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Modeling the Long-Term Market Penetration of Wind in the United States

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MODELING THE LONG-TERM MARKET PENETRATION OF WIND IN THE UNITED STATES

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ABSTRACT

This paper presents an overview of the **W**ind **D**eployment **S**ystems Model (**W**in**DS**). WinDS is a multiregional, multitime-period, Geographic Information System (GIS), and linear programming model of capacity expansion in the electric sector of the United States. WinDS is designed to address the principal market issues related to the penetration of wind energy technologies into the electric sector. These principal market issues include access to and cost of transmission, and the intermittency of wind power. WinDS addresses these issues through a highly discretized regional structure, explicit accounting for the variability in wind output over time, and consideration of ancillary services requirements and costs.

BACKGROUND and INTRODUCTION

There are several existing models that forecast capacity expansion in the U.S. electric sector. Many of these models were built to address the entire U.S. energy market with its emphasis on fossil fuels and nuclear energy. While these models generally include the more prominent renewable energy technologies, their large scope and focus on today's dominant conventional energy forms do not allow a detailed treatment of the more important issues for wind energy technologies. For example, in many existing models, conventional energy technologies can be adequately captured by regionally disaggregating to the 13 NERC regions and subregions. However, with this level of regional aggregation, these models cannot capture the transmission requirements that are unique to wind because they assume the resource is next to the load.

The WinDS model is designed to represent the market issues of greatest significance to wind energy. These include not only the transmission issues, but also the intermittency impacts of wind on grid ancillary service requirements. By explicitly addressing these issues, WinDS is able to remove many of the constraints due to large regions that the other models impose on wind energy. By doing so, WinDS can address questions including:

- What are the tradeoffs between low-quality wind sites near load, and higher quality sites that require significant transmission?
- Will wind energy penetrate the market if new transmission lines are required?

- How much does the capacity value of wind decrease as more wind energy is added to the system, and will this drop in value preclude further market penetration?

The answers from WinDS also should provide more realistic inputs and assumptions to other models that cannot afford to address wind market factors in great detail.

MODEL DESCRIPTION

Structure:

WinDS is a computer model of expansion of generation and transmission capacity in the U.S. electric sector spanning the next 50 years. It minimizes system-wide costs of meeting loads, reserve requirements, and emission constraints by building and operating new generators and transmission in each of 25 two-year periods from 2000 to 2050. It considers a wide range of generator types, including natural gas combined-cycle, natural gas combustion turbines, gas and oil steam generation, several coal-fired generator options, nuclear, hydroelectricity, wind, and other renewable electricity technologies[1].

The core of the WinDS model is a linear programming optimization of the electric sector capacity expansion in each two-year period. However, much of the data inputs to this optimization are derived from a detailed GIS model/database of the wind resource, transmission grid, and existing plant data. The GIS data and other inputs are transferred to the optimization through a spreadsheet input interface. Similarly, the results from the optimization are output through a similar spreadsheet interface, facilitating the review and graphing of the output. Eventually, NREL anticipates that the WinDS model will be accessible over the Internet to outside users.

One of the unique features of WinDS is its regional discretization of the U.S. electric sector. (See Figure 1 for a map of all regional levels.) At the highest level, it distinguishes among the three major synchronized interconnections within the United States – the Eastern, Texas (ERCOT), and Western (WECC) interconnections. Below the interconnection level, it considers ancillary service requirements at the NERC region and subregion level (13 regions in the continental United States). Once FERC and the states have settled on the structure of Regional Transmission Organizations (RTOs), these will be implemented in WinDS. Capacity expansion decisions are made one level lower for 134 power control areas. Finally, wind power is supplied from 356 wind regions. The wind resource available in these wind supply regions is drawn from the most recent, detailed wind resource estimates at the National Renewable Energy Laboratory (NREL). The fine regional disaggregation of wind supply allows WinDS to calculate transmission distances and the benefits of dispersed wind farms supplying power to a demand region.

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[1] Biomass power, geothermal, and concentrating solar power are not yet operative in WinDS, but are being implemented.

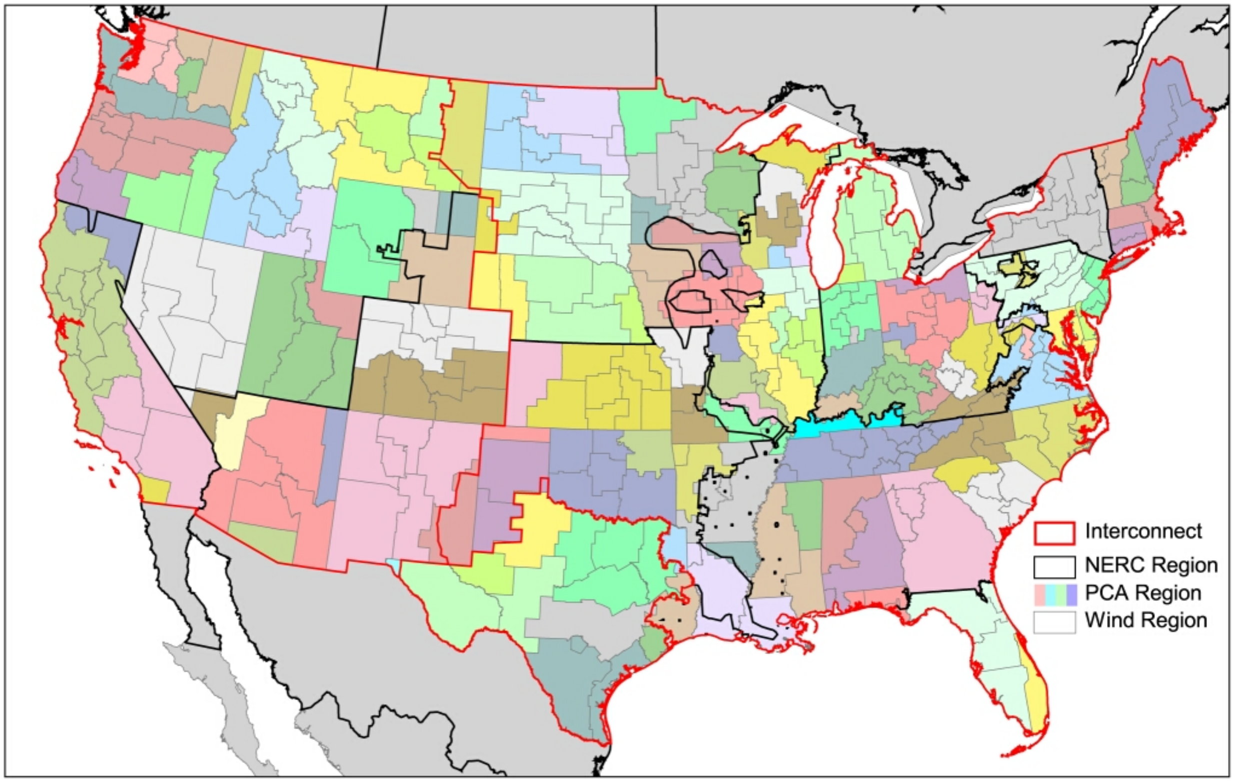

Figure 1: REGIONS WITHIN **W**IN**DS**

WinDS also is disaggregated somewhat finely with respect to time. Within each year, dispatch decisions are made separately for four different load levels in each of the four seasons of the year. Although data is currently sparse, WinDS accounts for the variation in wind output in these different time slices within each wind supply region, e.g. the wind capacity factor is frequently lower during the summer than the winter and also varies throughout the day. The time disaggregation not only helps to capture the correlation between wind output and loads, but is also important in capturing the dispatching of peaking units, spinning reserve requirements, transmission loading, etc.

WinDS disaggregates the wind resource into four classes ranging from Class 3 (5.4 meters/second at 10 meters above ground) to Class 6 (6.7 m/s). Class 7 wind is aggregated with Class 6. The amount of each class of wind available within each of the 356 wind supply regions (along with the capacity factor for each class, in each region, in each time slice) is derived by the GIS capability and input to the optimization. In addition, the GIS capability supplies the optimization with a supply curve for the cost of building transmission from each wind site within a region to an available transmission line within the existing grid.

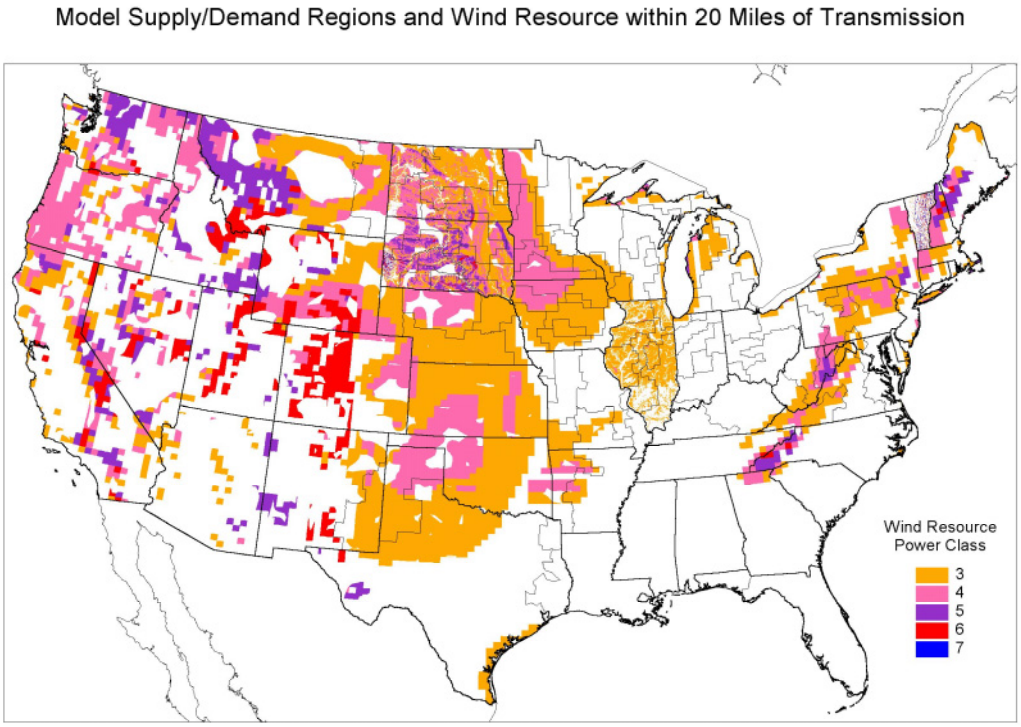

Figure 2: WIND RESOURCES IN **W**IN**DS**

Objective Function:

The driver in any optimization is the objective function. In WinDS, the linear program minimizes the total cost of providing power for the next 20 years by deciding which generators and transmission lines should be brought on-line in the current two-year period, and how they should be dispatched. The costs to be minimized are:

- the present value of the cost of both generation and transmission capacity installed in this period plus
- the present value of the cost of operating that capacity during the next 20 years (fixed and variable O&M and fuel costs) to meet load or for spinning reserve plus
- the cost of reserve capacity.

The capital costs for new generation equipment change over time according to either direct user-specifications on input or based on a learning curve. Similarly for new generators, the user can define the O&M and fuel costs, as well as heat rates and wind capacity factors, to change over time. Financing can be explicitly modeled with either corporate financing or project-specific financing with its consequent debt service coverage requirements. Depreciation for income tax purposes and federal tax credits are explicitly accounted for. Escalation of fuel prices over time can be input.

Costs for transmitting wind on existing lines are comprised of the capital cost to build a new line from the wind site to the grid and a service charge per MWH to use the existing lines. The capital cost of a new line is a linear function of the number of MWs the line must be able to carry and the length of the line. Lines built to transmit wind are assumed to do so exclusively, i.e., only wind is carried on the line. Thus, the cost of such lines is amortized over the relatively low capacity factor of wind.

Constraints:

The cost of capacity expansion and operation in the electric sector is minimized in each of the two-year period optimizations subject to a set of constraints. The principal constraints are described briefly below.

Wind resources: The total amount of wind energy capacity that can be developed in each of the 356 wind supply regions is constrained to be less than the wind resources shown in Figure 2.

Wind access to existing transmission lines: There are several constraints on the use of existing lines to transmit the electricity from new wind installations.

- For each of the four classes of wind within each of the 356 wind supply regions, GIS is used to develop a small supply curve for the cost of building a transmission line from the wind site to the existing grid. Because the GIS program considers the loading on the existing grid transmission lines (a user input) and how much wind from other sites is on the grid line, the length of this connecting line is typically much more than the shortest distance to the existing grid.
- In the linear programming optimization for each two-year time period, the amount of wind built to access existing lines is constrained by the transmission cost supply curve developed by the GIS (see paragraph directly above).
- The amount of wind transmitted to meet the demand in another one of the 356 wind supply regions is limited to the available capacity on the transmission lines entering the destination region.

Load constraints: The primary load constraint is that the load in each power control area must be met in each time slice throughout a year. The load is assumed to increase exponentially from one year to the next according to the user inputs. The load in a given power control area can be met either by generation from conventional technologies or wind generation within the power control area, or by power transmitted from other power control areas or wind supply regions. Wind generation in a given time slice is determined by the wind capacity available and the capacity factor for that time slice. The model dispatches conventional generation to minimize total costs while meeting the load constraint.

There is a secondary load constraint on wind. To better estimate the transmission distance required for wind, WinDS actually tracks the delivery of wind to demand subregions within the power control area. These demand subregions have the same geographic boundaries as the wind supply areas. WinDS does not allow the wind shipped from one wind supply region to a demand subregion (a different wind supply region) to exceed some user-specified fraction of the peak load in the demand subregion. This ensures that all the wind is not simply sent to the closest demand subregion. The peak load of a demand subregion is the peak load in the power control area to which it belongs, multiplied by the fraction of the power control area population that is within the demand subregion.

Reserve constraints: There are three types of reserves constraints – planning reserve margin, operating reserve, and regulation reserve. The first two of these constraints require the calculation of the variance in the wind output from all the wind supply regions contributing to the grid. This wind output variance is calculated by explicitly considering the dispersal of wind farms. If two wind farms are far apart, their output will be less correlated than two farms that are contiguous to one another. WinDS assumes the amount of correlation between the output of any two wind farms is proportional to the distance between the two wind farms. Thus, the variance in the total output from the two separated farms will be less than that of the two contiguous farms. This reduced variance for dispersed wind farms leads to higher wind capacity value and less need for operating reserve. The variance in output from all the wind generation is recalculated at the end of each two-year optimization period and used to calculate the coefficients on wind in the linear reserve constraints for the next two-year period.

The planning reserve margin constraint is applied to each interconnection area. It requires that the conventional capacity within the interconnection – and the product of the wind nameplate capacity and an effective load-carrying capability (ELCC) for the wind – exceed the peak load of the interconnection plus a reserve margin. The wind ELCC is based on stochastic calculations of the loss-of-load probability (LOLP) using the variance in wind output. The wind ELCC is the amount of additional load that can be met by the addition of one more MW of wind capacity without changing the LOLP.

The operating reserve constraint is applied at the NERC region/subregion level and captures the need for reserves to meet both contingencies (generation and transmission forced outages) as well as short-term (10-30 minutes) load-following requirements. These reserve requirements can be met by spinning reserves from hydroelectric facilities and combustion turbines, quick-start capacity, and interruptible loads controlled by the electric distribution company. Because the conventional generation that contributes to operating reserves is in different states (generating or idle) in different time slices (peak, off-peak), the operating reserve requirement is applied to each time slice within a year. Because wind generation can unexpectedly increase or decrease, it can increase the need for operating reserves. However, the changes in wind generation are not correlated with the conventional capacity contingency requirements or load changes. Thus, the additional operating reserve requirements due to wind are not proportional to the amount of wind, but rather to the variance in the sum of the normal operating reserve and the wind generation. In effect, this means that the operating reserves induced by wind are generally low per unit of wind capacity initially and can grow quickly if significant numbers of wind farms are installed close to one another (i.e., with highly correlated generation).

Regulation reserve is applied at the power control-area level and captures the need for reserves to meet very short-term fluctuations in loads on the order of seconds or less. Regulation reserve is normally provided through automatic generation control of conventional generating units. In as much as wind generation output can vary at intervals of seconds or less, wind can increase the need for regulation reserve. Using this timescale, there is essentially no correlation in wind generation between wind farms or even between individual wind turbines within a wind farm. There is also no correlation between wind generation and variations in load. Thus, the additional regulation reserve requirements from wind are not proportional to the amount of wind, but rather to the variance in the sum of the normal regulation reserve and the wind generation. In effect, this means that the regulation reserves induced by wind are generally low per unit of wind capacity initially, but will grow as more wind is installed.

Wind-generated electricity that is lost because it is surplus also is accounted for within WinDS at the interconnection region level. When demand is low and the wind is blowing, there can be instances where the wind generation cannot all be used. WinDS uses the variance of the sum of all wind generation together with a load duration curve and the forced outage rates of conventional technologies to stochastically compute the expected amount of wind that cannot be used. This surplus wind is calculated after each period’s optimization and used in the next period to reduce the amount of generation contributed by wind.

Emissions constraints: At the national level, WinDS caps the air emissions from fossil-fueled generators for sulfur dioxide, nitrogen oxides, mercury, and carbon. The annual national emission caps and the emissions per MWH are input by the user.

Variables:

By minimizing the objective function cost subject to the constraints described above, WinDS endogenously calculates the following variables for each time period

- Wind capacity installed in each wind supply region
- Wind generation transmitted from each wind supply region to each demand region using existing transmission lines
- Wind generation transmitted from each wind supply region to each demand region on new transmission lines
- New transmission lines built to transmit wind from supply regions to demand regions
- Conventional capacity by type installed in each power control area
- Conventional generation by type dispatched in each time slice within a year
- Transmission built in each year to transmit power between power control areas
- Interruptible load under contract in each power control area
- Spinning reserve operating in each time slice within a year in each NERC region

BASE-CASE ASSUMPTIONS AND RESULTS

WinDS is still undergoing development. While we are now obtaining reasonable results, we are still improving both the model and the data inputs. The results shown here should be considered preliminary and indicative of the capabilities of WinDS – not as projections for the future market penetration of wind energy into the U.S. electric sector.

At this point, we have made only a limited number of runs with the WinDS model. The results presented here are from our preliminary base case. Table 1 shows the fundamental inputs to this base case. Figures 3 and 4 show the evolution of two basic inputs over time – wind turbine capital costs by wind class and natural gas prices by NERC region/subregion.

Table 1: PRELIMINARY BASE-CASE INPUTS

PARAMETER	SOURCE OR VALUE
Electricity loads	AEO2003 Reference case extrapolated to 2050
Fossil-fuel prices	AEO2003 Reference case extrapolated to 2050
Wind cost/performance	DOE Wind Program goals
Wind resources	NREL
Conventional plant cost/performance	AEO2003 Reference case extrapolated to 2050
Conventional plant sizes and locations	RDI BASECASE GIS data
Fossil-fuel generation emissions	EPA's E-Grid data base
Financial analysis period	20 years
Real discount rate	12%
Nominal debt interest rate	8%
Debt-equity fraction	80%
Combined marginal income tax rate	40%
Depreciation schedule for tax purposes	MACRS

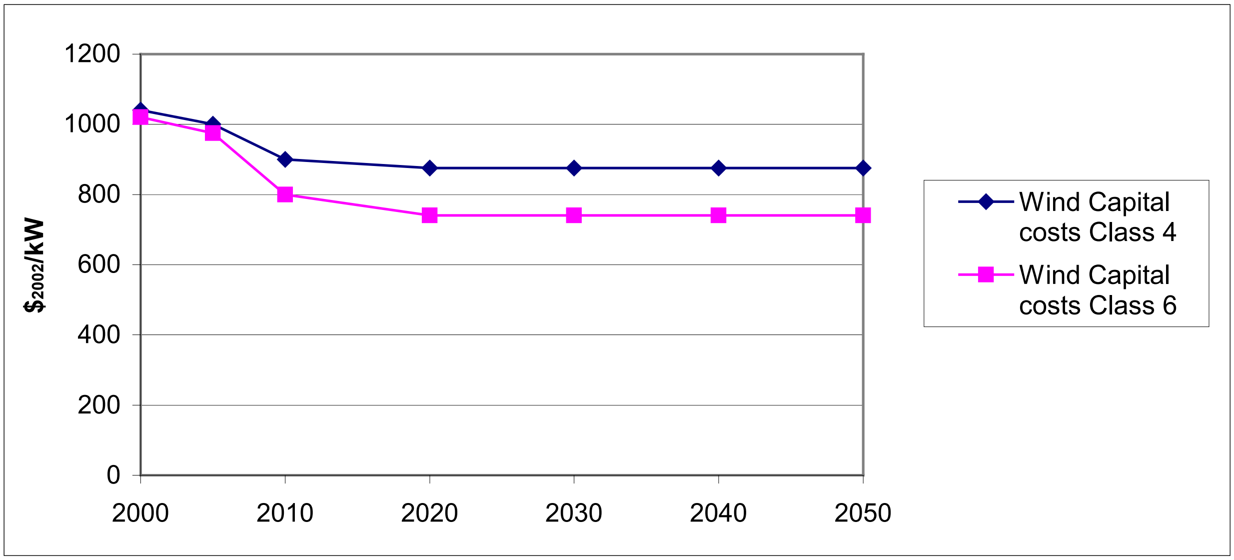

Figure 3: BASE-CASE WIND CAPITAL COSTS

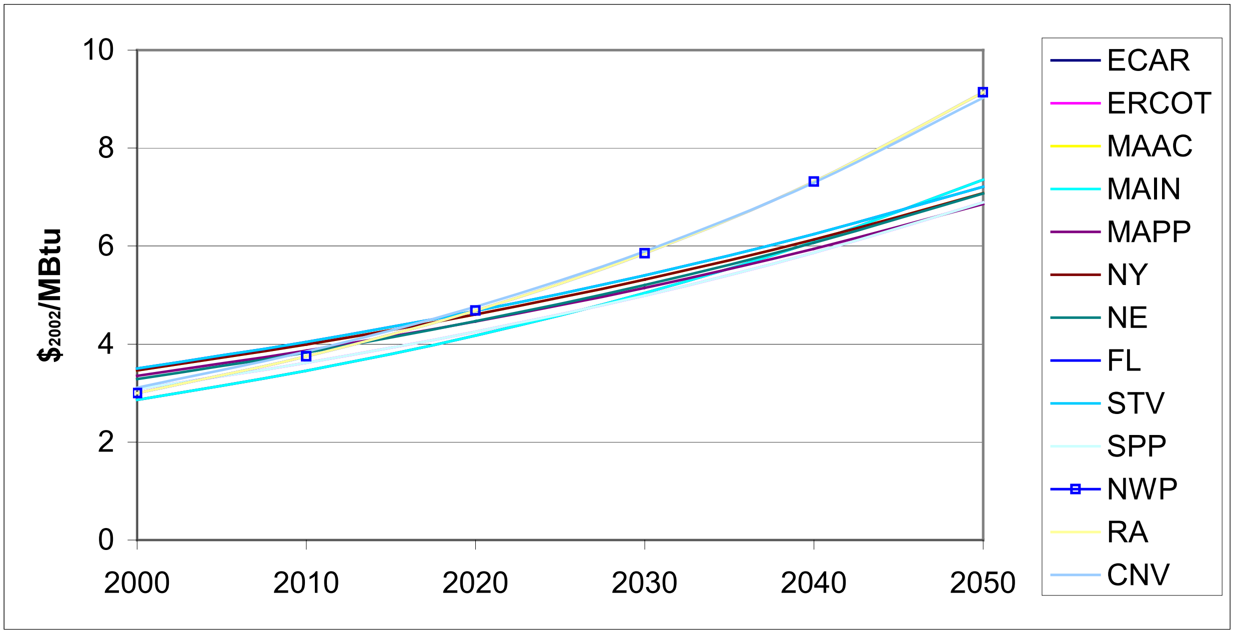

Figure 4: BASE-CASE NATURAL GAS PRICES

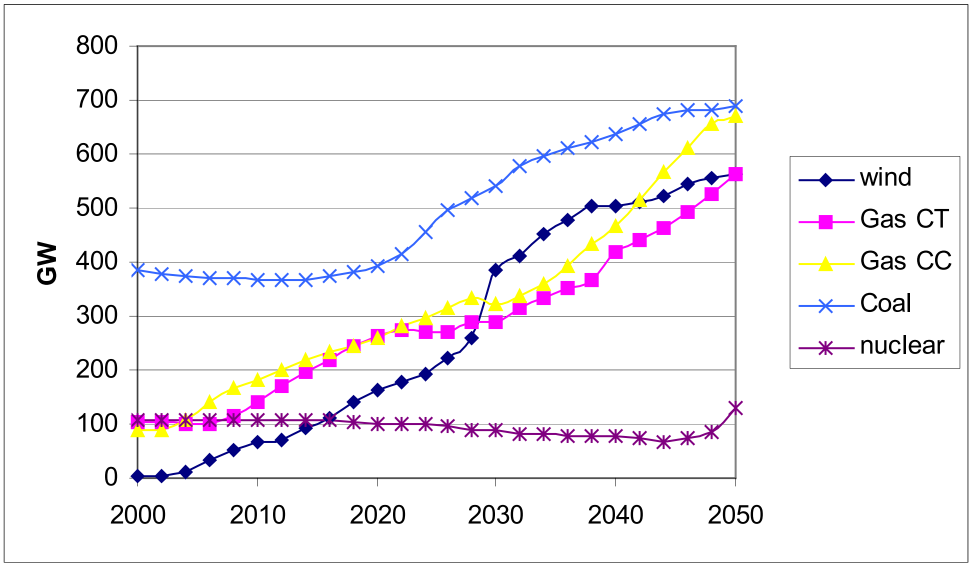

Figure 5: PRELIMINARY BASE-CASE CAPACITY EXPANSION

Figure 5 shows the capacity expansion by major fuel type out to 2050 for this preliminary base case. Through 2028, wind energy capacity grows rapidly and consistently, then increases abruptly in 2030, returns to its earlier growth pattern in 2032, and finally tapers off in the 2040s as the best sites (high-quality wind close to loads) are already developed and reserve requirements increase. Natural gas combined-cycle plants show continued growth throughout the planning horizon. Coal-fired generation largely holds its own in spite of retirements until the early 2020s; at which time, integrated coal gasification combined-cycle plants begin to penetrate in significant numbers. Even nuclear resurges on the basis of economics in the past couple of years before 2050.

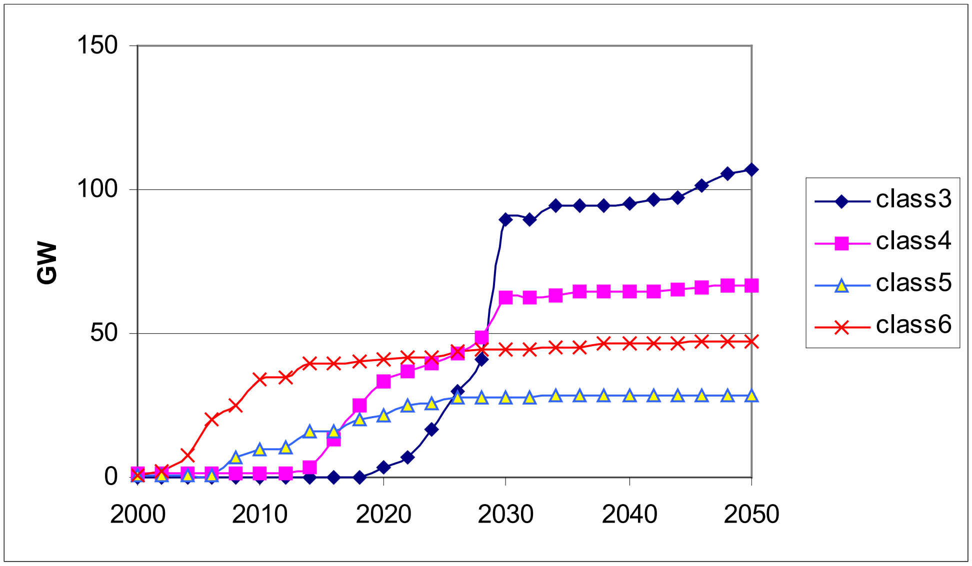

Figure 6: PRELIMINARY BASE-CASE WIND CAPACITY EXPANSION BY CLASS

As shown by Figure 6, the jump in wind installations in 2030 is driven largely by the development of Class 3 wind sites that become increasingly economic as natural gas prices continue to increase and wind technology performance improves. Figure 6 also shows the natural progression of development with Class 6 sites first, followed by the lower classes in sequence. Note, however, that substantial overlap occurs in the development of sites of different classes. For example, there are Class 3 sites being developed around 2020 with some Class 6 sites coming even later. This is evidence of the value of developing lower quality wind sites close to load, prior to the development of higher quality sites that require significant transmission expansion.

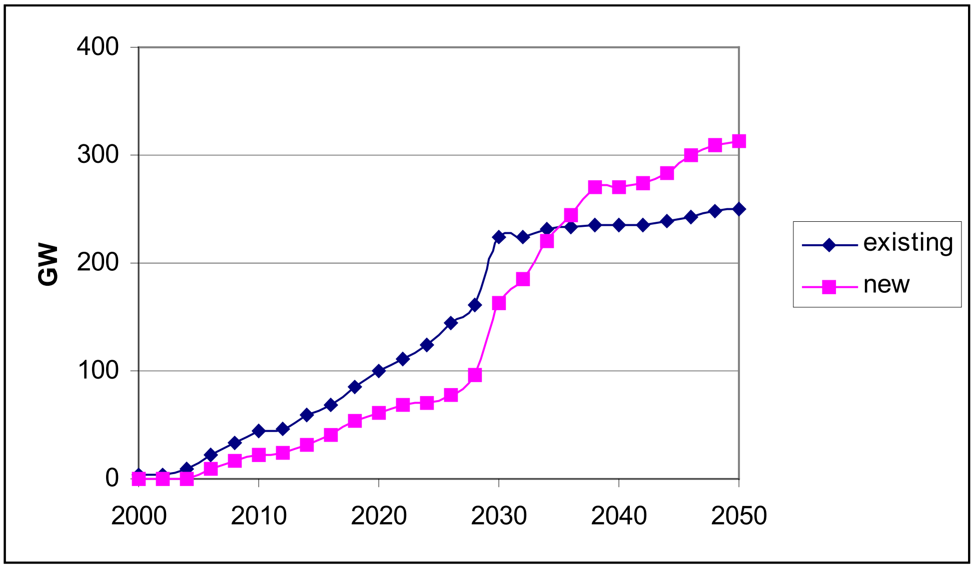

Figure 7: WIND BY TRANSMISSION LINE VINTAGE

Figure 7 shows the same growth in wind capacity as that shown in Figures 5 and 6, but distinguishes between wind that is transmitted on existing grid lines, versus that which requires the construction of new transmission lines from the wind site to the load. In the early years, the wind on existing lines is about twice that on new lines. However, the situation reverses in the 2030s as Class 3 wind comes on strong using mostly new lines.

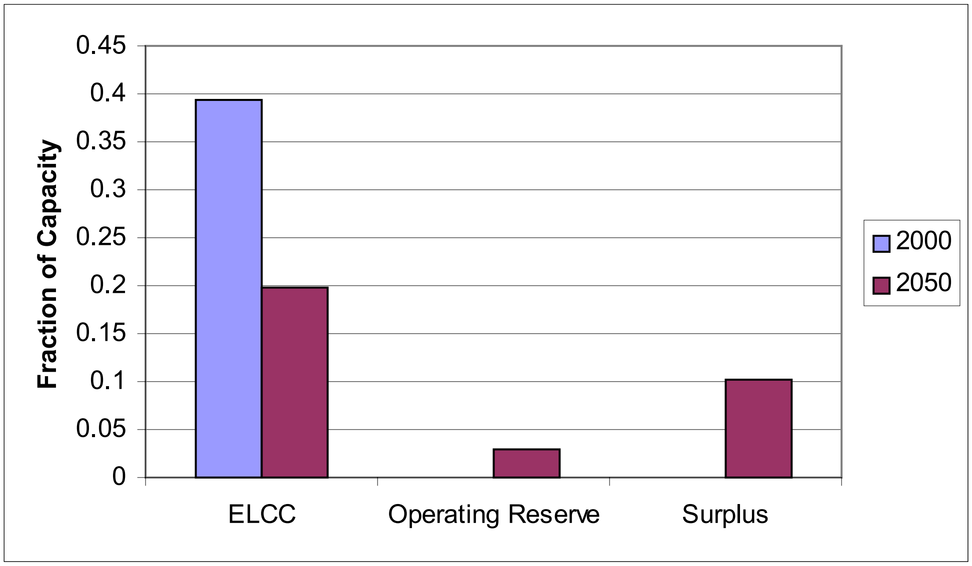

Figure 8: ELCC AND RESERVE REQUIREMENTS INDUCED BY WIND IN TEXAS

By the mid 2030s, the penetration of wind slows at least partially because the capacity value as represented by the effective load-carrying capability (ELCC) of wind is decreasing and the reserve requirements associated with wind are increasing. Figure 8 shows for Texas (ERCOT NERC region), the average value per MW of wind for ELCC, the operating reserve requirements induced by wind as a fraction of the wind capacity installed, and the surplus fraction of the wind generation that is lost because the wind energy supplied can exceed the power demand during off-peak load periods. The ELCC of wind in 2050 in Texas is about half that of 2000. The surplus wind has also risen to above 10% of generation. Operating reserves induced by wind have not increased substantially. We are currently examining these reserve requirements in greater detail to ensure they are being properly calculated.

CONCLUSIONS

The WinDS model can address some of the primary market issues for wind. Although still very preliminary, the results suggest that substantial levels of wind capacity will penetrate the U.S. electric sector even if that penetration requires the construction of new transmission. The results also show that in the long term, Class 3 wind sites also will be used in significant numbers. The reserve requirements calculated for this preliminary base case suggest that with high levels of wind penetration into the market, the capacity value of wind does decrease substantially and the wind generation lost at times of low loads can be significant. Further investigation is warranted of the operating reserves induced by wind, which don’t seem to be heavily influenced by wind penetration into the market.

Once WinDS has been thoroughly reviewed, we expect that it will serve many purposes including general analyses like the above, as well as policy analysis, R&D portfolio analysis, and more detailed regional analyses. The authors also are hopeful that the lessons and results gleaned from WinDS can be reduced into a form usable to other large energy models that are not able to focus so heavily on wind.

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