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Power System Modeling of 20% Wind-Generated Electricity by 2030

Preprint

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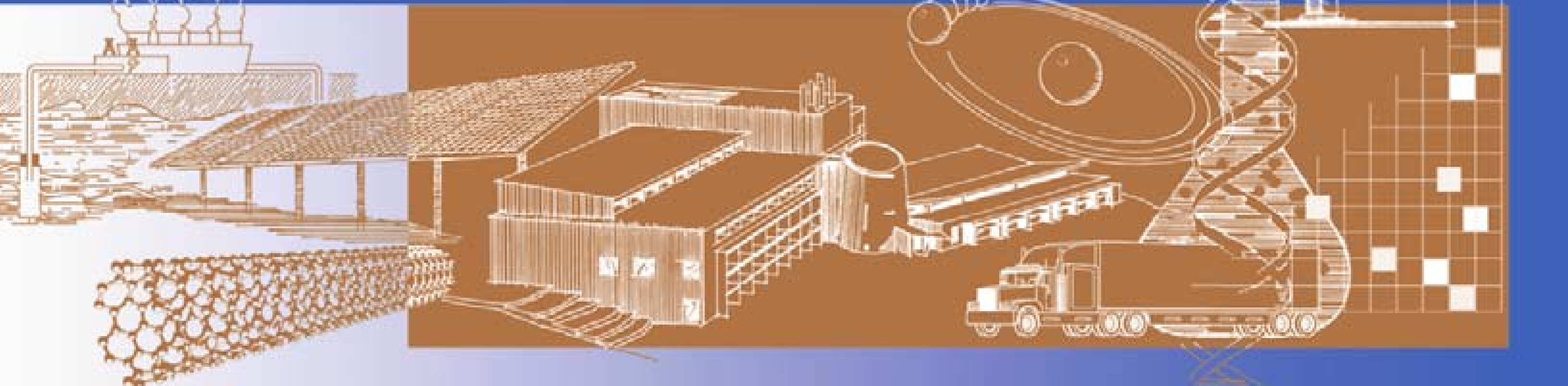

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Power System Modeling of 20% Wind-Generated Electricity by 2030

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Richard O'Connell[3], Tracy Hern[4], Bart Miller

***Abstract*—The Wind Energy Deployment System model was used to estimate the costs and benefits associated with producing 20% of the nation's electricity from wind technology by 2030. This generation capacity expansion model selects from electricity generation technologies that include pulverized coal plants, combined cycle natural gas plants, combustion turbine natural gas plants, nuclear plants, and wind technology to meet projected demand in future years. Technology cost and performance projections, as well as transmission operation and expansion costs, are assumed. This study demonstrates that producing 20% of the nation's projected electricity demand in 2030 from wind technology is technically feasible, not cost-prohibitive, and provides benefits in the forms of carbon emission reductions, natural gas price reductions, and water savings.**

***Index Terms*—power system modeling, wind energy**

I. INTRODUCTION

Generating electricity from wind technology has several advantages over conventional generation technologies. It helps avoid emissions of heavy metals and chemical precursors to acid rain, and of greenhouse gases that contribute to global climate change. It reduces the risk of fossil-fuel price fluctuations, and avoids electricity-sector water consumption. At the same time, wind resources are often in remote areas that require transmission investment, and the variability of wind electricity must be managed by electricity grids. Though wind reduces fossil-fuel usage, the investment cost of wind projects sometimes exceeds that of conventional fossil plants. This paper analyzes the technical feasibility, impacts, costs, and benefits of supplying 20% of the nation's electricity supply from wind technology by 2030. Though it does not explore the potential policy incentives that would be needed to achieve high levels of wind penetration in the U.S., it does intend to inform such discussions with credible analysis of the potentiaql costs and benefits of such policies.

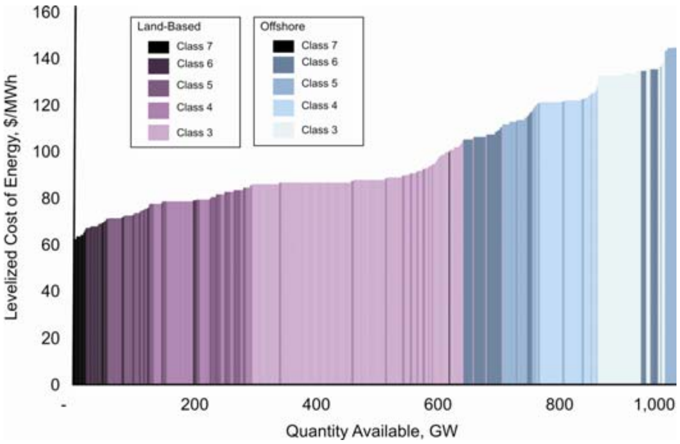

Fig. I. Supply curve for wind energy: energy costs including connection to 10% of existing transmission grid capacity within 500 miles of wind resource and excluding the Production Tax Credit.

The United States possesses ample wind resources, technically more than 8,000 GW, that could be harnessed to produce electricity at reasonable cost, if transmission expenditures are excluded. Considering some elements of the transmission required to access these resources, a supply curve that shows the relationship between wind power class and cost is shown in Fig. 1. It includes the cost of accessing the current transmission system and shows that more than 600 GW of potential wind capacity is available for $60 to $100/MWh. The data used to develop this supply curve is an input to the Wind Energy Deployment System (WinDS) model.

The WinDS model was developed by the National Renewable Energy Laboratory (NREL) and simulates electricity generation capacity expansion [1]. Numerous assumptions about the future cost and performance of conventional generation technology, as well as wind technology, transmission system operation and expansion, and future fuel prices, were developed by a broad group of wind industry stakeholders, including Black & Veatch [2] and using a variety of sources including the *Annual Energy Outlook* [3]. WinDS is a multi-regional, multi-time period, geographic information system (GIS) and linear programming model of electricity capacity expansion in the continental U.S. wholesale market. Generation capacity expansion is selected to achieve a cost-optimal generation mix over a 20-year planning horizon for each 2-year period from 2000 to 2050. For this study, however, all simulations were concluded at 2030.

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The WinDS model uses GIS-based supply curves for wind resources, along with projected costs and performance for other generation technologies such as pulverized coal plants, nuclear plants, combustion turbine natural gas plants, and combined cycle natural gas plants. Wind energy can be used to meet local loads in a region or it can be transmitted to other geographic regions via transmission lines. We assumed that 10% of the current transmission system capacity could be made available to wind-generated electricity. Beyond this, WinDS builds new transmission to deliver wind generation to load centers. To integrate variable resources into the electricity system, the WinDS model considers planning and operating reserve margins at the North American Electric Reliability Corporation (NERC) region level. The wind plant's capacity value is a function of its capacity factor (CF), seasonal and diurnal wind variations, and correlations with other wind capacity installations.

The primary assumptions governing the cost and performance of the various electricity generation technologies considered in this scenario are summarized in Table I.

This paper presents one possible scenario that reflects the costs, impacts, and benefits of producing 20% of the nation's electricity from wind. Annual wind energy generation was specified in each year from 2007 through 2030, based on a trajectory proposed by Laxson et al. [4]. Fig. 2 shows the resulting wind capacity required to meet that energy generation level. This trajectory was designed to produce an aggressive annual growth rate that reached a sustainable level resulting in 20% wind penetration by 2030, accounting for both demand growth and the repowering of aging wind plants. Based on the assumptions used in this study, the wind industry must grow from an annual installation rate of 3 to 4 GW/year in 2006 to a sustained rate of more than 15 GW/yr by 2018.

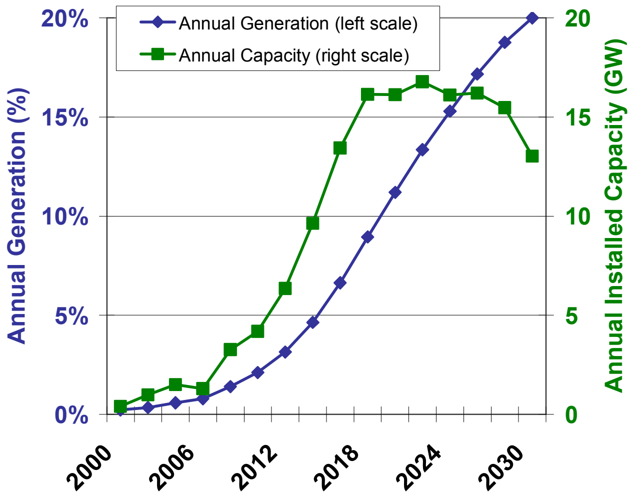

Fig. 2. Prescribed annual wind energy generation and corresponding annual wind capacity additions through 2030

TABLE I
ASSUMPTIONS USED FOR WINDS ANALYSIS (2006 DOLLARS)

	Scenario Assumptions
Land-Based Wind Technology Cost	• $1730/kW in 2005 and 2010, decreasing 10% by 2030 • Regional costs vary with population density, and are an additional 20% higher in New England
Shallow Offshore Wind Technology Cost	• $2520/kW in 2005, decreasing 12.5% by 2030
Wind Technology Performance	• CF improves about 15% on average over all wind classes between 2005 and 2030
Current Transmission	• 10% of current transmission capacity available to wind plants at point of interconnection
New Transmission	• $1600/MW-mile • 50% of cost covered by wind project • Regional cost variations prescribed as follows: 40% higher in New England and New York, 30% higher in PJM East, 20% higher in PJM West, 20% higher in California
Wheeling Charges	• No wheeling charges between balancing areas
Conventional Generation Technology Cost and Performance	• Natural gas plant cost ($780/kW in 2005) and performance flat through 2030 • Coal plant capital cost ($2120/kW in 2005) increases about 5% through 2015 and then flat through 2030 • Coal plant performance improves by about 5% between 2005 and 2030 • Nuclear plant capital cost ($3260/kW in 2005) decreases 28% between 2005 and 2030 • Nuclear plant performance flat through 2030
Fuel Prices	• Natural gas prices follow AEO 2007 high fuel price forecast • Coal prices follow AEO 2007 reference fuel price forecast • Uranium fuel price is constant

II. DESCRIPTION

Providing 20% of projected U.S. electricity demand by 2030 would require 305 GW of wind technology producing 1200 TWh annually (for reference, 16.6 GW of wind capacity were installed at the end of 2007 and produced about 1% of national electricity demand). Assuming wind turbine size increases from today's average of 1.6 MW to roughly 3 MW, this would result in around 100,000 wind turbines.

Based on the WinDS economic optimization model, Fig. 3 provides one scenario for the possible location of this 305 GW of wind capacity. Wind capacity installations are distributed among most U.S. states, with some regional concentration in those areas with the most robust wind resources. Additionally,

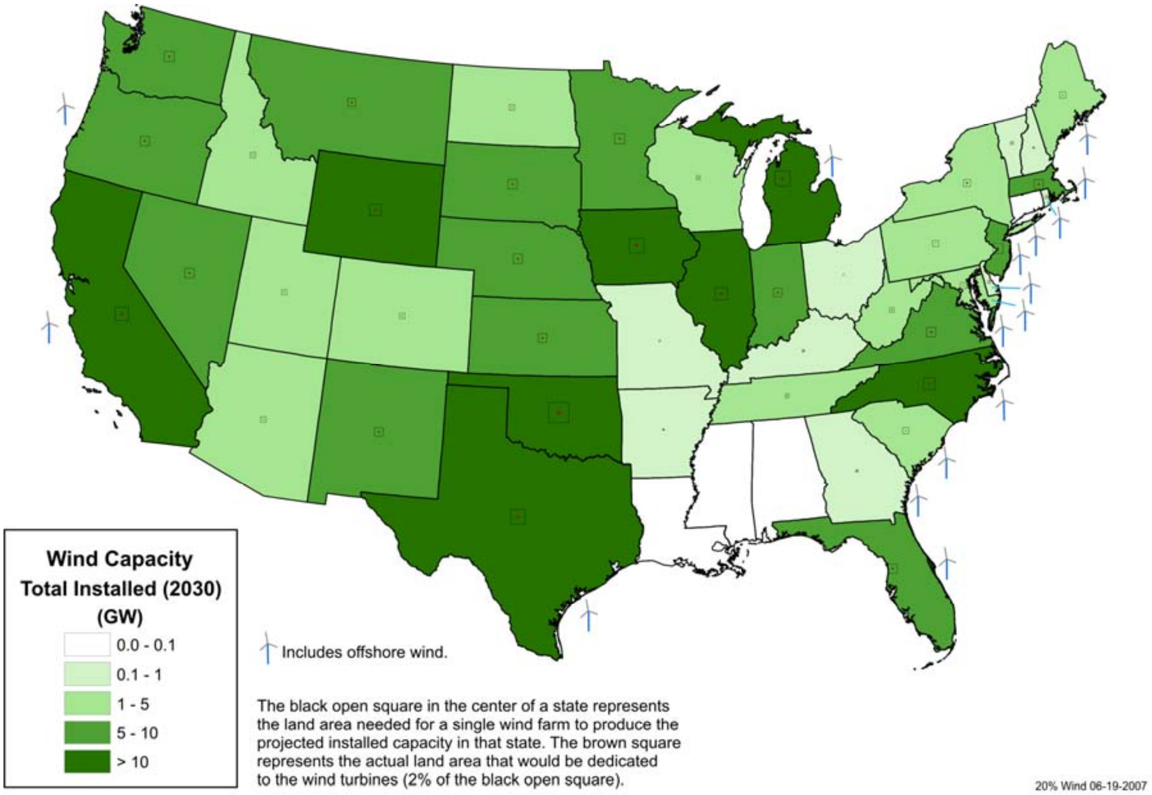

Fig. 3. Installed wind capacity by state in 2030[5]

of the total installed capacity in this scenario, 54 GW is estimated to be installed offshore in order to minimize transmission expenditures, primarily located along the eastern seaboard.

The land area required to support the 251 MW of land-based technology is about 50,000 km^2, but only 2% to 5% of that area (smaller than Rhode Island) is occupied by turbine towers, roads, etc. The balance remains available for its original uses such as farming and ranching.

Wind resource quality varies with geography. In general, the highest quality resources are distant from population centers. Transmission infrastructure must be improved and extended into these wind-rich areas to optimize the use of the nation's wind resource. The WinDS model evaluates three levels of transmission infrastructure:

1) In-region transmission – in any of the 358 wind regions in the United States that are modeled by WinDS, the costs of building transmission lines directly from the wind resource to loads within the region are evaluated.
2) Current grid – assuming that 10% of the current grid capacity is available to transport wind energy, the cost of feeder lines to access this existing transmission and costs to transport power across regulation boundaries[6] is evaluated.
3) New transmission lines – the WinDS model can evaluate the use of straight-line transmission lines between any of the 358 wind regions. The model assumes that new transmission lines are planned and constructed as additional capacity is needed.

In this analysis, reserve margin constraint planning occurs at the NERC region level, and load growth planning and operations occur at the balancing area (BA) level.

Fig. 4 illustrates one scenario, based on WinDS economic optimization analysis, of the wind energy capacity associated with the various categories of transmission modeling. For visualization purposes, wind capacity used within the local region is displayed at the BA level (136 distinct regions) rather than the 358 wind regions. These BAs are shaded in purple. The blue arrows represent wind energy estimated to be transported on current transmission lines; the red arrows represent new transmission lines constructed by WinDS to transport wind energy between BAs.

Clearly, significant investment in transmission infrastructure is needed to meet projected load growth and improve the reliability of the electric system. This analysis does not

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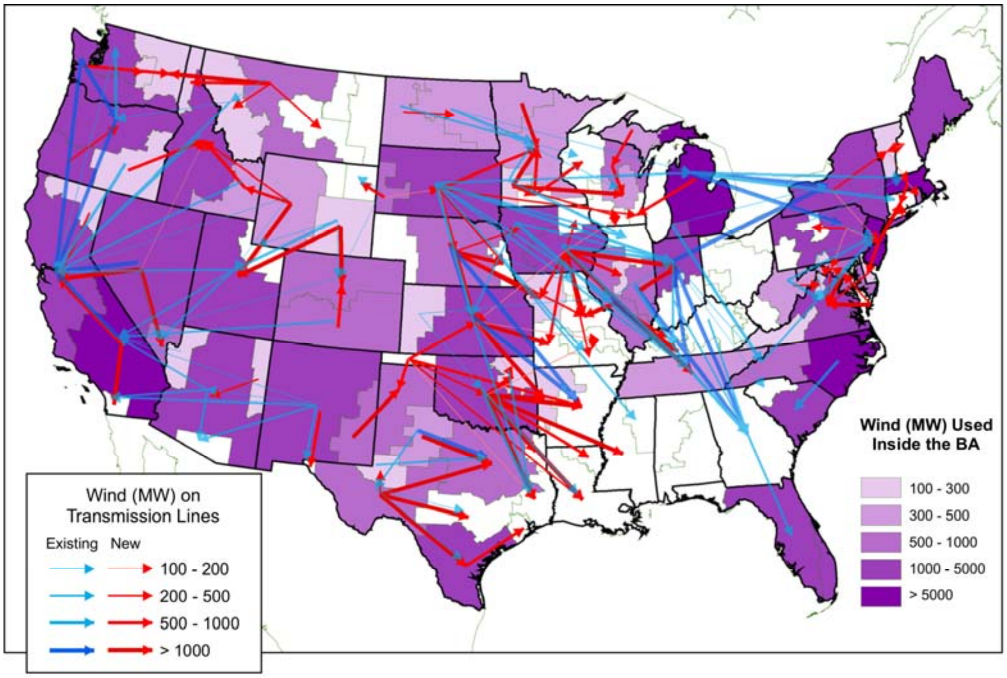
[5] Wind capacity levels in each state depend on a variety of assumptions and the national optimization of electricity generation expansion. Based on the perspectives of industry experts and near-term wind development plans, wind capacity in Ohio was modified and offshore wind development in Texas was included. In reality, each state's wind capacity level will vary significantly as electricity markets evolve and state policies promote or restrict wind energy production.

[6] In this study, large regional markets for electricity were modeled by eliminating costs to transport power across regulation boundaries.



Total Between BA Transfer >= 100 MW (all power classes, land-based and offshore) in 2030.
Arrows originate and terminate at the centroid of the BA for visualization purposes; they do not represent physical locations of transmission lines.

20% Wind 06-19-2007

Fig 1-7; A-18

Fig. 4. Use of wind-generated electricity within a region or transmitted on current or new transmission lines in 2030

explicitly estimate additional transmission lines required to improve reliability[7]. A national transmission expansion plan using 765-kV lines that could accommodate up to 400 GW of new capacity was developed by AEP [2]. A plan of this nature would improve reliability and provide access to geographically dispersed wind resources. Although the methodologies used by the WinDS analysis (shown here) and the AEP study (not shown here) are different, the resulting cost of both scenarios is similar, about $60 billion (with no discounting).

III. COSTS AND BENEFITS

The *20% Wind* scenario is contrasted with a scenario in which no additional wind energy is added after 2006 (*No New Wind*) to quantify the potential costs and benefits of incorporating this level of wind technology in the nation's electricity generation portfolio. In both scenarios, the various conventional generation technologies are economically optimized in the absence of any policies that would alter the composition of the generation portfolio from that of today, e.g., no carbon mitigation policies are assumed.

The capacity and corresponding energy generation by technology in the year 2030 are shown in Fig. 5 and Fig. 6, respectively, for the *20% Wind* scenario and the *No New Wind* scenario. Incorporating 305 GW of wind energy by 2030 avoids the installation of about 80 GW of coal-based generation technology and reduces coal-based electricity generation by 18%. Natural gas combustion turbine capacity is increased in the *20% Wind* scenario to maintain grid reliability, though the use of this combustion turbine capacity is limited. Electricity generated largely from combined-cycle natural gas plants is reduced 50% in the *20% wind* scenario relative to the *No New Wind* case. Installed capacity and electricity generation from hydro and nuclear technologies are essentially the same in both scenarios.

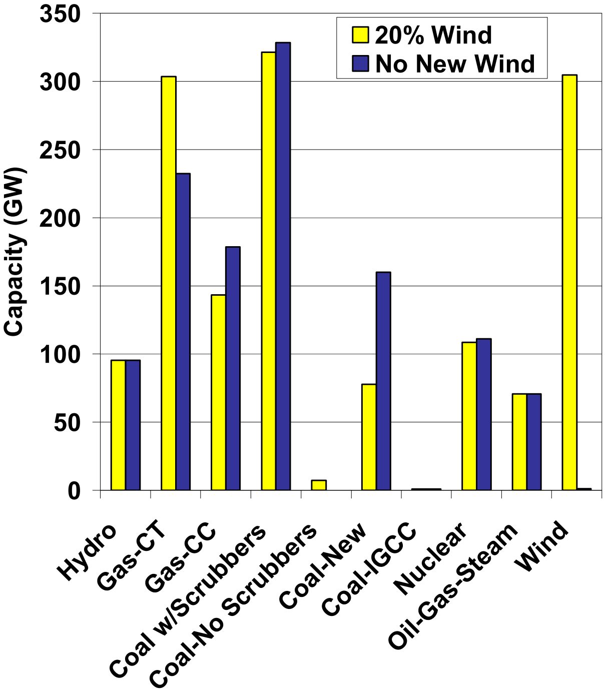


Fig. 5. Electricity sector capacity by technology in 2030

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[7] In the WinDS model the cost of each new transmission line is augmented with the cost of a portion of a duplicate transmission line to maintain system reliability.

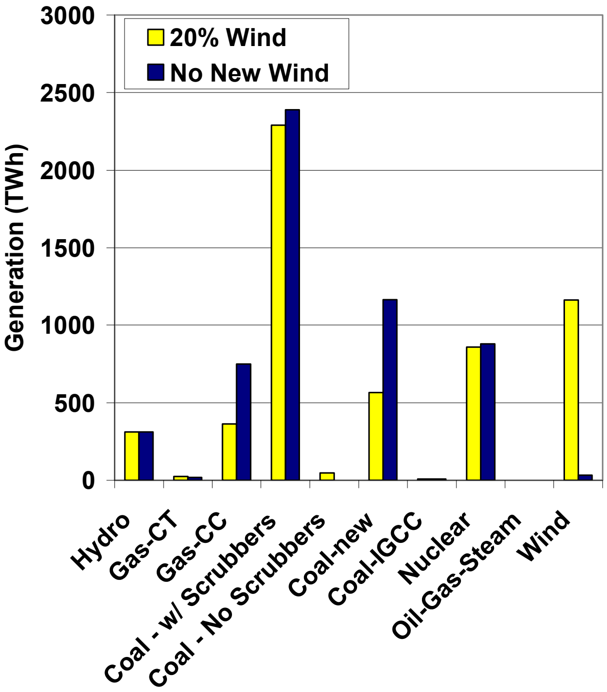

Fig. 6. Electricity sector generation by technology in 2030

Based on the differences in capacity and generation type between the *20% Wind* and *No New Wind* scenarios, one can calculate both the costs and benefits of the *20% Wind* scenario. Costs include differences in both capital and financing costs of wind versus the displaced conventional energy technologies, as well as differences in transmission, operations and maintenance (O&M), and fuel costs. Also included in these estimates is the additional cost of integrating variable wind generation into the electricity grid. The potential benefits associated with using wind energy to offset coal- and natural gas-based electricity generation analyzed here include decreased natural gas prices, avoided financial risk of future carbon regulation, and reduced water consumption.

A. Electricity Sector Cost

Direct costs to the electricity sector for each scenario include the capital and financing costs of wind and conventional energy technologies, transmission, operations and maintenance (O&M), and fuel. Included in the O&M category are the integration costs associated with wind power. The cost implications of 20-year investment decisions (fuel consumption and O&M costs) made after 2010 extend beyond 2030, and are included here as extrapolations beyond the 2030 timeframe of WinDS. Capital and transmission expansion costs are calculated for generation capacity added through 2030.[8] Other costs and benefits presented here assume a 20-year project life for wind technology installed after 2010.

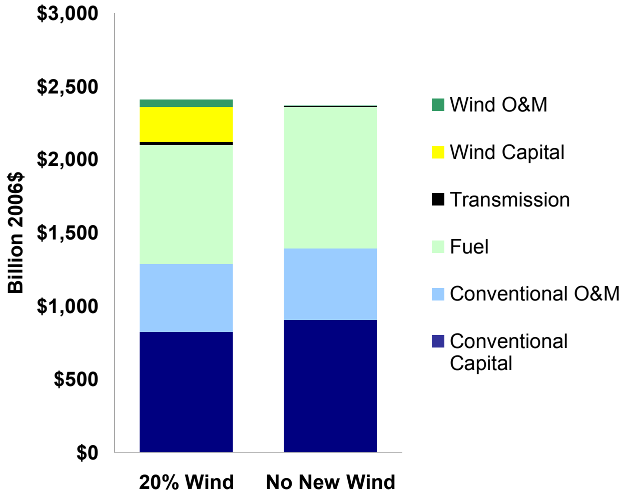

Fig. 7. Total electricity sector direct costs in net present value using 7% discount rate per OMB guidance.. The time period of analysis is 2007-2030, with WinDS modeling used through 2030 and extrapolations of fuel usage and O&M requirements used for 2030-2050

Fig. 7 shows the net present value of these costs for both scenarios. Both scenarios show a significant investment in generation capacity expansion and operations through 2030, in excess of $2 trillion dollars. There is a higher capital investment in wind technology for the *20% Wind* Scenario, but that investment is largely offset by reduced fuel requirements. The net incremental cost of the *20% Wind* scenario relative to the *No New Wind* scenario is $43 billion in net present value terms, or 2% of the total direct electricity-sector costs predicted by WinDS over this timeframe.

B. Natural Gas Price Reduction

Offsetting demand for natural gas in the electricity sector by increasing wind energy's contribution offers three potential "hedge" benefits. First, by replacing variable-price gas-fired generation with fixed-price electricity, wind power directly reduces exposure to gas price risk, given uncertainties in the gas price forecast [5]-[8]. Second, by reducing the need for imported liquefied natural gas, wind power may provide energy security benefits. Finally, by reducing demand for natural gas, wind power may relieve gas supply pressures and thereby reduce its price [9].

Based on WinDS analysis, the *20% Wind* scenario could result in a substantial (~11%) reduction in natural gas demand in the United States by 2030. Using the simplified analysis presented by Wiser et al. [9], which is benchmarked against a large number of respected energy sector models (including the EIA's National Energy Modeling System), a mid-case estimate suggests that this demand reduction may lead to a corresponding decrease in natural gas prices of $0.9/MMBtu by 2030 relative to the *No New Wind* scenario. Table II shows estimated natural gas price reductions in 2030 of $0.6/MMBtu to $1.5/MMBtu under a plausible range of analysis assumptions, leading to present value consumer benefits of $86 to $214 billions.[9]

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[8] Transmission cost estimates represent additional capacity for wind energy and do not include transmission capacity expansion to improve grid reliability, which would be needed in both scenarios.

[9] The mid-case assumes an inverse price elasticity of natural gas supply of 1.2; low and high cases assume 0.8 and 2.0, respectively. This range of inverse price elasticity has been found by Wiser et al. [9] to be consistent with those included in other integrated energy models that are regularly used in the United States.

TABLE II
SECONDARY NATURAL GAS SAVINGS FROM *20% WIND* SCENARIO
(2006 DOLLARS)

% Reduction in National Gas Consumption in 2030 (%)**	Natural Gas Price Reduction in 2030 ($/MMBtu)			Present Value Benefits (billion $)*		
	low	mid	high	low	mid	high
11%	0.6	0.9	1.5	86	128	214

* 7% real discount rate is used, per OMB guidance; the time period of analysis is 2007-2050, with WinDS modeling used through 2030 and extrapolations of fuel usage and O&M requirements used for 2030-2050.
** This estimate reflects the entire natural gas sector; the estimated reduction in the electricity sector alone is 50%.

C. Carbon Emission Avoidance and Corresponding Financial Risk Mitigation

Avoiding carbon emissions in the electricity sector provides a hedge against the risk of financial consequences of future carbon regulation. The likelihood of carbon regulation is substantial, and electric utilities increasingly include the implications of potential future carbon regulations in their planning efforts [10]. A recent report by Synapse Energy Economics [11] provides a comprehensive review of the risk of carbon regulation. It reports on the results of a diverse set of modeling studies and experiences from emerging carbon markets in Europe and elsewhere. Reflecting the fact that the probability and severity of future carbon regulations are difficult to predict, the study arrives at a range of carbon costs for the 2010 to 2030 timeframe is as follows: 1) low – \$9.8/ton-CO_2; (2) mid – \$21.8/ton; and (3) high – \$33.9/ton[10].

Cumulative carbon emissions from the *20% Wind* scenario relative to the *No New Wind* scenario are reduced by 4,182 million metric tons of carbon equivalent (MMTCE) from 2007 through 2050. Applying the proposed range of carbon costs, the benefit of wind energy in reducing the financial consequences of future carbon regulations is estimated in Table III. A saving of \$98 billion through reduced exposure to carbon regulation costs is attributed to wind energy when considering Synapse's [11] mid-case for carbon costs. These savings vary from \$50 billion to \$145 billion in present value terms, depending on the stringency and timing of future carbon regulation.

Concerns about the uncertain, but potentially substantial, effects of climate change have spurred some industries, policymakers, environmentalists and utilities to call for a 60% to 80% reduction in greenhouse gas emissions by 2050 [12]. Producing 20% of the nation's electricity from wind by 2030 would provide a significant contribution to such aggressive carbon emission reduction targets, at least within the electricity sector (see Fig. 8).

TABLE III
CARBON SAVINGS FROM *20% WIND* (2006 DOLLARS)

Cumulative Carbon Savings (2007-2050, MMTCE)	Present Value Benefits (billion $)*		
	low	mid	high
4,182 MMTCE	50	98	145

* 7% real discount rate is used, per OMB guidance; the time period of analysis is 2007-2050, with WinDS modeling used through 2030 and extrapolations of fuel usage and O&M requirements used for 2030-2050.

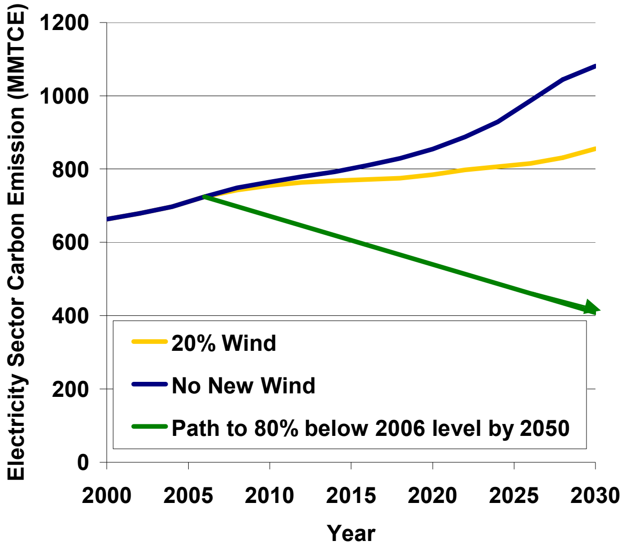

Fig. 8. Annual electricity sector carbon emissions

D. Water Consumption Savings

Displacing large amounts of fossil-fueled power generation with wind energy reduces water consumption in the electricity sector. Water consumption rates associated with electricity generation for each generation technology were applied to the electricity generation for the *20% Wind* and No New Wind scenarios. Producing 20% of the nation's electricity from wind by 2030 would result in a saving of 4 trillion gallons of water by 2030 as shown in Fig. 9. This is a cumulative reduction in water consumption in the electricity sector of 8% over the study period and an annual reduction of 17% in 2030. Of the 4 trillion gallons of water saved nationally, 29% is predicted to be in the West,[11] 41% in the Midwest/Great Plains,[12] 14% in the Northeast,[13] and 16% in the Southeast.[14]

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[10] Synapse provides three cost streams that vary over the 2010-2030 timeframe. These time-variant assumptions are used in the 20% Wind benefit calculations; the average of those cost streams is reported here. For the period beyond 2030, the Synapse estimates for 2030 are assumed to be held constant.

[11] Alaska, Arizona, California, Colorado, Hawaii, Idaho, Montana, Nevada, New Mexico, Oregon, Washington, Wyoming, Utah

[12] Illinois, Indiana, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, Oklahoma, South Dakota, Texas, Wisconsin

[13] Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont

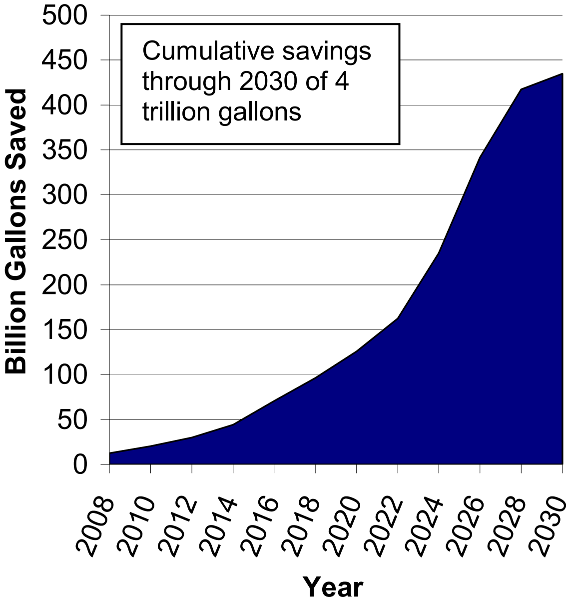

Fig. 9. Annual water consumption savings resulting from deployment of wind energy

IV. OTHER BENEFITS

Other benefits associated with wind energy include lower particulate and other chemical emissions such as acid rain or mercury, and/or lower incremental costs of complying with cap-and-trade environmental regulations. Wind energy facilities also employ people during the construction and operating phases over the life of the plant. Beyond the direct impacts, many indirect and induced benefits are associated with manufacturing, construction, and operational sectors of the wind industry [2]. These and other benefits have not been quantified in this study.

V. CONCLUSIONS AND FUTURE WORK

This scenario supports the technical feasibility of significantly increasing wind energy's contribution to the national electricity generation portfolio. Although this scenario does not explore the myriad permutations that would lead to this growth or that would affect the costs and benefits, it does provide a quantifiable estimate of the costs, impacts, and benefits associated with producing 20% of the nation's projected electricity demand from wind technology. Several important assumptions could affect the resulting mix of generation technologies and corresponding direct electricity sector costs, including fuel price forecasts, fuel price elasticity, and carbon regulation. Further work is needed to explore these effects and to further quantify the benefits associated with significant wind energy penetration.

VI. ACKNOWLEDGMENTS

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This paper shows the results of the Wind Energy Deployment System model used to estimate the costs and benefits associated with producing 20% of the nation's electricity from wind technology by 2030.

15. **SUBJECT TERMS**

wind-generated electricity; wind energy; 20% wind energy by 2030; Wind Energy Deployment System model; WinDS

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