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The Sensitivity of Wind Technology Utilization to Cost and Market Parameters

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Abstract

This study explores the sensitivity of future wind energy market penetration to available wind resources, wind system costs, and competing energy system fuel costs for several possible energy market evolution scenarios. The methodology for the modeling is described in general terms. Cost curves for wind technology evolution are presented and used in conjunction with wind resource estimates and energy market projections to estimate wind penetration into the market. Results are presented that show the sensitivity of the growth of wind energy use to key cost parameters and to some of the underlying modeling assumptions. In interpreting the results, the authors place particular emphasis on the relative influence of the parameters studied.

Background

To estimate the energy that might be obtained from renewable energy sources, the U.S. Department of Energy requested that the appropriate national laboratories jointly undertake an assessment study. The results of this effort were documented in the report entitled, *The Potential of Renewable Energy, An Interlaboratory White Paper* (1) (hereafter referred to as "the White Paper"). This work subdivided the contiguous 48 states into four regions and then looked at the potential for the use of renewable energy sources over the time frame 1990 to 2030. The study considered the availability of resources, three scenarios for technology development, and a common projection for future market growth and fossil-fuel cost escalation. This study was accomplished for all the renewable technologies on a very tight schedule that allowed no time to explore the sensitivity of the resulting projections to the underlying assumptions.

The purpose of the current effort is to expand the modeling approach of the White Paper to determine the sensitivity of the estimated wind energy market penetration to the key cost parameters and to some of the underlying modeling assumptions. To accomplish this for the current study, a spreadsheet computer model was developed. The key cost parameters for study were fossil-fuel costs and wind-turbine costs. In the White Paper the potential market for which the renewable technologies were competing was assumed to be projected new generation growth. Because wind energy is an intermittent energy source, this study considered it to be a fuel saver that displaces only fuel and variable operation and maintenance (O&M) costs of fossil-based generating systems. In this situation, wind systems could be installed in addition to other generation sources just to save on fuel costs. Because no capacity credit for displacing conventional generation is assumed, this study expands the potential market to all existing fuel-based generation sources, as well as new generation growth.

Because the major focus of this study is to explore the sensitivity to various parameters and modeling assumptions, the results are useful in developing a better understanding of how market, resource availability, and technology-related variables are likely to influence the growth in use of wind technology. The results indicate which variables are most important and which variables just don't matter. The authors make no claim that the results presented are more realistic than those presented in the White Paper, nor are these results considered to be accurate predictions of the future. The results simply demonstrate general trends and specific sensitivities to input assumptions.

Methodology

Estimating the potential energy contribution for wind technology requires projections of the future energy market for competing sources, knowledge of the available wind resource, projections for future wind system costs, and assumptions concerning the likely rate of penetration of wind technology into the market. The potential contributions for wind energy were computed for a particular region and time as follows:

1) Future energy market projections were used to establish a regional avoided cost for a particular time frame. Avoided cost for this study is defined as fuel plus variable O&M costs and is calculated on a regional basis.

2) Wind system cost curves as a function of wind speed and time were used to determine the minimum cost competitive mean wind speed for each time frame.

3) The resource available in a region that had a site mean wind speed equal to or greater than the minimum required to be competitive was determined from the resource estimates. During the time-sequenced calculations, wind resources used at an earlier time were removed from the resource base.

4) Penetration assumptions were used to estimate the fraction of economically competitive wind energy that could actually be developed for the region. This multiplicative penetration fraction reflects investor, marketplace, and institutional constraints.

5) A wind energy cost parameter and a fossil fuel cost parameter were embedded in the analysis. These parameters apply incremental variations to the wind costs and fuel costs in order to look at the sensitivity to these costs for each basic scenario.

Two basic scenarios of technology development were considered. The baseline scenario, which assumes current research and development R&D funding levels, has been termed the BAU scenario, or Case 1. The second is a case where the development of wind technology is intensified, and it has been called the R&D Intensified scenario, or Case 2. Both scenarios are also subjected to the application of an economic incentive program, termed "National Premiums," where a $0.02/kWh premium is applied to the cost of fossil-fuel generation sources.

Energy Market Projections

The White Paper provided estimates for the electrical energy market between 1988 and 2000. Cost of fuel, variable O&M, and projected electrical energy supplies were provided for each of the four geographic regions for coal, natural gas, oil, nuclear, and hydro power. After the year 2000, the fuel mix ratios for each region were held constant.

In the White Paper, the assumption was made that wind energy would compete primarily against oil and natural gas during the early years but would not compete with coal directly until about 2010, when oil and natural gas were displaced from the marketplace for new generation. For this reason the avoided cost was taken to be the price of oil and gas until it was displaced. In addition, as discussed above, the potential market for wind energy was assumed to be only the projected new generation growth for the fuels that wind was competing against. Thus, during the near term, wind was competing against relatively high-priced fuels, but the market was restricted to supplying new generation only. Wind was not allowed to displace oil and gas energy from existing plants. In this study, the model has been modified to allow the avoided cost to be computed as the weighted average cost of coal, gas, and oil for each region, and wind is allowed to compete with all fuel-based generation.

Wind Energy Cost Projections

The cost of energy (COE) estimates used for wind technology are presented in Figure 1, along with the avoided cost range for the four study regions used in this study. The avoided cost is shown as a range to represent the regional differences in fuel costs, which include fuel transportation costs. The wind energy COE estimates are identical with those used for the White Paper. The rationale for these COE estimates was developed in some detail by Hock, Thresher and Cohen (2). The data in these COE curves were least-squares fit, using an exponential equation of the form

$$VWIND = A \cdot EXP(B \cdot COE) \qquad (1)$$

where the values for A and B were determined from the technology cost and performance assumptions for each time frame: 1990, 1995, 2000, and then at 10-year increments to 2030. Substitution of the avoided cost into Eq. (1) for COE provides an estimate of the minimum required site average wind speed at which wind will be cost competitive. Two sets of regression coefficients were determined in this manner for each region; one set for the Business As Usual (BAU) scenario(Case 1), and a second set for the R&D Intensification scenario(Case 2).

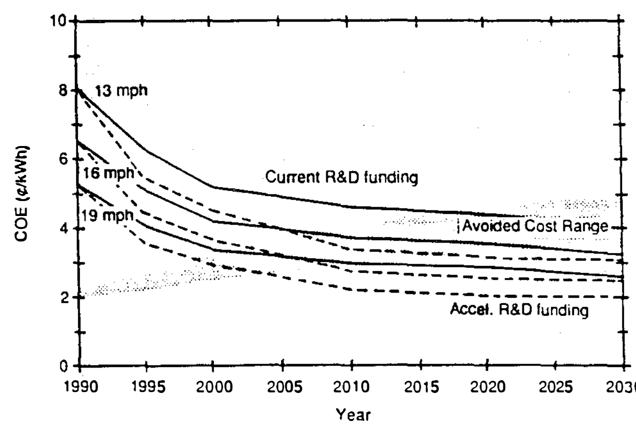

FIGURE 1. WIND TECHNOLOGY COST CURVES

Wind Resource Estimates

The resource potential was estimated by dividing the United States into four regions as defined in the White Paper. These four regions are the Northeast, North Central, South, and West. The wind resource potential used for this study was developed by Elliott, Wendell, and Gower (3). These estimates include realistic land exclusion allowances for environmental, urban, forest, agricultural, and range land requirements, and assume wind farm arrays with a spacing of 10 diameters between rows in the downwind direction and 5 diameters in the cross-wind direction. The average energy capability is then estimated assuming an overall wind turbine conversion efficiency of 25% and overall losses of 25%. The available energy density potential for each study region is shown in Figure 2 as a function of mean wind speed. Also shown in the figure is a set of regression curves that were fit to the data using an exponential equation of the form

$$\text{(Avail Energy/Unit Windspeed)} = C \cdot EXP(D \cdot V) \qquad (2)$$

where C and D are the regression coefficients and V is windspeed. Integration of this expression over all windspeeds equal to, or greater than, the value of VWIND obtained from Eq. (1) yields the economically available wind resource for a given region. Subtracting the previously developed resource gives the net available resource in any given time period.

The resource estimates used in the White Paper came from estimates made by Cherry(4) in 1981. The more recent estimates by Elliott, et al.(3) include more restrictive land-use exclusions and updated wind data analysis and were therefore used for this study.

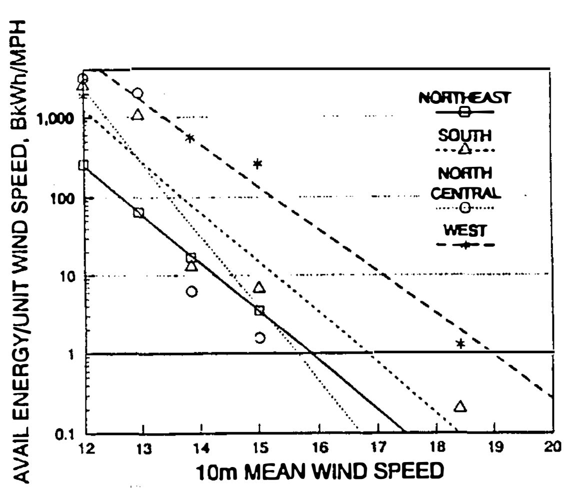

FIGURE 2. THE AVAILABLE WIND ENERGY FOR THE STUDY REGIONS

<u>Constraints</u>

The penetration of a market by a new technology does not occur instantly, even when the new technology enjoys a significant cost or performance advantage. For wind systems there are manufacturing and installation rate constraints; and, perhaps most importantly, investors and users must be convinced that the technology will operate reliably and efficiently over its expected 20- to 30-year life. For these reasons, penetration rate constraints were placed on the potential wind market. After determining the amount of wind energy that could economically be supplied, a penetration fraction was applied to represent these constraints. The assumed penetration factors are presented in Table 1.
These factors were selected to be quite small during the near term, reflecting a high degree of caution on the part of users and investors concerning the economic value and potential problems of operating an intermittent energy-generating system. In later years, it was assumed that confidence in the technology would build significantly, but it still seemed unlikely that wind technology could capture the entire market.

TABLE 1. PENETRATION CONSTRAINTS

(% of Economic Market)

Year	Case 1	Case 2
1995	2%	5%
2000	5%	10%
2010	10%	20%
2020	15%	30%
2030	20%	40%

Higher penetrations are assumed for the Premium and Intensified RD&D scenarios, reflecting the implied greater market demands. In the longer term when wind energy costs become competitive with coal, these assumed penetration factors are the only constraints preventing wind energy from capturing the entire energy market. It should be noted that these penetration factors represent the subjective judgment of the authors.

In addition to these penetration constraints, an overall wind penetration limit of 20% of total electrical generation was placed on each region. This constraint greatly slows the growth of wind generation in the long term. The current rule of thumb is that intermittent generation sources, such as wind energy, should not make up more than 10% of a utility system's generation capacity. The higher 20% limit for this study was assumed to reflect improvements in operating strategies, better transmission among utilities, and the introduction of low-cost storage over the next 30 to 40 years.

<u>Results</u>

Incremental wind energy penetration estimates developed during this study are presented in Figure 3, for each 5- or 10-year period. Cases 1 and 2 are shown both with and without the National Premium (denoted +P in the figure). The results for the Intensified R&D case in the White Paper are also shown for comparison. The bars in Figure 3 also show the breakdown of energy contributed by each region. As a reference , note that current annual wind energy production in California is about 2 BkWh.

For Case 1, wind does not begin to make a noticeable contribution until the 2000-2010 time frame and then begins to grow modestly with time. The reason for this can be explained by studying Figure 1 which shows the wind technology and avoided cost curves. Under the BAU scenario (Case 1) assumptions, wind energy costs are greater than avoided costs until 2000, even for the better wind sites. The addition of the $0.02/kWh premium shifts the avoided cost curves, which makes wind competitive sooner, as shown by the (1+P) bars. However, the very low penetration rate constraints imposed in the near term slow early market penetration. Thereafter, the addition of wind generation grows rapidly until the 2020-2030 time frame, when so much wind has been added to the generation pool that it is approaching the overall supply limit of 20%, and growth is curtailed.

Under the Intensified RD&D scenario(Case 2), the cost of wind energy declines more rapidly with time, but still does not

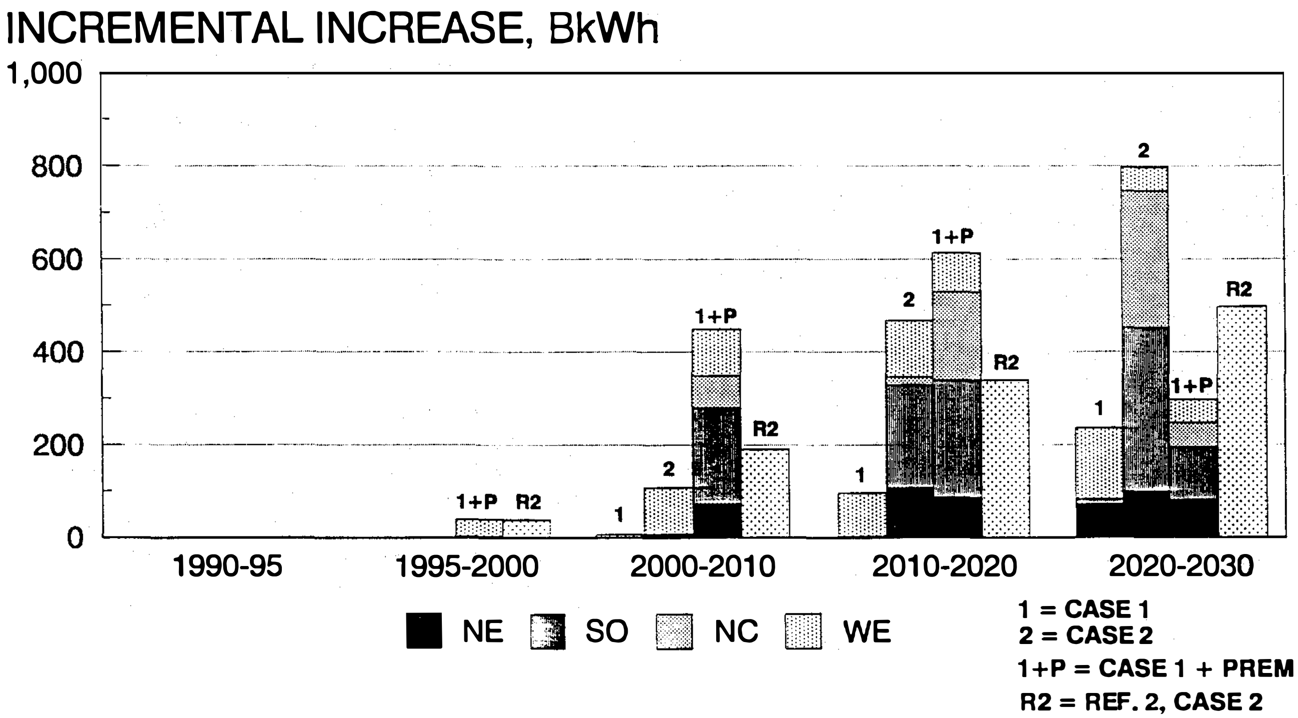

FIGURE 3. WIND PENETRATION ESTIMATES BASED ON REGIONAL WEIGHTED AVERAGE FUEL COST

drop below the avoided costs until the 2000-2010 time frame. After this crossover point, however, the growth is rapid because there is a much broader economical wind resource potential. The Intensified RD&D case from the White Paper (R2) is also shown in Figure 3. It should be remembered that for this case, wind was competing with oil and gas in the near term and coal in the long term, but could only supply new energy growth needs. As can be seen in Figure 3, the cost advantage of competing against oil and gas helps in the near term, but growth is slower in the long term because of the smaller market size.

Figure 4 shows the wind energy supplied as a percentage of total U.S. electricity generated. This figure also shows results for Case 2 with the addition of the $0.02/kWh premium. This figure illustrates the cumulative differences for each scenario. Case 1 shows the slowest market penetration, while Case 2 + Premiums shows the most rapid penetration. Notice, however, that in both cases including the premium, the 20% overall supply limit is reached in the 2010 to 2020 time frame, which thereafter limits wind utilization to 20% of new energy growth only.

Figures 5 and 6 illustrate the sensitivity of wind penetration to variations in the wind COE estimates. The ordinate of these plots shows wind generated electricity production and the abscissa shows fractional variations from the nominal wind cost curves of Figure 1. Thus a wind COE variation of 0.2 implies that the Figure 1 cost curves have been shifted upward by 20%. Figure 5 shows the sensitivities of the incremental penetrations for Cases 1 and 2 with premiums for the near term. The curves for the 1990-1995 time frame show a high sensitivity to variations in wind turbine-costs. A 10% variation in

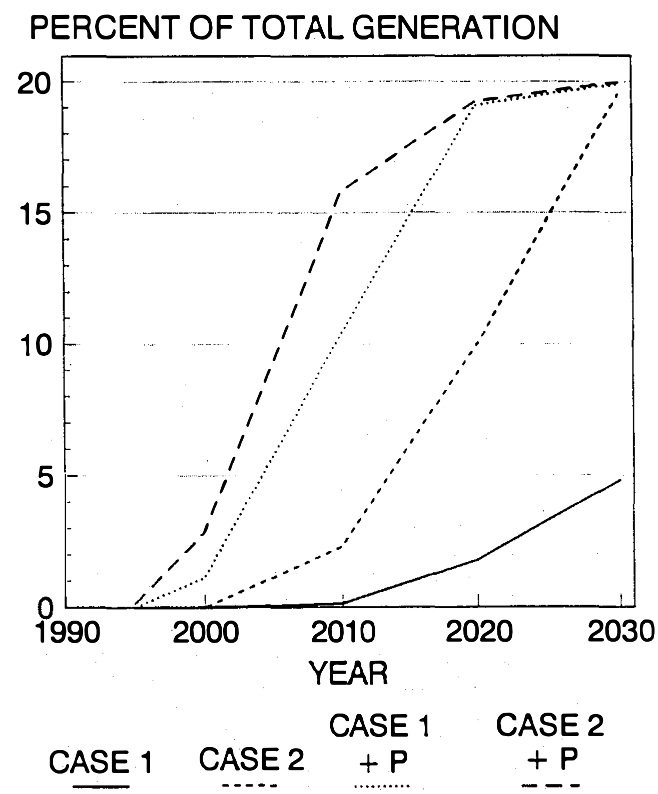

FIGURE 4. WIND ENERGY SUPPLIED AS A PERCENTAGE OF TOTAL U.S. ELECTRICITY GENERATED

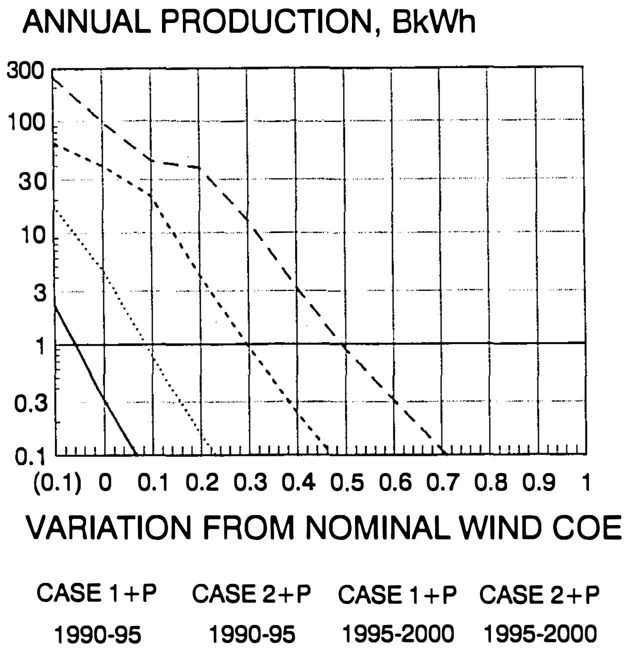

FIGURE 5. THE SENSITIVITY OF WIND PENETRATION TO VARIATIONS IN WIND COSTS

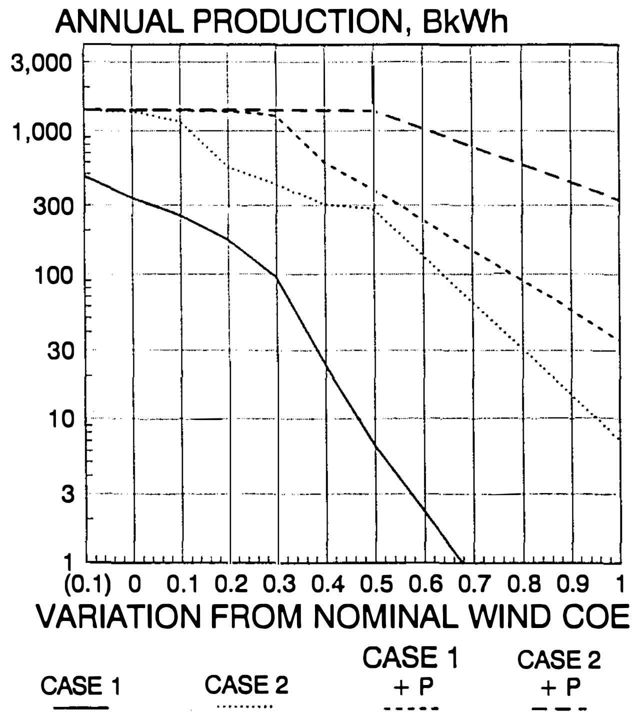

FIGURE 6. THE SENSITIVITY OF CUMULATIVE WIND PENETRATION TO VARIATIONS IN WIND COSTS

wind COE results in an order of magnitude difference in penetration. In the 1995-2000 time frame, this sensitivity is reduced for small variations in COE, but is still high for large variations. Figure 6 shows the sensitivity of long-term cumulative wind penetration to variations in wind costs. This curve illustrates a marked reduction in sensitivity except for Case 1 without premiums. This lack of sensitivity is due to the effect of saturating the overall electrical energy supply limit of 20%. Once that limit is reached, cost variations have little influence on further market growth.

Figure 7 demonstrates the sensitivity of wind penetration to variations in fuel cost projections during the near term. This plot shows an extreme sensitivity to fuel costs. A 50% variation in fuel cost assumptions results in a penetration change of more than an order of magnitude for Case 1. As has been demonstrated quite recently, a 50% variation in some fossil-fuel costs may not be unreasonable. These sensitivity plots should give the reader an intuitive feel for the difficulties of developing accurate predictions for wind turbine market growth, particularly over the span of 40 years.

Figure 8 illustrates the use of the economical wind resources as a function of time. As wind technology improves with time and wind COE is reduced, the technology can be used at lower windspeed sites. This means that the economically available wind resource is increasing with time. The resource is also being depleted with time as turbines are being installed, shown by the solid portion of each bar.

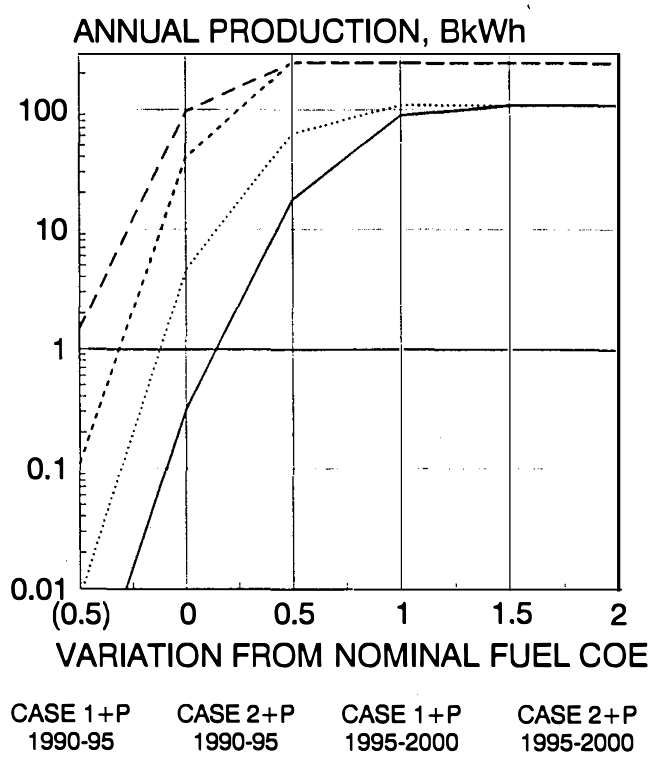

FIGURE 7. THE SENSITIVITY OF WIND PENETRATION TO VARIATIONS IN FUEL COSTS

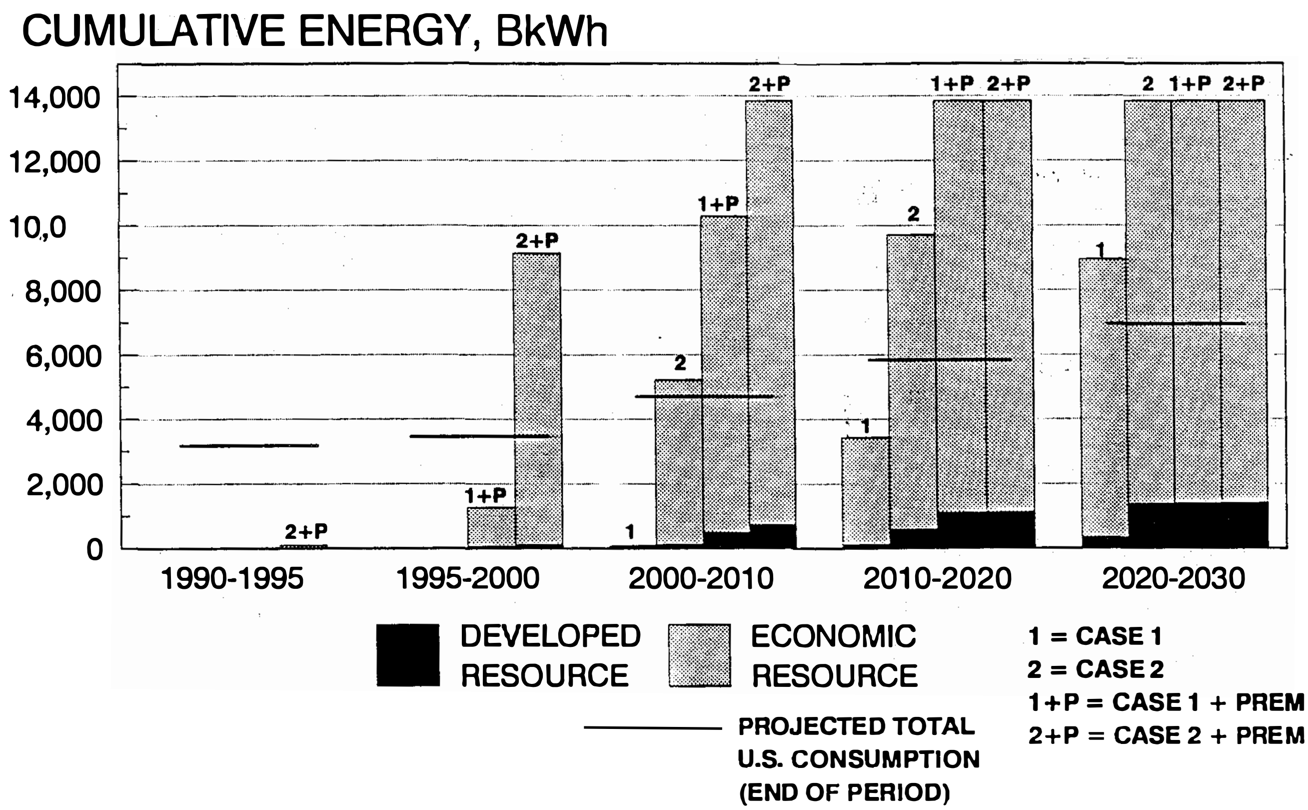

FIGURE 8. DEPLETION OF ECONOMICAL WIND RESOURCES WITH TIME

The projected electricity demand for each time frame is also indicated on the graph for reference. The single most important point illustrated by this plot is that no more than 10% of the economically available wind resource is needed to supply 20% of the U.S. total electrical needs in the year 2030.

Conclusions

The authors offer the following conclusions based on the modeling in this sensitivity study:

1) Wind resource availability was not the limiting factor for the growth of wind generation. Other factors such as avoided cost and the competitive market size influence the results much more dramatically.

2) Both the RD&D Intensification Scenario (Case 2) and the addition of the $0.02/kWh premium greatly accelerate the market penetration of wind technology. This study indicates that the premium increases the penetration more rapidly than the RD&D Intensification Scenario.

3) The penetration of wind technology into the energy market is extremely sensitive to future variations in both fuel costs and wind energy costs, making accurate long-term predictions difficult. However, the general trends should be correct and are very promising.

4) The results of this study depend on the market penetration rates assumed and the 20% overall electrical energy supply limit. If these assumptions are modified, for example, to include the effects of storage and removal of transmission restrictions, the projections may vary dramatically.

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