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Reduced Form of Detailed Modeling of Wind Transmission and Intermittency for Use in Other Models

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Reduced Form of Detailed Modeling of Wind Transmission and Intermittency for Use in Other Models

WINDPOWER 2005

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This paper, to accompany the corresponding poster, presents reduced-form outputs from the **W**ind **D**eployment **S**ystems Model (**W**in**DS**) that can be implemented in other models with less-detailed wind power modeling capabilities. Other models will be able to use the reduced-form results to improve the accuracy of the wind power portion of their models.

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 market issues related to the penetration of wind power into the electric sector. These principal market issues include the geographic dependency of the resource, access to and cost of transmission, and the intermittency of wind power.

WinDS was used to create a supply curve of wind power transmission cost as a function of national wind power capacity growth by exercising the model with and without including the costs associated with the differences between the WinDS model and a one-region model. This supply curve can be used by other capacity-expansion models (assuming the same representation of wind as the one-region model) to obtain an accurate cost of wind capacity, even though the model doesn't contain the same extensive geographical information as WinDS.

These supply curves also provide the electric-sector community with an estimate of the additional costs associated with wind beyond just wind capital and operating costs.

Section 1: WinDS Overview

WinDS is a computer model that optimizes the regional expansion of electric generation and transmission capacity in the continental United States over the next 50 years. To do this, it employs a Geographic Information System (GIS) to develop region-specific data for input to a linear program (LP). Most of the methodology description that follows addresses the linear-program portion of the model and is simply referred to as WinDS. Where it is important to distinguish that which is done in the GIS from the LP, the GIS capability is specifically identified.

WinDS minimizes system-wide costs of meeting electric loads, reserve requirements, and emission constraints by building and operating new generators and transmission in 26 two-year periods from 2000 to 2050. The primary outputs of WinDS are the amount of capacity and generation of each type of prime mover—coal, gas combined cycle, gas combustion turbine, nuclear, wind, etc.—in each two-year period. **Figure 1** shows an example of WinDS capacity estimates for the United States for different generation technologies over the next 50 years.

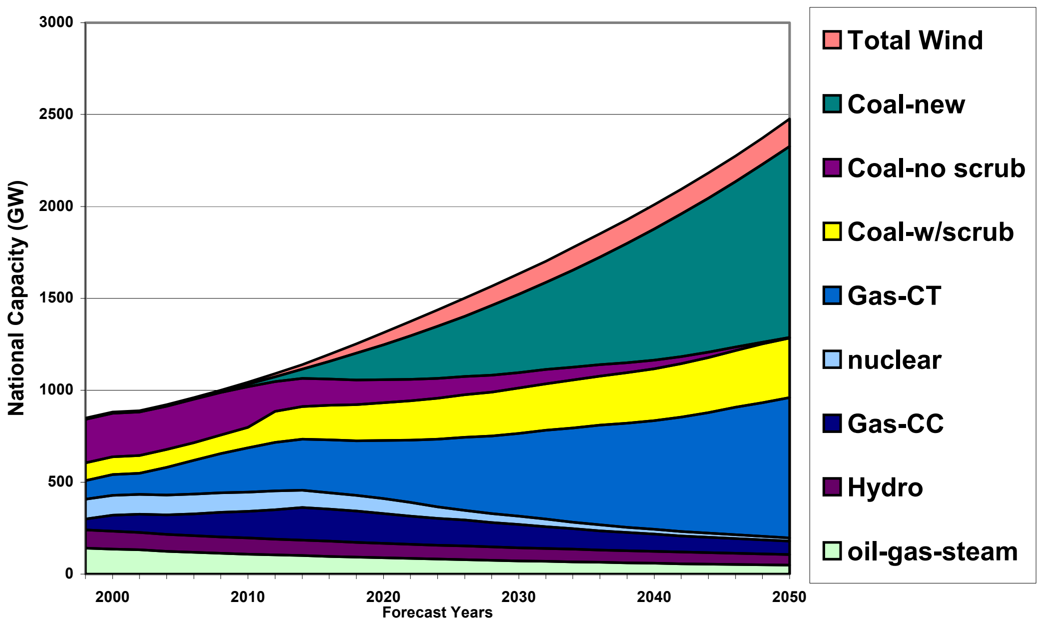

Figure 1. Base Case WinDS Capacity Estimates

While WinDS includes all major generator types, it was designed primarily to address the market issues of greatest significance to wind—transmission and intermittency. The WinDS model examines these issues primarily by using a much higher level of geographic disaggregation than other models. As **Figure 2** represents, WinDS uses 358 different regions in the continental United States. Much of the data inputs to WinDS are tied to these regions and derived from a detailed GIS model/database of the wind resource, transmission grid, and existing plant data. The geographic disaggregation of wind resources allows WinDS to calculate transmission distances, as well as the benefits of dispersed wind farms supplying power to a demand region.

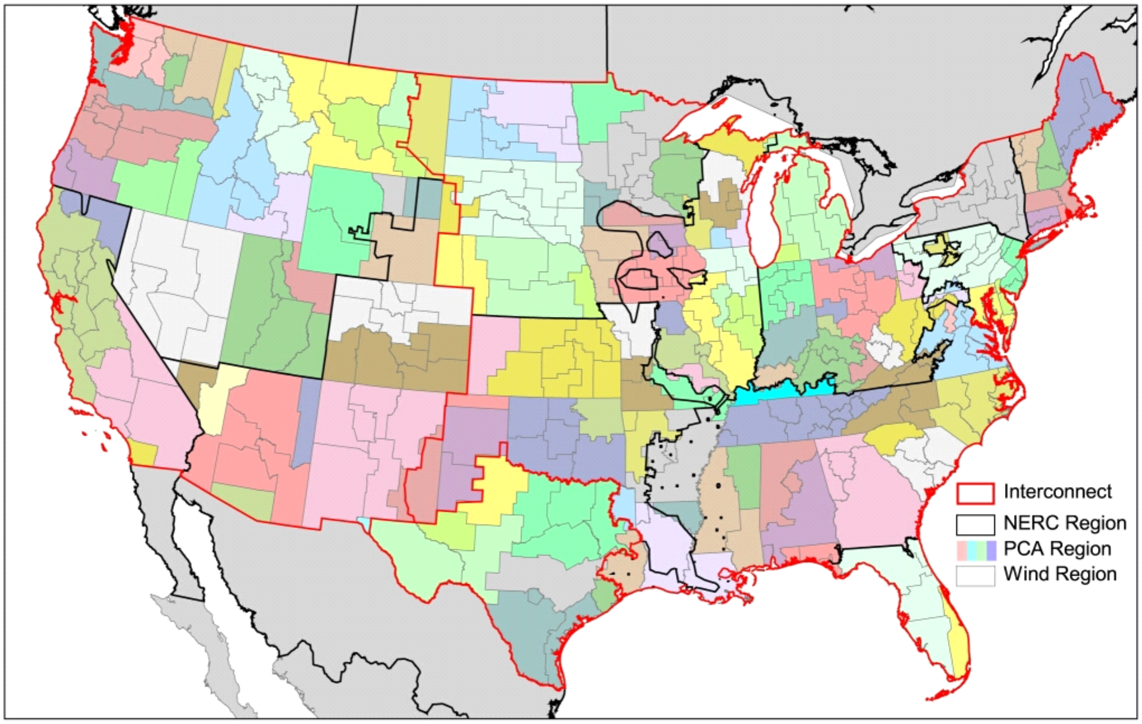

Figure 2. Regions within WinDS

As shown in **Figure 3**, WinDS disaggregates the wind resource into five classes ranging from Class 3 (5.4 meters/second at 10 meters above ground) to Class 7 (>7.0 m/s). WinDS also includes offshore wind resources and distinguishes between shallow and deep offshore wind turbines. Shallow-water turbines are assumed to have lower initial costs, because they employ a solid tower with an ocean-bottom pier; while deep-water turbines are assumed to be mounted on floating platforms tethered to the ocean floor. For the current analysis, offshore wind was disabled in both the WinDS model and the one-region model (described below).

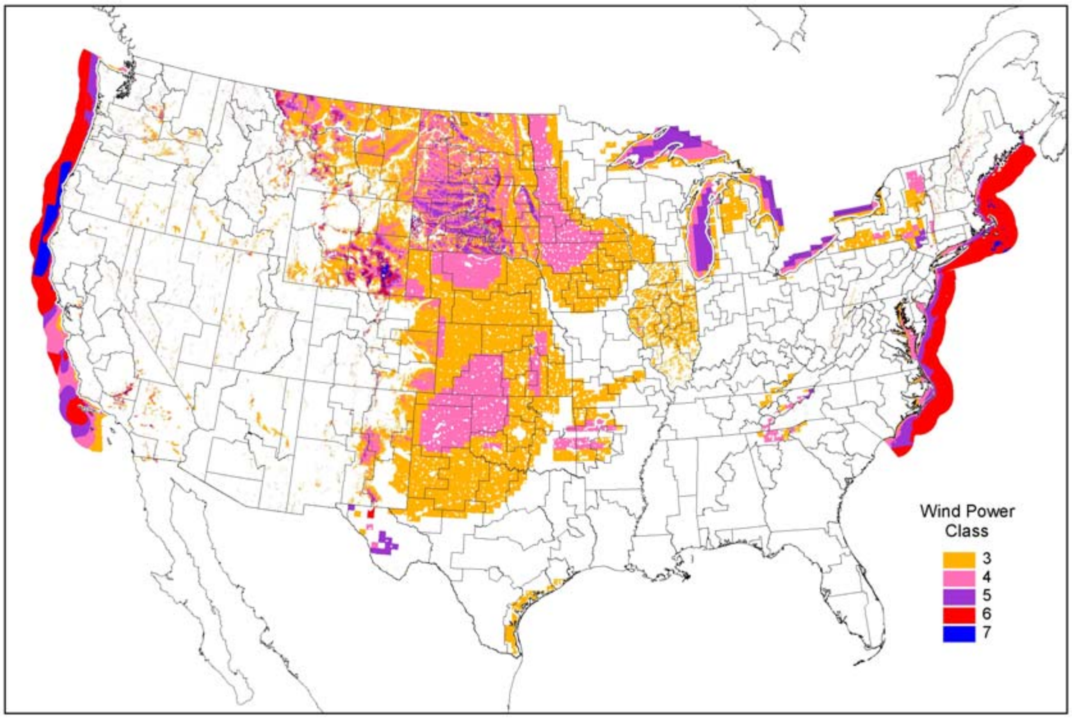

Figure 3. Wind Resources in WinDS

These different classes and types of wind have different costs and performance characteristics. Generally the higher wind-class sites (i.e. Class 7), are the preferred sites. However, **Figure 4** shows that, at any given point in time, the wind turbines installed will be at a mix of sites with different wind resource classifications. This occurs because, in selecting the installation sites, WinDS considers not only the resource quality, but also factors such as transmission availability, costs and losses, correlation of the wind output with neighboring sites, environmental exclusions, site slope, and population density.

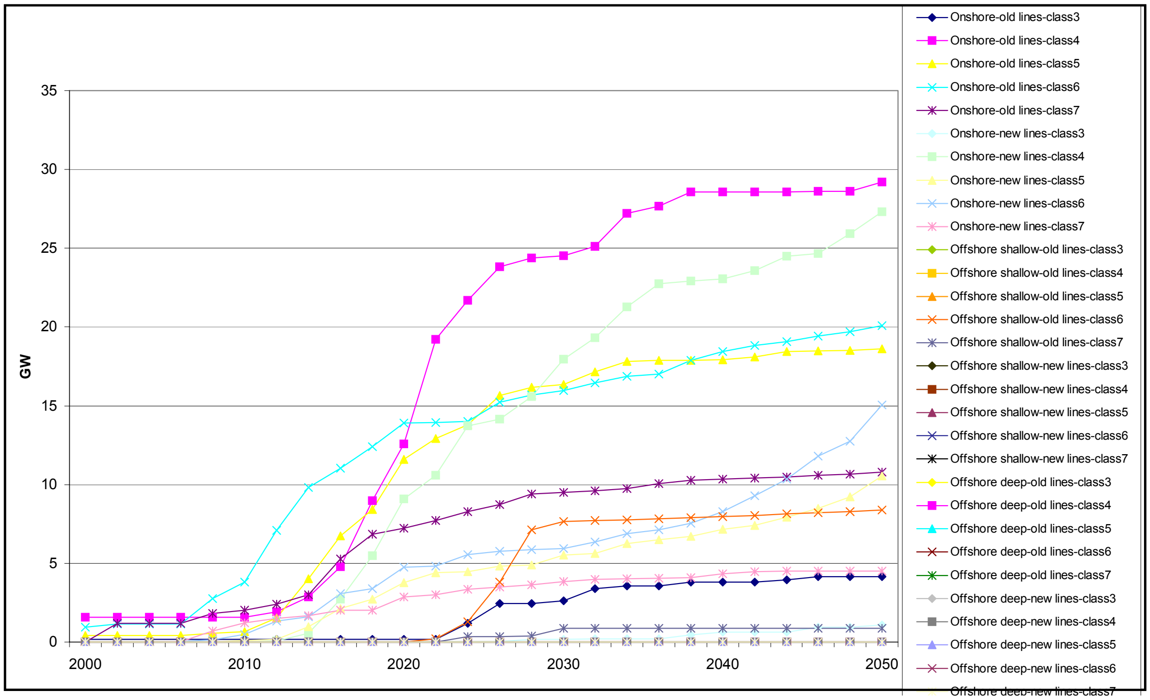

Figure 4. Wind Capacity Results by Type and Class

WinDS is also disaggregated over time —not only with the 26 two-year periods between 2000 and 2050, but also within each year. Each year is divided into four seasons with each day of each season divided into four diurnal time slices. These 16 time slices during each year allow WinDS to capture the intricacies of meeting peak electric loads, both with conventional sources and intermittent wind generators.

WinDS models the major conventional electricity generators, including:

- pulverized coal
- integrated gasification combined-cycle coal
- existing unscrubbed coal boilers
- existing scrubbed coal boilers
- natural gas combined cycle
- natural gas combustion turbines
- nuclear
- hydroelectricity

Fuel costs are exogenously specified over time by NERC region, as are electric loads. WinDS is a national electric capacity expansion model, not a general equilibrium model. Assessing the potential of wind energy under any given scenario requires that the scenario be exogenously specified in terms of fuel costs and electric loads by NERC region over the 50-year time horizon of WinDS.

While the focus of WinDS is on wind-energy technologies, the model does include some detail on other generation technologies. For example, there are four types of coal-fired power plants within WinDS—existing boilers without SO2 scrubbers, existing with scrubbers, new advanced pulverized coal plants, and new integrated-gasification combined-cycle plants. These plants can burn either high-sulfur or, for a cost premium, low-sulfur coal. Generation by coal plants is restricted to base and intermediate load with cost penalties (representing ramping/spinning costs) if power production during peak load periods exceed production in shoulder-peak hours. Nuclear is considered to be base load. Combined-cycle natural-gas plants are considered capable of providing some spinning reserve and quick-start capability, but the primary source of peak power and operating reserves are combustion turbines and hydroelectricity. Hydroelectricity is not allowed to increase in capacity, due to resource and environmental limitations. Hydro is also energy-constrained, due to water resource limitations.

WinDS tracks emissions from both generators and storage technologies of carbon, sulfur dioxide, nitrogen oxides, and mercury. Caps can be imposed at the national level on any of these emissions. Alternatively, a carbon tax can be imposed that linearly escalates to the maximum tax level over time.

Section 2: Motivation

As stated above, WinDS is designed to address the issues of intermittency and geographic dispersion associated with wind. This focus primarily came from the observation that existing models were unable to address these issues in a highly rigorous way, because they do not have the geographic disaggregation that is in WinDS. For example, while WinDS has 356 regions in the continental United States, NEMS has only 13 regions, and the U.S. MARKAL model has only a single region. For conventional sources of electricity generation, this geographic approximation is adequate, because there is minimal geographic dependency. However, these models cannot track the geographic dispersion of the installed wind and, therefore, cannot estimate the transmission costs— or the true capacity value of the wind—because the penetration level increases over time.

The question, therefore, remains about the best way to improve the representation of renewable, geographically tied power generation within models with minimal geographic regionality. Unfortunately, the additional computational effort needed to modify these models to contain all the necessary geographic information would be overwhelming and represent a major change. An alternative is to develop supply curves that capture the additional system costs associated with intermittency and transmission as the amount of installed wind increases. The developers of the other models can then more easily modify their models to add this cost (depending on the amount of installed national wind capacity) onto the base capital cost of the wind supply. As the conceptual graph shows in **Figure 5**, the additional costs associated with intermittency, wind transmission, and multiple wind classes add to the base system costs that are independent of both models. The goal of this project is to get an accurate accounting of these additional system costs as a function of U.S. wind capacity installed and provide that as a supply curve.

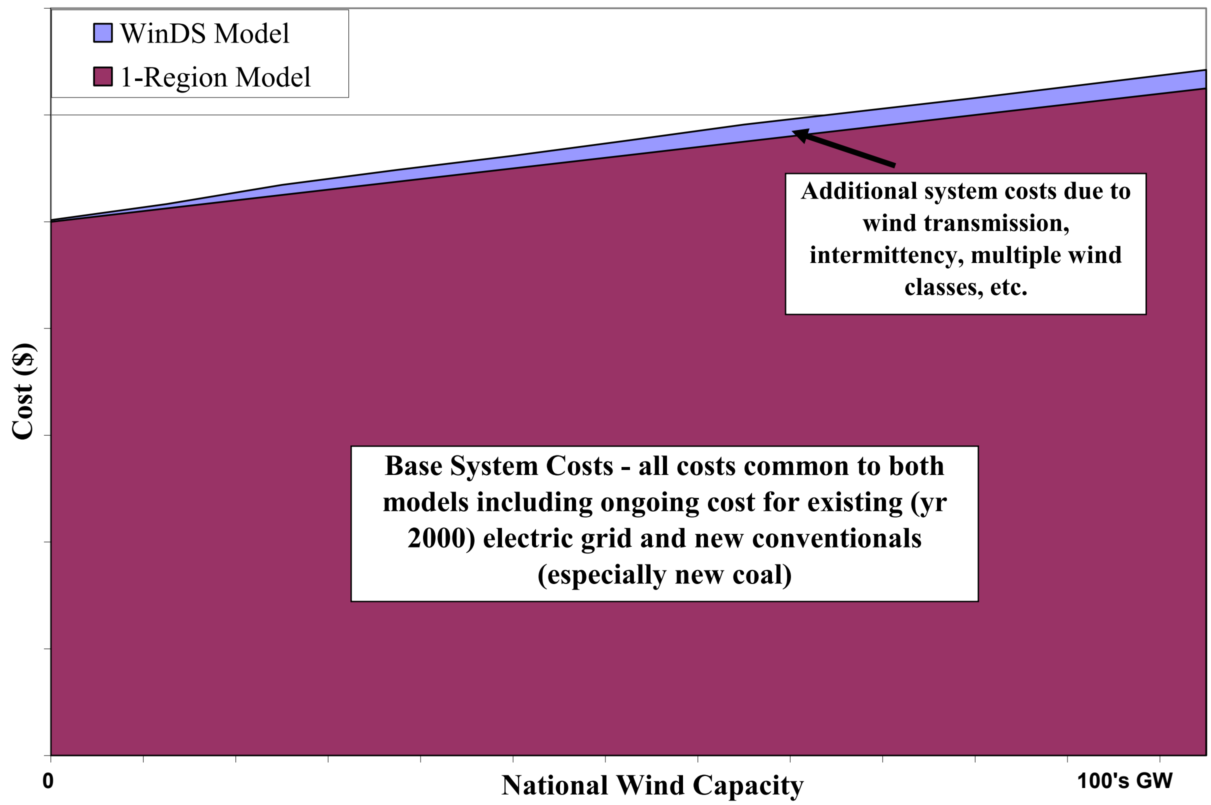

Figure 5. Conceptual Cost Graph

Specifically, the additional system costs accounted for in the supply curve will include:

- the transmission cost for the distance from the wind resource to the load where it is used
- the cost of surplus wind[1]
- the cost of decreasing capacity value of wind, due to greater penetration within the same region
- the cost of providing operating reserve for the wind
- the cost for changes to the conventional generation and capacity, due to these differences in treatment of wind power
- the difference in cost between having only a single class of wind versus having five different classes of wind with different performance.

[1] Surplus wind generation is defined here as the wind generation that must be discarded because it exceeds the net load after allowing for “must-run” conventional generation from nuclear and base-load coal plants.

Section 3: Methodology

In a normal run of WinDS, the first two-year period (1999-2000) is optimized with a linear program, parameters are updated for the next two-year period (2001-2002), and that next period is optimized with the linear program. This continues until all 26 two-year periods between 2000 and 2050 have been optimized in sequence, building on one another.

To develop the supply curve, an additional step is added to this process for each period. Once a period has been optimized, as just described for a normal WinDS run, it is immediately reoptimized to represent wind power as it would be represented in a one-region national model. The difference in the total system costs between the two optimizations for the same period represents the differences in costs between WinDS and a one-region model that can't capture the intermittency, transmission, and wind class effects.

Dividing the difference in total system costs by the amount of wind capacity (in kW) added in the normal WinDS run for that period yields the marginal additional system cost per kW of wind. This is the value to be shown in the supply curve. Typically, this additional system cost per kW of wind will increase in later periods as the wind sites added are not as attractive as the wind sites added initially, e.g. they are further from existing transmission lines, they are lower-quality wind resources, and they don't contribute as much to system reserve requirements (because their output can be coincident with that of wind farms already installed).

To be sure that the differences in the system costs are due only to wind, a constraint is imposed on the one-region model optimization for the period that ensures that the electricity delivered to each PCA from new wind installations is the same as that in the normal WinDS optimization for that period. Thus, in both optimizations, the generation delivered by conventional power sources is identical in each PCA. This does not mean that the total cost associated with conventional power will be the same in the two optimizations. For example, more conventional capacity (as opposed to generation) is required in the normal WinDS optimization. because the marginal capacity value of a new wind farm decreases as more wind is deployed. Conventional peaking plants must be built in the normal WinDS optimization to compensate for this decrease in wind-capacity value.

In applying the supply curve developed by this process, care must be taken to ensure that costs associated with wind are not counted twice. More specifically, any model applying this wind supply curve must make the same assumptions as our one-region model optimizations. More specifically, any model applying this supply curve to capture the additional system costs associated with wind must not already include:

a. Wind transmission costs (either on existing lines or new lines)
b. Wind transmission losses (either on existing or new lines)
c. Cost penalties for building wind farms on steep terrain and/or populated
d. Penalties for wind capacity value below the average capacity[2]
e. Operating reserve additions required by wind capacity
f. Surplus wind generation.

[2] Average capacity is defined here as the nameplate capacity times the annual capacity factor of the wind farm.

g. Varying costs and capacity factors for different classes of wind resources. The supply curves presented here assume the one-region model will model all wind costs as Class 5 costs.

Section 4: Discussion of Results

Figure 6 demonstrates the change in total system costs for each period between the standard WinDS model optimization and the one-region model optimization. As demonstrated, the cost difference is highest during the period from 2012 to 2032, indicating that the largest impact of the wind transmission, intermittency, and other differences is during this period. However, this graph is somewhat misleading because it is not normalized for the amount of wind capacity added during each period.

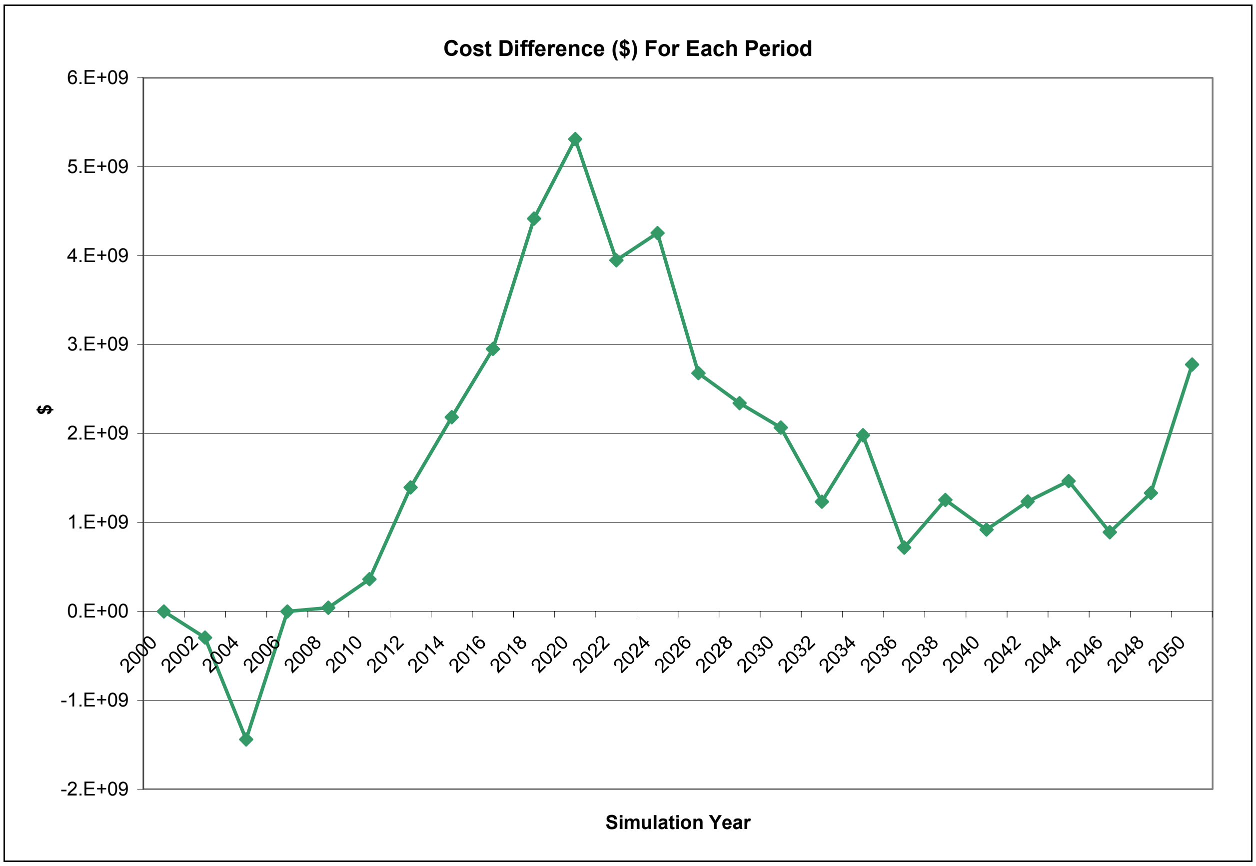

Figure 6: The Cost Difference ($) for Each Simulation Period

To correct this, **Figure 7** shows the basic supply curve that plots the marginal cost ($/kW) of new wind against the amount of total installed national wind capacity. This is the supply curve to be used in a one-region model. This graph represents the additional cost (above capital, installation, and operating costs) that needs to be added (or subtracted) to each additional kW of wind-power capacity installed in a one-region model.

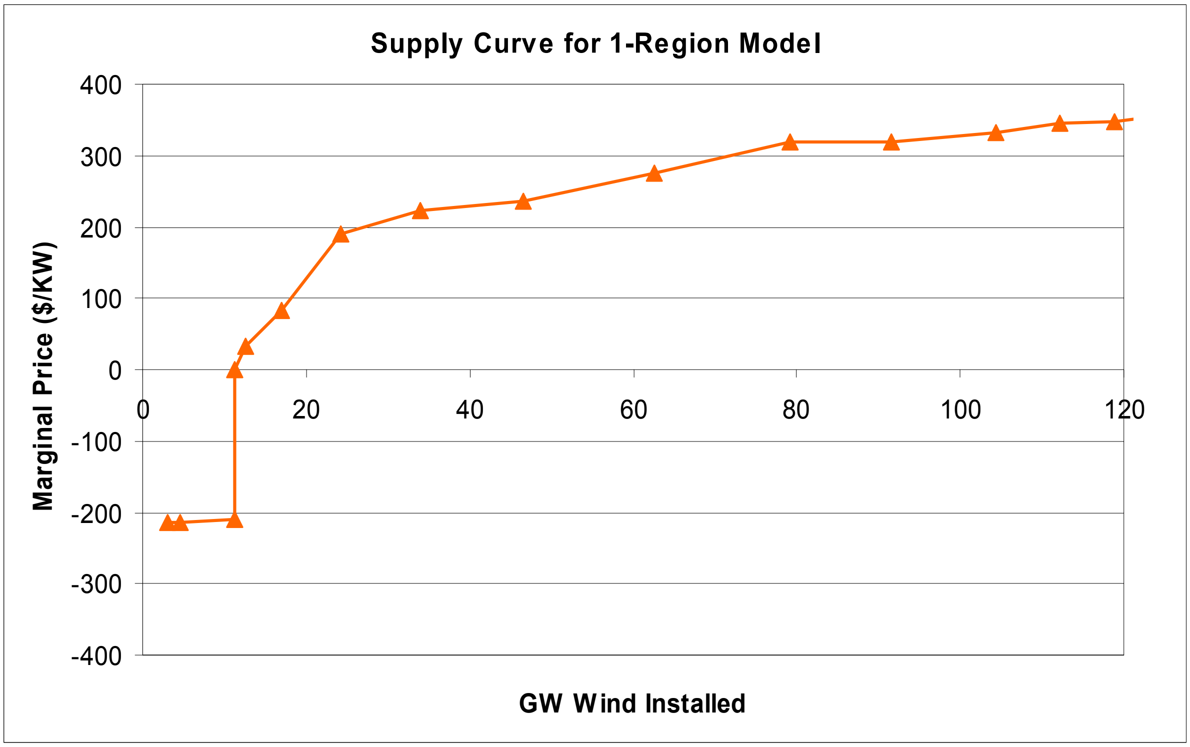

Figure 7: Supply Curve for One-Region Models without Transmission or Intermittency Impacts or Separate Wind Classes

As expected, the supply curve cost increases as the wind penetration level increases. This is due to the need, in reality, to use wind resources that require greater transmission costs, and increasing penalties on wind due to intermittency impacts (greater operating reserve necessary, lower capacity value, potential for surplus) as the cheaper resources are consumed. This graph shows that for the initial increase in wind capacity, the additional cost to account for the model differences is negative. This negative number indicates that the first 12 GW of wind will actually have a negative additional cost to the system. Therefore, any model that includes only Class 5 wind turbines and uses this supply curve will subtract a sum of roughly 220 $/KW from the capital cost of the initial wind-power installations. This $220/kW accounts for the fact that, in reality, Class 6 and 7 wind would be used for that initial wind capacity and not the average undifferentiated resource used in the run for the one-region model.

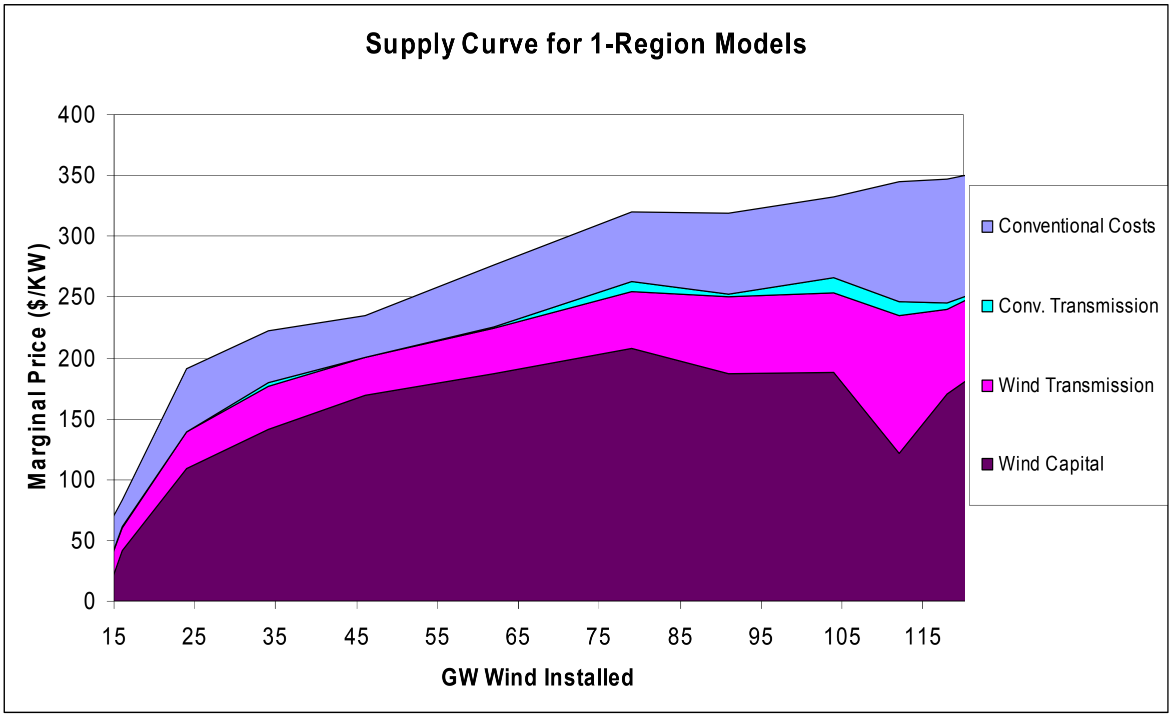

Figure 8: Supply Curve for One-Region Models with Major Components Plotted[3]

In **Figure 8**, the same supply curve as in Figure 7 is represented as a stacked chart to demonstrate the major drivers on the overall supply curve. The line labeled "Wind Capital" represents the difference in cost of the wind capacity installed in the one-region model and the WinDS model. As shown, this is a major component of the overall cost difference. The level is generally increasing, because the WinDS optimization requires a greater amount of wind capacity for the same amount of wind generation. The WinDS optimization requires more capacity and thus has higher costs because:

- The WinDS optimization gets less generation from the same amount of capacity due to increasing use of Class 3 and 4 wind (as opposed to representing all wind as Class 5 in the one-region model) as the penetration level increases.
- The WinDS optimization gets less generation for the same amount of capacity, due to transmission losses that are not present in the one-region model.
- The difference in cost due to the penalty imposed on densely populated regions and mountainous regions in the WinDS optimization - a penalty that is not included in the one-region optimization
- The possibility of wind surplus within the WinDS optimization, which is not present in the one-region optimization

The next major component is the "Wind Transmission" cost. This increases throughout, as the WinDS optimization has to use increasingly more expensive wind that is further from the load, thereby increasing the transmission costs (which, again, are not considered in the one-

[3] Note that the X-axis starts at 15 GW. Prior to this point are a series of negative values, which do not display reasonably on a stacked area chart.

region optimization). The value of the wind transmission cost might be less than one would expect based on other studies. The WinDS model (using base case assumptions) assumes 20% line availability for existing lines and also allows the building of short lines from one region to the next or within a region. This allows a great deal of wind to use existing lines and build very short new transmission lines especially at low penetration levels. These features keep the cost of transmission lower than they would be without these features. Future work includes sensitivities to the amount of existing lines available for new capacity.

In contrast to the wind transmission cost difference, the "Conventional Transmission" cost difference is minor. Although conventional transmission is treated the same in both models, there is a slight difference because of the increased conventional capacity installed in the WinDS model.

The final cost difference, "Conventional Costs", is attributable to the capital and operating costs for conventional capacity. This difference is caused by:

- Additional conventional capacity built in the WinDS optimization to meet additional operating reserve requirements imposed by wind that are not considered in the one-region model
- Additional conventional capacity built in the WinDS optimization to compensate as the capacity value per kW of wind installed decreases in the WinDS optimization as more wind is installed (the one-region model assumes a constant capacity value equal to the class 5 capacity factor).

We have presented the supply curve in Figures 7 and 8 as a function of the cumulative wind capacity installed nationwide. However, to a limited extent, these supply curve costs depend not only on the total wind installations, but also on the fraction of load met by wind and a host of other conditions that vary over time. To examine the significance of these other factors, we conducted a sensitivity analysis in which the wind penetrated much more rapidly. To do this, we used the same methodology as above, but extended the production tax credit to 2010. **Figure 9** compares the supply curve created using this fast market penetration and the supply curve created using the standard assumptions. Notice that only a few points are on the Fast-Penetration (FP) graph, indicating that the same amount of wind is installed in far fewer periods. The shape and cost levels are similar but not identical. There are a variety of factors contributing to these differences which are greatest early in the supply curve. For example, the difference is greatest when the FP case reaches roughly 31 GW in 2006 while the base case doesn't reach that level until 2014. By 2014, there are significant differences in wind cost, conventional fuel costs, electricity loads, and reserve margin requirements between these cases. Additionally, in the FP case the amount of wind added in one period is significantly higher than in the base case. This creates an inaccuracy in the FP case as the values used for wind capacity value, necessary operating reserve, wind surplus, etc. are all based on the wind level at the end of the preceding period. Therefore, the more moderate penetration rate found in the base case is the more accurate one to use.

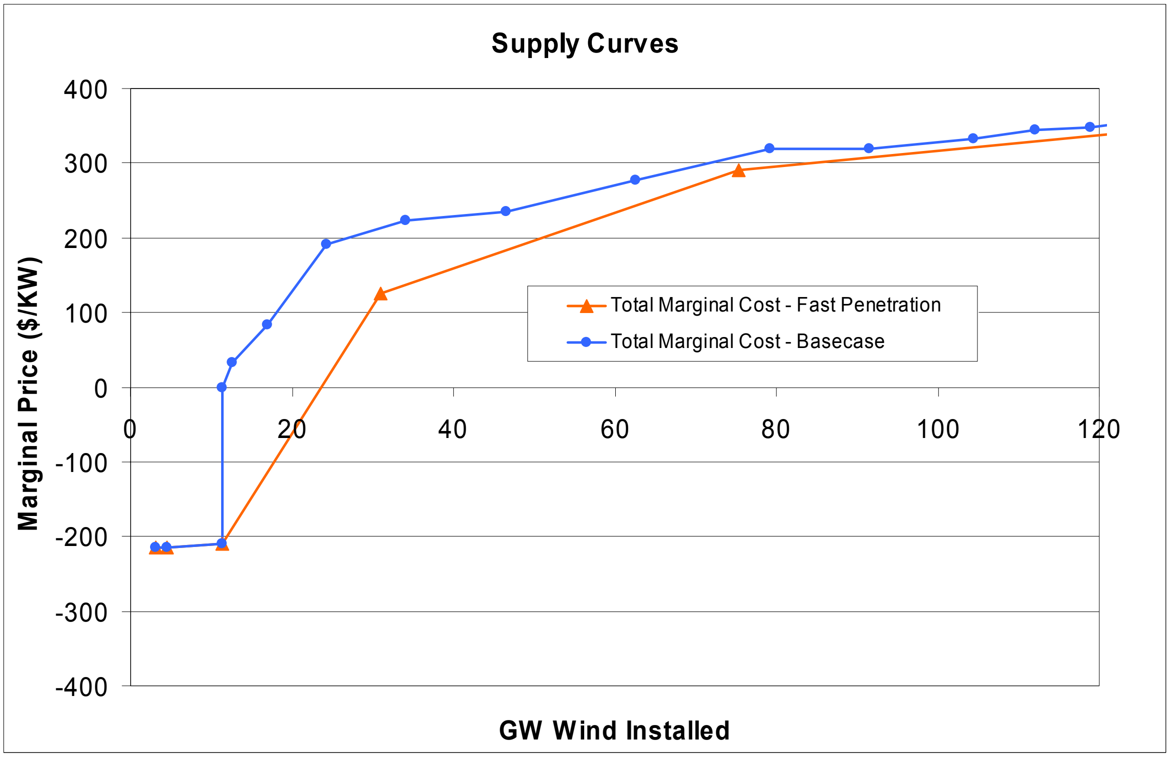

Figure 9: Comparison of Supply Curves for One-Region models with Typical Market-Penetration Rate and Fast Market-Penetration Rate

Section 5: Next Steps

First, the WinDS model itself is continually being improved. New methodologies and improvements to the treatment of transmission and intermittency for wind are being added currently and are planned. Therefore, as the WinDS model improves, improved versions of the reduced form outputs will also be generated.

Hopefully, the supply curves that can be generated using the WinDS model and the methodology presented in this paper will be useful to other modelers as they attempt to obtain a more accurate representation of renewables in their models. Immediate next steps to accomplish this include:

- Develop supply curves with the "one-region" model having multiple wind classes (but still no transmission costs or intermittency impacts).
- Develop supply curves like the above, but replacing the one-region model with a number of large regions, e.g. the NERC regions used in NEMS
- Work with the developers of other models to implement these results in their models.
- Continue to document and publish these results on our WinDS Web site

In addition to providing such supply curves for wind, we will be providing reduced form outputs for other renewable technologies. WinDS currently has the ability to model offshore wind, hydrogen production from wind, and other sources—and the ability to model concentrating solar power is currently being included. Supply curves for models wanting an accurate representation of costs associated with these technologies could be created.

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15. SUBJECT TERMS
Wind Deployment Systems Model; WinDS; GIS; wind; analysis models; wind power; production tax credit; PTC; renewable portfolio standard; RPS; wind resources; wind classes; wind markets; load constraints; offshore wind; PERI; Walter Short; Nate Blair; Donna Heimiller

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