	0	0	0	0.0	0	0	0.0
Maine	80,277	11.5	372	12,500	6,570	5,930	7.4	6,390	56	486	2.1	573	154	0.7
Maryland	25,477	59.5	1,414	1,040	726	314	1.2	338	3	5	0.1	30	2	0.0
Massachusetts	20,265	45.3	1,346	5,970	3,470	2,500	12.3	2,880	25	56	0.9	258	19	0.3
Michigan	147,511	82.7	2,753	15,900	8,960	6,940	4.7	7,460	65	79	2.4	668	24	0.8
Minnesota	206,030	47.4	1,315	98,700	37,600	61,100	29.7	75,000	657	1,390	24.4	6,720	511	8.5
Mississippi	122,333	31.9	938	0	0	0	0.0	0	0	0	0.0	0	0	0.0
Missouri	178,568	54.7	1,511	10,700	4,910	5,790	3.2	5,960	52	95	1.9	534	35	0.7
Montana	376,564	13.2	334	137,600	40,300	97,300	25.8	116,000	1,020	7,710	37.7	10,400	3,110	13.1
Nebraska	198,508	17.8	536	131,400	41,300	90,100	45.4	99,100	868	4,880	32.3	8,890	1,660	11.2
Nevada	284,624	16.9	355	7,840	3,910	3,930	1.4	5,740	50	298	1.9	515	145	0.6
New Hampshire	23,292	9.1	243	1,090	717	373	1.6	502	4	48	0.2	45	19	0.1

TABLE B.1. (Contd)

State	Area, km^2	Electricity Consumed (1990), Billion kWh	Total Energy Consumed (1988), Trillion Btu	Windy Land Area[a]				Wind Energy Potential[c]						
				Total, km^2	Excluded,[b] km^2	Available		Average Power, MW	Annual Energy, Billion kWh	% of 1990 Electricity		Annual FF Equiv,[d] Trillion Btu	% of 1988 Total Energy	
						km^2	% of State			In State	In U.S.[e]		In State	In U.S.[e]
New Jersey	19,342	62.6	2,286	2,700	1,560	1,140	5.9	1,200	10	17	0.4	107	6	0.1
New Mexico	314,258	13.7	524	64,900	18,300	46,600	14.8	49,700	435	3,180	16.2	4,450	850	5.6
New York	122,707	130.1	3,586	15,700	9,130	6,570	5.4	7,080	62	48	2.3	635	18	0.8
North Carolina	126,504	89.5	1,947	1,920	1,241	679	0.5	835	7	8	0.3	75	4	0.1
North Dakota	183,113	7.1	311	143,600	42,900	100,700	55.0	138,400	1,210	17,100	45.0	12,400	3,990	15.6
Ohio	106,210	141.9	3,785	1,120	754	366	0.3	410	4	3	0.1	37	1	0.0
Oklahoma	177,817	38.3	1,280	113,200	40,300	72,900	41.0	82,700	725	1,890	26.9	7,420	579	9.3
Oregon	249,117	42.6	680	9,970	6,260	3,710	1.5	4,870	43	100	1.6	436	50	0.5
Pennsylvania	116,260	115.6	3,601	10,500	5,950	4,550	3.9	5,120	45	39	1.7	459	13	0.6
Rhode Island	2,732	6.4	216	237	136	101	3.7	109	1	15	0.0	10	5	0.0
South Carolina	78,227	55.5	1,143	144	90	54	0.1	59	1	1	0.0	5	1	0.0
South Dakota	196,715	6.3	203	138,200	44,500	93,700	47.6	117,200	1,030	16,200	38.1	10,500	5,180	13.2
Tennessee	106,591	76.6	1,714	517	372	145	0.1	166	2	2	0.1	17	1	0.0
Texas	678,623	237.7	9,583	191,400	67,700	123,700	18.2	136,100	1,190	602	44.3	12,200	127	15.4
Utah	212,569	15.2	534	5,150	3,190	1,960	0.9	2,770	24	160	0.9	249	47	0.3
Vermont	24,017	4.8	129	1,140	746	394	1.6	537	5	99	0.2	48	37	0.1
Virginia	102,832	72.6	1,840	3,480	2,210	1,270	1.2	1,360	12	17	0.4	124	7	0.2
Washington	172,264	88.5	1,807	7,740	5,030	2,710	1.6	3,740	33	37	1.2	335	19	0.4
West Virginia	62,468	23.4	778	1,620	1,134	486	0.8	594	5	22	0.2	53	7	0.1
Wisconsin	140,964	49.2	1,392	12,100	5,970	6,130	4.3	6,440	56	115	2.1	578	42	0.7
Wyoming	251,201	11.7	377	88,900	25,500	63,400	25.2	85,200	747	6,400	27.7	7,640	2,030	9.6
TOTAL[e]	7,675,265	2692.7	79,421	1,607,700	567,700	1,040,000	13.5[f]	1,230,300	10,777		400	110,300		139

(a) Annual average wind power density greater than 300 W/m^2 at 50 m (wind resource $\geq$ class 3).
(b) Excluded lands: environmental - 100%, urban - 100%, forest - 50%, agriculture - 30%, range - 10%.
(c) Assumptions: 10D by 5D spacing, 50-m hub height, 25% efficiency, 25% losses.
(d) FF Equiv is fossil-fuel equivalent displaced by wind systems, assuming a thermal conversion rate of 10,235 Btu/kWh (average U.S. value in 1988).
(e) Contiguous 48 states.
(f) Percent of U.S. area (48 contiguous states).

percent of the total energy consumed (in 1988) in the state and in the contiguous United States. The 1988 total energy consumption data, which were the most recent available from the EIA at the time of this writing, are given in column four.

The TOTAL line at the bottom of Table B.1 provides information for the contiguous United States.

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