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

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Pacific Northwest Laboratory
Richland, Washington 99352

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D. L. Elliott, L. L. Wendell, G. L. Gower
Pacific Northwest Laboratory
Richland, WA 99352

ABSTRACT

In support of the U.S. Department of Energy's National Energy Strategy initiative, estimates of the land area with various levels of wind energy resource 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 owing to environmental or land-use considerations. These exclusions assume that 100% of the environmentally sensitive land and various percentages of land designated as urban, agricultural or range would be unavailable for wind energy development. Despite these exclusions, the amount of wind resource thus estimated is surprisingly large. For example, estimates of available wind resource and resultant wind electric potential from advanced turbine technology show that a group of 12 states in the midsection of the country could produce more than three times the nation's 1987 electric energy consumption.

INTRODUCTION

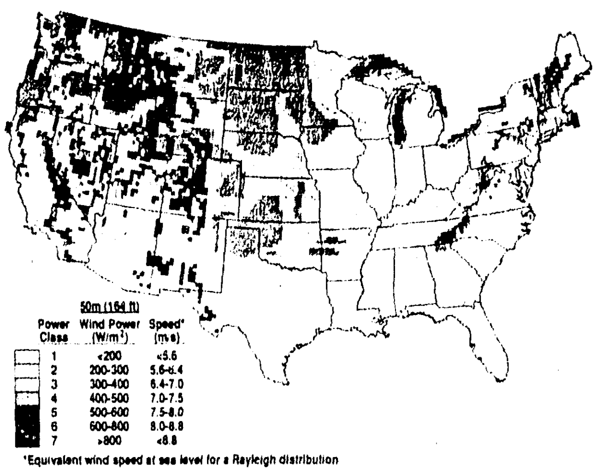
Although wind energy development may be an attractive option for areas where the wind energy potential has been shown to be high, the actual installation of wind turbines must be based on the availability of land on which to site the turbines. The land availability may be constrained by land-use considerations; 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 initiative, we developed estimates of the land area available for wind energy development under various scenarios of land-use restriction and several levels of wind energy resource. This paper presents the estimates of land area and wind electric potential developed for four scenarios of land exclusion and describes the data bases and methods used to make the estimates.

WIND RESOURCE DATA

The wind resource data base used for the results presented here was published in a National Wind Resource Atlas (SERI 1986). Estimates of the wind resource are expressed in wind power classes ranging from class 1 (the lowest) to class 7 (the highest). A map of the annual average wind energy resource for the contiguous United States is shown in Figure 1a. The wind resource data base includes estimates of the areal distribution of the wind resource digitized in grid cells of 1/4° latitude by 1/3° longitude. Gridded land surface form classifications were used with the gridded wind resource data to produce the gridded areal distributions, like those shown in Figure 1b, which show percent land area for class 3 and higher wind resource. The areal distribution data do not account for environmental or economic restrictions, i.e., 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 for calculating the land areas that would be affected by the environmental and land-use exclusions.

(a) Annual Average Wind Resources Estimates



(b) Percent Land Area with Class 3 or Higher Wind Resource

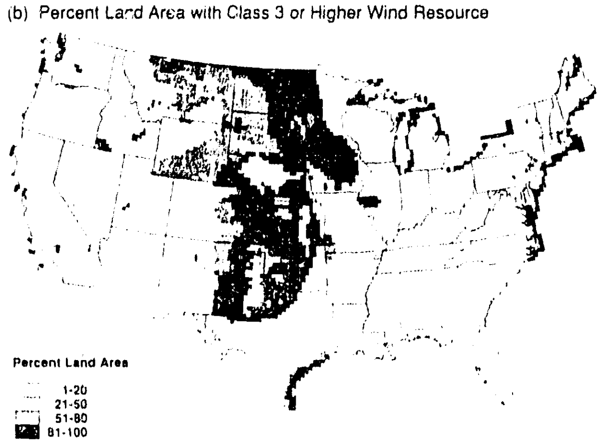


Fig. 1. Graphical Representation from Gridded Data Base of (a) Annual Average Wind Resource Estimates, and (b) Percent Land Area with Class 3 or Higher Wind Resource. Grid size is 1/3° longitude by 1/4° latitude.

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 shown in the sections on environmental and land-use restrictions.

ENVIRONMENTAL EXCLUSIONS

Environmental exclusion areas include parks, monuments, wilderness areas, preserves, and wildlife refuges (as well as some other types of natural areas) where industrial developments are restricted or very limited. We developed a data base to approximate the distribution and extent of the environmental exclusion areas from maps of Federally administered environmental areas and from maps of land surface form. Environmentally sensitive areas may be inferred from maps of land surface form because these areas are often correlated with certain land forms.

Special care was taken not to exclude the wind corridors that exist at relatively low elevations within mountainous regions, such as the wind corridors in California, Montana, and Washington. The wind corridor areas were identified; an exclusion of 10% to account for roads and existing structures was assigned.

In all coastal regions, at least 50% of the land area was excluded (as opposed to 10% for inland areas) because coastal lands 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 developments would be restricted. These coastal lands included the coasts and coastal islands of the Atlantic and Pacific oceans, the Gulf of Mexico, and the Great Lakes.

A map of the approximated environmental exclusion areas is shown in Figure 2. (The exclusions display the percentage of land per grid cell that is environmentally sensitive.) The 90% exclusion areas are the most rugged mountainous regions of the West where local relief exceeds 3000 ft. The mountains throughout the Great Basin Plateau, such as 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 environmental areas, for the most part, occupy only a small fraction of the total land area.

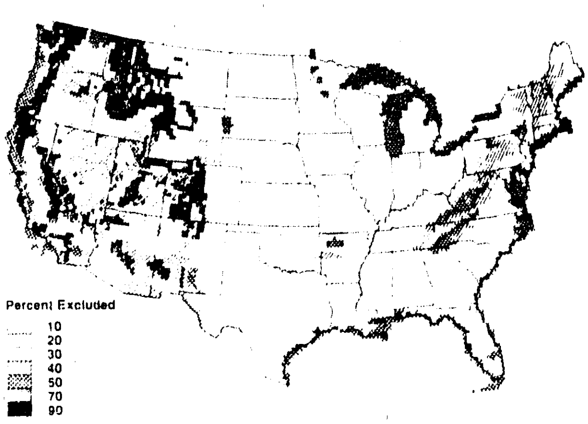


Fig. 2. Percent of Each Grid Cell Excluded Due to Environmental Considerations

In general, the estimates of land excluded for environmental reasons probably exceed the exclusions that would be encountered in practice. For power class 3 and greater, the total reduction in U.S. land area due to environmental exclusions is 14%. Areas of class 7 are most affected by the environmental exclusions; 75% of the class 7 area is eliminated after environmental restrictions are applied because most of the class 7 areas represent ridge crest sites in the high mountains of the West where environmental exclusions are greatest. The percent reduction in land area for classes 3, 4, 5, and 6 is 13%, 13%, 31%, and 40%, respectively. Most of the class 3 and 4 areas are located in flatter regions where only 10% of the land is excluded for environmental reasons.

LAND-USE EXCLUSIONS

For estimating land-use exclusions, a suitable land-use data base in digital form was obtained from EPA-Las Vegas that included the percent of each grid element associated with these 11 land-use types: 1) urban land, 2) agricultural land, 3) range land, 4) deciduous forest, 5) coniferous forest, 6) mixed forest, 7) water, 8) barren land, 9) non-forested wetland, 10) mixed agricultural and range land, and 11) open, low scrub land. For each land-use type, the percent of the land area to be excluded from wind energy development was estimated.

As might be expected, the raw estimates of land area excluded because of land use are fraught with uncertainty. To deal with this uncertainty, estimates were made for three land-use exclusion categories: no exclusions at all, realistic land-use exclusions, and extreme land-use restrictions. The realistic and extreme categories differ only in the percentage of forest and agricultural land use.

EXCLUSION AND POWER CLASS EFFECTS ON AREAL RESOURCE ESTIMATES

The environmental exclusions and land-use exclusion categories can be applied in a number of combinations to evaluate the effect on the available land in the United States at each power class level. For the purpose of this paper, we have chosen four land exclusion scenarios for comparison and present a summary of the results in Figure 3.

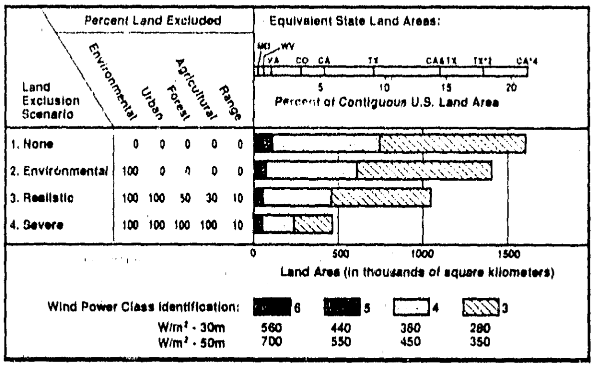


Fig. 3. Windy Land Area in the Contiguous United States Considering Environmental and Land-Use Exclusions

Scenario 1 represents the base case, from areal estimates produced in the resource assessment analyses, with no environmental or land-use exclusions. To put the areas of the power classes into perspective, we have included a representation of equivalent state land areas in Figure 3. For the no-exclusion scenario, the area for class 5 and above (the power class levels of the California passes currently supporting successful wind plants) is equivalent to an area approximately the size of the state of Virginia. Similarly, the areas for power classes 4 and greater and 3 and greater are equivalent to areas approximately the size of Texas and four times the size of California, respectively.

Scenario 2 (where we exclude 100% of the land area under environmental restrictions) shows a 39% decrease from the base case in the area of power class 5 and greater, but only a 13% decrease in the area from class 3 and greater.

Scenario 3 (where we exclude all environmental and urban land, 50% of forest land, 30% of agricultural land, and 10% of range land) is judged to be the most realistic of all the exclusion scenarios. For this scenario, the U.S. land area with class 3 or greater is 64% of that with no exclusions (Scenario 1).

Scenario 4 (where all environmental, agricultural, forest, and urban land are excluded) severely reduces the resource. The factor that most considerably reduces the land area in Scenario 4 is the 100% agricultural exclusion. For this scenario, the percent 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 27% is range lands in the West.

In some areas of the United States, use of Scenario 4 would severely reduce and practically eliminate the wind resource. For example, Iowa would lose 99% of its wind resource potential. The resource potential would 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 not forested is agricultural land. Thus, the resource potential in many of the eastern states that don't have some good coastal resources is essentially eliminated using Scenario 4. On the other hand, many of the western states survive Scenario 4 quite well, since a large fraction of their wind resource areas is classified as range lands. Wyoming, under Scenario 4, loses only about 30% of its resource potential, because most of the wind resource is located in range lands.

The distribution of windy land on a state-by-state basis is shown in Figure 4a for class 5 and greater and in Figure 4b 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 3 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.

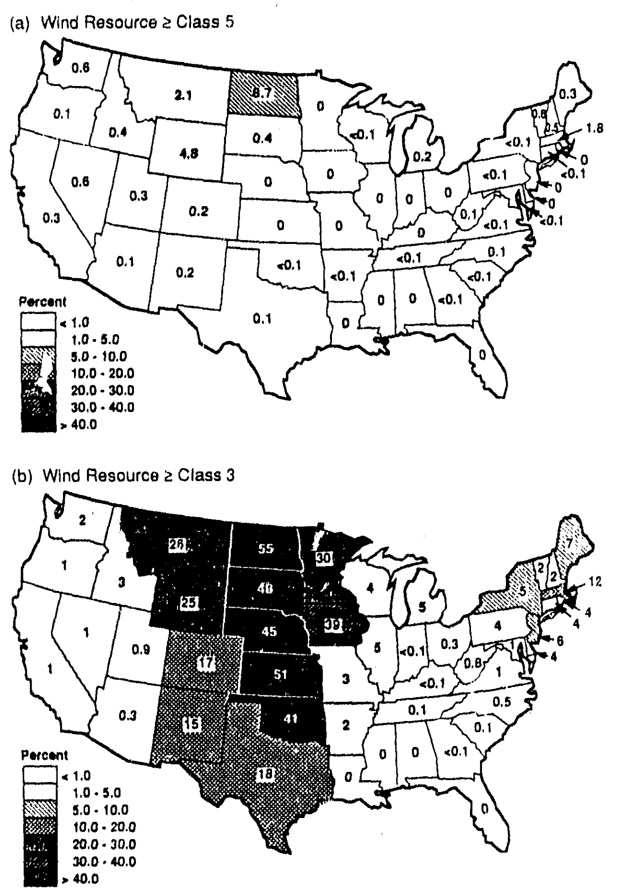


Fig. 4. Available Windy Land as a Percent of a State's Total Area for Land Exclusion Scenario 3 and for a Wind Resource Specification of (a) ≥ Class 5 and (b) ≥ Class 3

WIND ENERGY POTENTIAL ESTIMATES

To estimate the potential value of wind energy as an alternative or a supplement to conventional energy sources, the areal estimates of the wind resource must be converted to a quantity that is comparable to current and projected energy consumption levels. This conversion can be accomplished with the gridded areal resource data, the gridded exclusion data, and some 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:

$$P_I = P_c A_t N_t \qquad (1)$$

where P_I is the power intercepted, P_c is the average wind power density (W/m^2) in a vertical plane perpendicular to the wind, A_t is the rotor-swept area of the wind turbine, and N_t is number of wind turbines. N_t depends on the total land area and the wind turbine spacing:

$$N_t = A_L/(S_l D)(S_r D) \qquad (2)$$

where A_L is the land area, D is the turbine rotor diameter, S_l is lateral spacing between the turbines in rotor diameters, and S_r is the spacing between turbine rows in rotor diameters. By substitution of Eq. (2) into Eq. (1), the average power intercepted (MW) per square kilometer of land area can be calculated using:

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

The average power intercepted (MW/km^2) in each wind power class 3 through 7 is given in Table 1 for a 10 D by 5 D spacing. The estimated power output (MW/km^2), shown in Table 1 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 to be 0.25 in this case. Since the average power density values used for this paper represent mean annual values, energy production (in units of billion kWh) can be calculated by multiplying the average power values in Table 1 by 8760 hours.

To obtain the average power output for each grid cell over the contiguous United States, the value

Table 1. Total Wind Power in a Vertical Plane of one Square Meter, Total Power Intercepted by all Wind Turbines in One Square Kilometer of Land Area, and Estimated Power Output from all Wind Turbines

Power Class	Wind Power Density (W/m^2) at 50 m	Power Intercepted (MW/km^2)	Estimated Power Output (MW/km^2)
3	350	5.50	1.03
4	450	7.07	1.33
5	550	8.64	1.62
6	700	11.00	2.06
7	900	14.14	2.65

of the estimated power output for each power class in the grid cell is multiplied by the area of the land with the corresponding power class in the grid square. These values are then summed for all the grid cells in each state; then, a total of the 48 states is computed to determine the wind energy potential for the contiguous United States. The results of this computation are shown in Figure 5, for the same set of land exclusion scenarios shown in Figure 3.

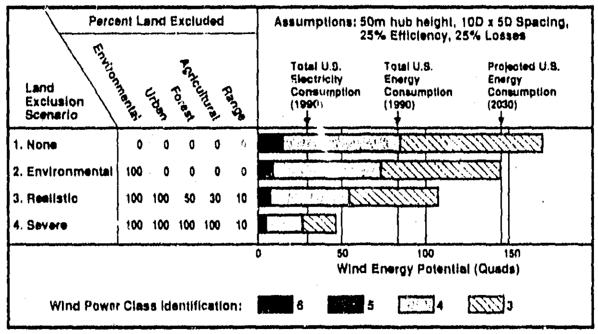


Fig. 5. Wing Energy Potential of the Contiguous United States Considering Environmental and Land-Use Exclusions

The assumptions about the turbine were intended to include some features of an advanced design. Specifically, the 50-m hub height is not typical of the vast majority of today's operational turbines. This hub height takes advantage of the increase of wind speed with height typical over much of the area in the central United States. As can be seen from the 30- and 50-m power density values shown in Figure 3, the difference in power is 25%. If there is some disagreement with the other assumptions of turbine spacing, efficiency, or power losses, the wind energy potential shown in Figure 5 can be easily adjusted with ratios of the preferred assumptions to the ones used here.

The striking feature of Figure 5 is that the wind energy resource, even at the levels being tapped in California today (class 5 and above), shows the potential to make a substantial contribution to the nation's electrical (27%) and total energy (10%) consumption. When the technology is advanced to the point of allowing power classes 3 and 4 to be tapped in a cost-effective manner, the potential contribution will increase substantially. Thirty-seven percent of the U.S. energy consumption in the year 2030 could be supplied by using areas of power class 4 and above and exclusion Scenario 3; the percentage contribution could increase to 75% if areas of power class 3 and above were to be developed.

To show the wind resource distribution over the country, wind electric potential by state is shown in Figure 6. Figure 6a is intended to represent the contribution possible with today's technology, while Figure 6b is intended to represent the possible contribution with advanced technology, which allows areas with power classes 3 and 4 to be developed. Probably the most dramatic change between the potential for

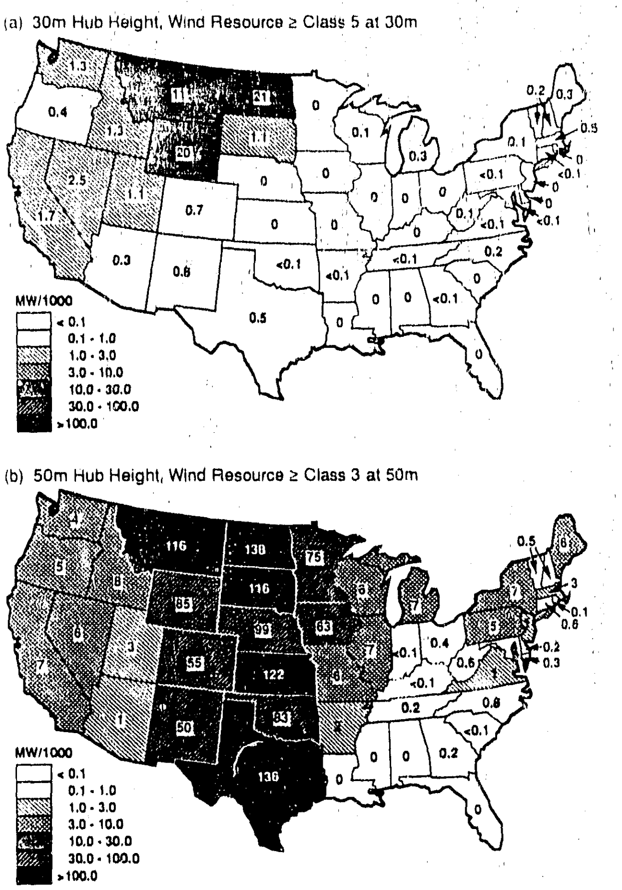


Fig. 6. Wind Electric Potential (in Thousands of MW_{avg}) for (a) 30-m Hub Height and Wind Resource ≥ Class 5 at 30 m, and (b) 50-m hub height and wind resource ≥ Class 3 at 50 m. Other specifications are 10D x 5D spacing, 25% efficiency, 25% losses and land exclusion Scenario 3.

individual states occurs in several states in the central portion of the country (Iowa, Kansas, Nebraska, and Oklahoma, for example), which go from virtually no potential in Figure 6a to being ranked in the top 12 states in Figure 6b.

The enormous contrast between the wind energy potential shown to be available in Figure 6a and b tends to detract from the fact that there are some notable contributions within particular states. For example, although the wind energy potential for the contiguous 48 states shown in Figure 6a is less than 8% of that shown in Figure 6b, the wind electric potential in North Dakota and Wyoming exceed their local electric consumption by factors of 7 and 4.3, respectively.

To put the wind electric potential available with advanced turbine technology in perspective with recent (1987) electric and total energy consumption, we computed the percentage of the entire U.S. current electric and total energy consumption that could be supplied by wind energy from a given state. These percentages were calculated from the wind electric potential values shown in Figure 6b. We chose current rather than future consumption for the comparison to present what might be possible with accelerated technology development. The results are shown in Figure 7a and 7b for electric and total energy consumption, respectively. We note here that the sum of the percentage values in the 48 states sums to 350% in Figure 7a and to 125% in Figure 7b.

It may also be worthwhile to point out in Figure 7a and b that there are 12 contiguous states in the midsection of the country that contribute over 90% of the wind energy potential of all 48. In addition to the fact that these states contribute such a high percentage to the overall electric consumption and total energy consumption, they also have the potential to produce several times their 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 7a is that, in addition to the 12 states that seem to be the major contributors to wind electric potential, there are four states in the West and seven states in the vicinity of the Great Lakes and Northeast regions that show a wind electric potential of around 2% of the total electric consumption for the contiguous United States.

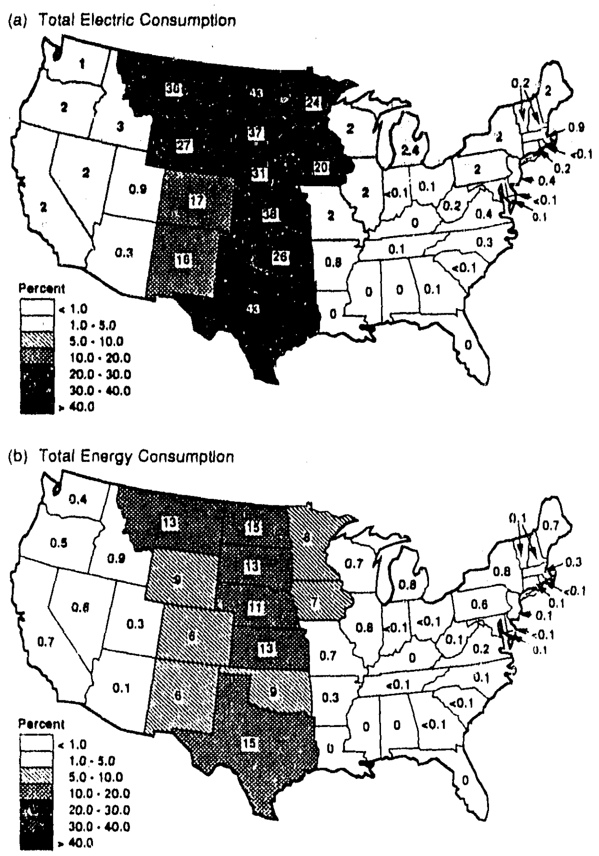


Fig. 7. Wind Electric Potential as a Percent of Contiguous U.S. 1987 (a) Total Electric Consumption, and (b) Total Energy Consumption. (See Figure 6b for other specifications.)

CONCLUSIONS AND RECOMMENDATIONS

The primary conclusion to be drawn from this analysis is that wind energy over the contiguous United States is not resource limited. 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.

Future advances in technology will further enhance the wind energy potential in the United States. Today's technology allows the exploitation of the wind resource in certain "hot spots" with resource class 5 or greater. To date, development of these spots has occurred primarily in California. As advances in turbine technology allow lower levels of the wind resource to be developed, say down to class 3, more than a 10-fold increase in the wind energy potential will result. Twelve states in the midsection of the country would then have the potential of producing more than 3 times the nation's 1987 total electric consumption, while other states in the west and northeastern sections of the country could each provide up to 2% of the country's electrical needs.

This study has provided a quantitative estimate of the overall resource. We need to emphasize two things concerning this study. First, the results presented herein must be regarded as estimates only, and would be subject to change with the use of different assumptions and specifications. Second, this study does not diminish the need for careful siting and array design efforts before the actual installation of a wind plant.

Acknowledgments

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