Conf-930726--4

PNL-SA-22090

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July 1993



Presented at the
Windpower '93
July 12-16, 1993
San Francisco, California

Prepared for
the U.S. Department of Energy
Contract DE-AC06-76RLO 1830

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## ABSTRACT

Seasonal wind electric potential has been estimated for the contiguous United States based on the methods previously used to estimate the annual average wind electric potential. National maps show estimates of the seasonal wind electric potential averaged over the state as a whole, and gridded maps show the distribution of the seasonal wind electric potential within a state.

The seasons of winter and spring have highest wind electric potential for most windy areas in the United States. Summer is the season with the least potential for most of the contiguous United States. Wind electric potential patterns in autumn generally resemble the annual average potential map.

Excellent matches between seasonal wind electric potential and electric energy use occur during winter for the northern parts of the nation. California has a good match between summer wind potential and electric use.

## INTRODUCTION

A 1987 wind energy resource atlas of the United States (1) showed that areas potentially suitable for wind energy applications were dispersed throughout much of the contiguous United States. Later studies by Pacific Northwest Laboratory in 1991 (2) and 1992 (3) estimated the available windy land area and annual average wind electric potential under a variety of land-restriction scenarios for several levels of wind resource for each state and for grid cells (1/4° latitude by 1/3° longitude) across the contiguous United States. The grid-cell estimates (3) accounted for the actual distribution of environmental exclusion areas (including parks, monuments, wilderness areas, wildlife refuges, and other protected areas where wind energy development would be prohibited or severely restricted), as well as land-use restrictions for various types of land (e.g., forest, agriculture, range, and urban lands).

Although annual estimates of wind electric potential are useful for preliminary assessments in a given state or region, energy planners and utilities are also interested in correlating the seasonal variability of the wind resource with seasonal electric loads. The national wind energy resource base includes gridded files of seasonally averaged wind power density. These gridded data files of wind resource plus the gridded files of terrain exposure, land-use types, and environmental exclusion areas provided the basis for developing estimates of seasonal wind electric potential. In this paper, the seasons are defined as they were in the wind resource atlas (1): winter is December-February, spring is March-May, summer is June-August, and autumn is September-November.

## WIND ELECTRIC POTENTIAL CALCULATIONS

The formulas used to calculate the available windy land area in a grid cell and the power produced per grid cell are unchanged from the 1992 study (3). The available windy land per grid cell is based on a "moderate" land-use scenario; this means that the percentages of land excluded from wind energy development are 10% for range and barren lands, 20% for mixed agricultural/range land, 30% for agricultural land, 50% for forested land, and 100% for urban land and wetland. The amount of potential electricity that can be generated from the available windy land is dependent on the turbine hub height, spacing between wind turbines, the efficiency of the machines, and the estimated energy losses. The specifications used in this paper and the resulting average power output per square kilometer of land are presented in Table 1.

For this paper, the seasonal potential was evaluated for areas where the average annual wind resource was at least class 4 (Table 2). Many of these areas are expected to be suitable for wind energy development using advanced turbine technologies. These technologies are either just now becoming commercially available or will become commercially available in the near future.

TABLE 1. WIND ENERGY POTENTIAL PER SQUARE KILOMETER OF LAND AREA (BY WIND POWER CLASS)

**Assumptions: 50-m hub height, 10 D x 5 D 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 $kWh/km^2$ |
|---|---|---|---|---|
| 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 |

TABLE 2. 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, $W/m^2$ | Speed[b], m/s (mph) | Wind Power Density, $W/m^2$ | Speed[b], m/s (mph) | Wind Power Density, $W/m^2$ | 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.

SEASONAL VARIABILITY OF WIND ELECTRIC POTENTIAL

Figure 1 is a map of the gridded annual wind electric potential in megawatts of average power output for areas with class 4 and above (assuming a 50-m hub height). The Great Plains and the Rocky Mountain States have the greatest wind electric potential, but other good wind resource areas are located in the Northeast, along the shores of the Great Lakes, and the wind corridors of the western United States. Gridded seasonal maps of the wind electric potential for areas with class 4 and above (Figure 2) show interesting variability in the seasonal potential in various parts of the country. For most of the windy areas, winter and spring are the seasons with the greatest wind electric potential. In winter, the highest-power-producing grid cells (>800 MW) are located in Wyoming and Montana. In the area from northern Texas to North Dakota, grid cells have electric potential up to 601-800 MW. In spring, the highest-power-producing grid cells (>800 MW) are located from Texas to Wyoming, and in North Dakota and California. Grid cells with 601-800 MW potential are abundant in the southern Great Plains and in North and South Dakota. Wind corridors in California, Oregon, and Washington also have high wind electric potential in spring. Summer is also a good wind resource season in these wind corridors, with wind electric potential values at or near the springtime values. In summer, the highest-power-producing grid cells in the Great Plains are located from northern Texas to Kansas, with values of 601-800 MW. Areas of relatively high potential (401-600 MW) in summer also occur in parts of the Great Plains. Autumn wind electric potential patterns generally resemble the annual average potential map, with individual grid cells having electric potential values close to their annual averages.

The seasonal average wind electric potential was also evaluated for each state as a whole and expressed as a percentage of the annual average wind electric potential. Figure 3 shows the percentage of the annual average electric potential that can be produced from areas with class 4 and above for each of the contiguous states for each season. In winter, most of the states have a seasonal average wind electric potential that is greater than the average annual potential. In the northeastern United States, for instance, the winter average potential is generally 30-40% higher than the average annual potential. In winter, about half the contiguous states have a seasonal average

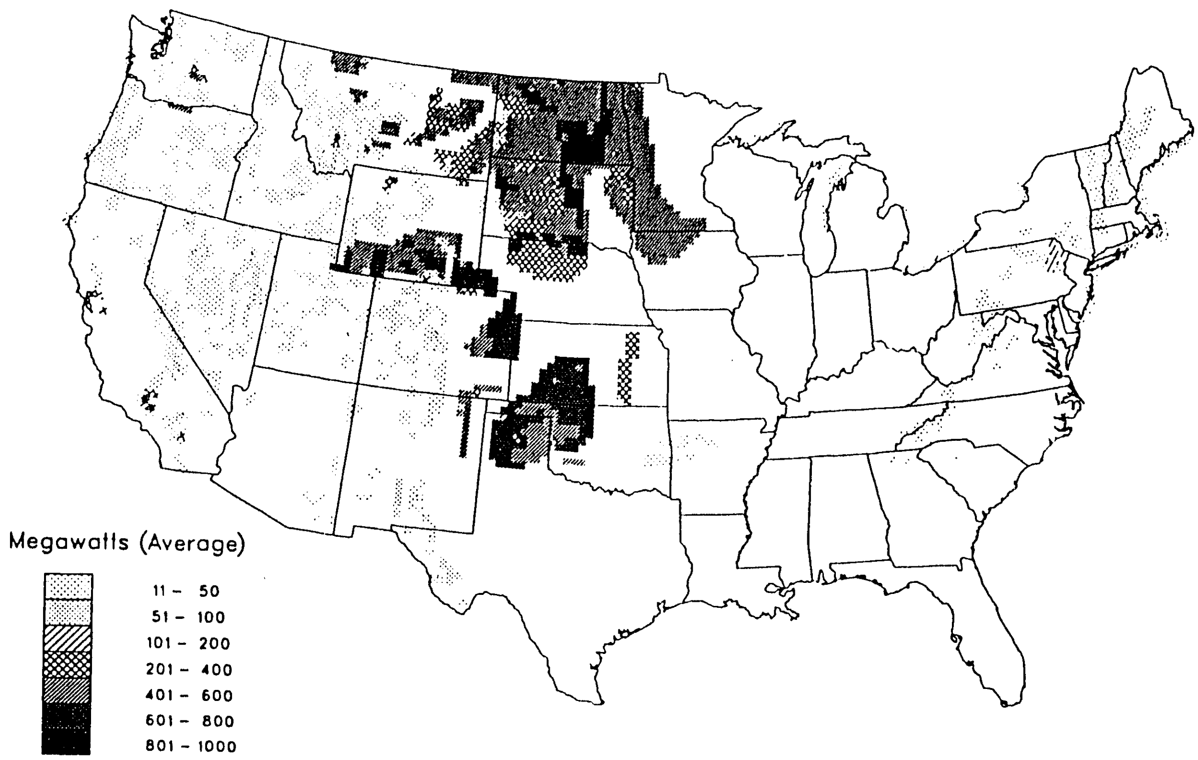


FIG. 1. AVERAGE ANNUAL WIND ELECTRIC POTENTIAL FOR EACH GRID CELL (IN MEGAWATTS) FOR CLASS 4 AND ABOVE (50-M HUB HEIGHT).

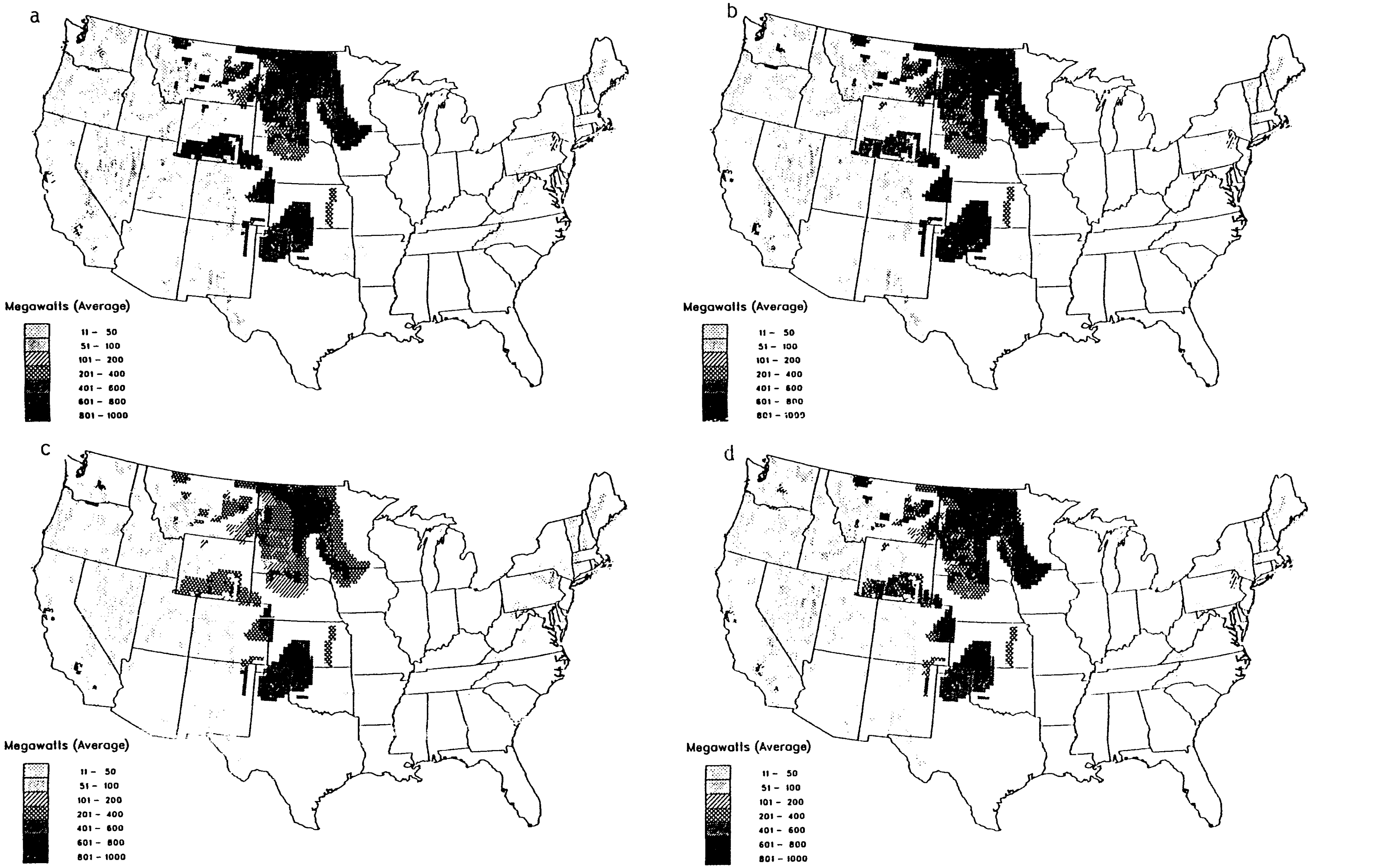


FIG. 2. SEASONAL WIND ELECTRIC POTENTIAL FOR EACH GRID CELL (IN MEGAWATTS) FOR CLASS 4 AND ABOVE (50-M HUB HEIGHT) FOR a) WINTER, b) SPRING, c) SUMMER, and d) AUTUMN.

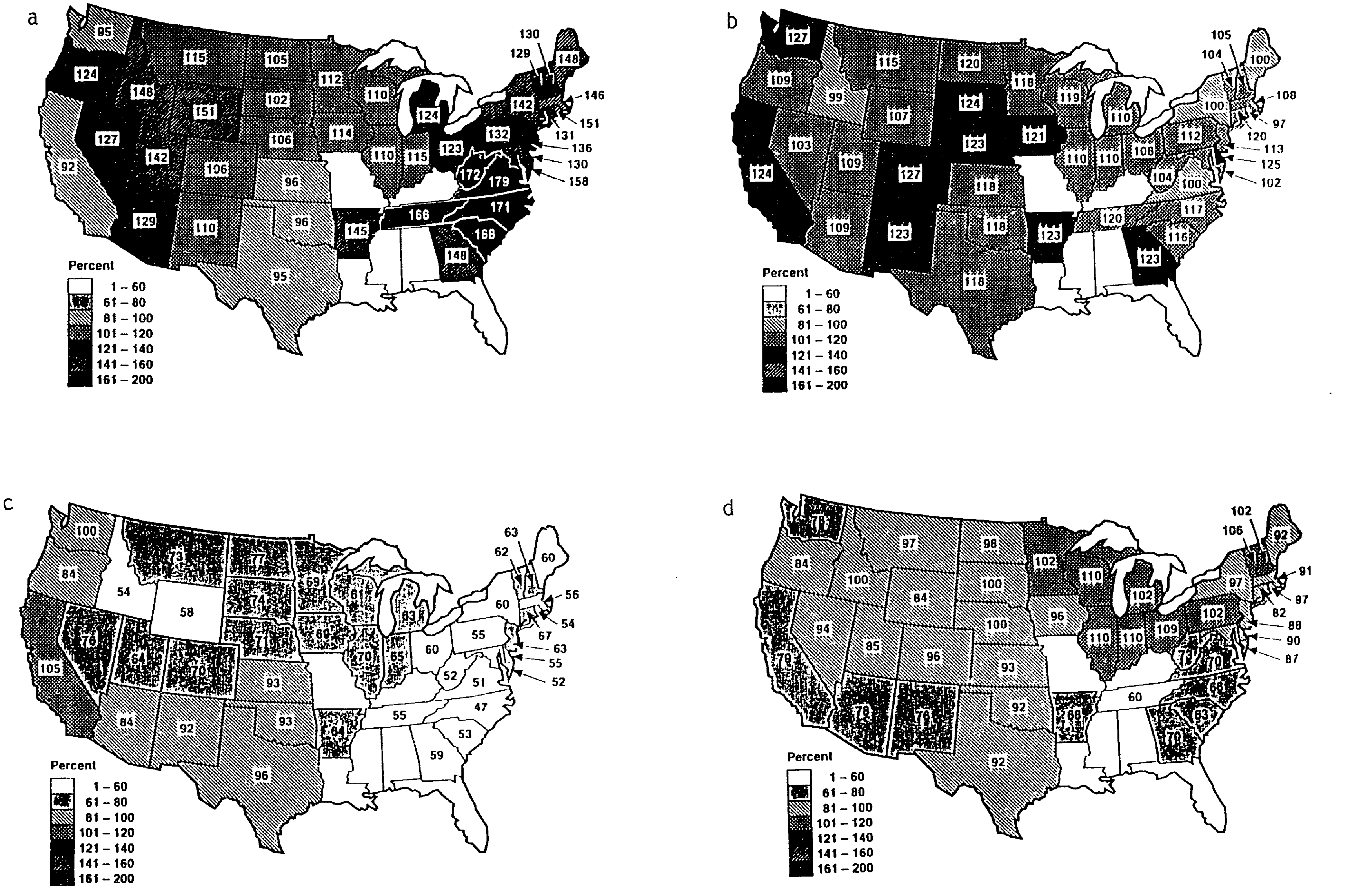


FIG. 3. SEASONAL PERCENTAGE OF ANNUAL WIND ELECTRIC POTENTIAL FOR EACH CONTIGUOUS STATE FOR CLASS 4 AND ABOVE (50-M HUB HEIGHT) FOR a) WINTER, b) SPRING, c) SUMMER, and d) AUTUMN.

potential that is at least 20% higher than the annual average potential. California, Washington, and the southern Great Plains have winter potentials below their annual average potential, but the difference is less than 10%. The spring map (Figure 3b) shows that many states have a seasonal electric potential that is higher than the annual average potential by 10% or more. The Great Plains have a spring potential around 20% higher than the annual average potential. Summer is the season with the least potential for most of the contiguous United States. However, a few areas of the nation, such as California, Washington, and the southern Great Plains (Texas, Oklahoma, and Kansas), have good summer potential; values in California are 5% above the annual average electric potential and values in the other areas are at or only 5 to 10% lower than the annual average potential. In autumn, many states have a seasonal potential just below or just above the annual average potential. The states with autumn potential equal to or greater than the annual average potential are mostly located in the northern Great Plains, the Great Lakes region, and the Northeast.

## COMPARISON OF SEASONAL POTENTIAL WITH ELECTRIC ENERGY USE

Energy planners and utilities are interested in correlating the seasonal variability of the wind electric potential with seasonal electric loads. Table 3 presents estimates of the seasonal matches between the wind electric potential and electric energy use for several regions in the United States. These estimates are based on regional electric energy use for the four seasons during the year 1990 and the seasonal wind electric potential, based on areas with class 4 and above wind resource, both normalized to a yearly value.

In three of the six regions, there is an excellent match between the season of highest wind potential and the season of highest electric use. In the Northeast, North Central, and Northwest regions, both the wind electric potential and electric use peak in the winter. California has a good match in summer, when the highest electric use and high potential both occur. In the South Central region, the wind potential in summer (the season of highest electric use) is only slightly lower than the annual average wind potentiai. The Central region has the poorest match between seasonal wind potential and electric use; the season of highest electric use (summer) is also the season of the lowest wind potential. Nevertheless, even in summer the wind resource in the Central region is substantial (see Figure 2c) and averages only about 20% less than the annual average wind potential.

TABLE 3. NORMALIZED SEASONAL WIND ELECTRIC POTENTIAL AND ELECTRIC ENERGY USE (Electric potential is the top number, and electric use the bottom number for each season). Class 4 and above, for a 50-m hub height.

| Region[a] | Winter | Spring | Summer | Autumn |
|---|---|---|---|---|
| Northeast | 1.40<br>1.06 | 1.05<br>0.96 | 0.60<br>1.01 | 0.95<br>0.97 |
| Central | 1.05<br>0.99 | 1.21<br>0.89 | 0.78<br>1.13 | 0.96<br>0.99 |
| South Central | 1.00<br>0.92 | 1.20<br>0.86 | 0.94<br>1.18 | 0.87<br>1.04 |
| North Central | 1.20<br>1.04 | 1.17<br>0.93 | 0.69<br>0.97 | 0.93<br>1.05 |
| California | 0.92<br>0.98 | 1.24<br>0.93 | 1.05<br>1.07 | 0.79<br>1.01 |
| Northwest | 1.22<br>1.12 | 1.12<br>1.01 | 0.79<br>0.94 | 0.87<br>0.94 |

(a) Northeast = Maine, Vermont, New Hampshire, Massachusetts, Rhode Island, Connecticut, New York

Central = Iowa, Kansas, Nebraska

South Central = Texas, Oklahoma, New Mexico

North Central = Colorado, Wyoming, Utah, Montana, North Dakota, South Dakota

Northwest = Oregon, Washington, Idaho

## CONCLUSION

Seasonal estimates of the wind electric potential have been calculated for the contiguous United Sates for each $1/4^{\circ}$ latitude by $1/3^{\circ}$ longitude grid cell and for each state as a whole. Winter and spring are the seasons with highest wind electric potential for most areas of the country, although the wind corridors of the far western United States have their maximum wind electric potential in spring and summer. The match between seasonal wind electric potential and seasonal electric use is generally excellent during the winter for northern parts of the nation. California has a good match between summer wind potential and electric use.

Important factors not addressed in this study that influence the total electric potential include seasonal peak load data, diurnal production/demand match, transmission and access constraints, public acceptance, and other technological and institutional constraints.

This study of the quantitative estimate of the seasonal wind resource should enhance the development of resource verification and siting studies using improved terrain resolution in areas estimated to have excellent wind resource potential.

## ACKNOWLEDGMENTS

We would like to thank Randy Johnson of Princeton Economic Research Incorporated for providing regional information on electric energy use in the United States for the year 1990. This work was supported by the U.S. Department of Energy under Contract DE-AC06-76RLO 1830 at the Pacific Northwest Laboratory, which is operated by Battelle Memorial Institute.

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