Emerging Technologies, Data, and NEM Modeling

Issues in Wind Resource Supply Data and Modeling

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This is a working document prepared by the Energy Information Administration (EIA) in order to solicit advice and comment on statistical matters from the American Statistical Association Committee on Energy Statistics. This topic will be discussed at EIA's fall 2006, meeting with the Committee to be held October 5 and 6, 2006.

1. Introduction

This discussion paper was prepared in response to a request from the American Statistical Association Committee on Energy Statistics for information on data needs to support Energy Information Administration (EIA) efforts to improve modeling of renewable energy resources for mid-term energy market projections. EIA has developed and maintains the National Energy Modeling System (NEMS) to analyze U.S. energy markets and develop projections of these markets over a 20 to 25 year time horizon. NEMS is also used by EIA to analyze the impact of proposed energy legislation on domestic markets, and by others inside and outside DOE to evaluate policies, technology, and other energy related issues. Renewable energy, and in particular wind energy, has been the focus of many policymakers and others in the energy sector. Largely as the result of an on-again, off-again Federal subsidy, installed wind capacity in the U.S. has grown over 5-fold in the past 10 years. State-level policies are in place in almost half the states to encourage further renewable energy development, with wind seen as one of the lower-cost options for meeting these goals. Finally, increased concern over the potential for increasing greenhouse gas emissions has some policymakers interested in developing carbon-free energy sources to a much greater degree. From a relatively obscure basis, with little historical data or information to analyze, renewable resources, such as wind, are fast becoming high-visibility output in analyses of the domestic energy economy.

Although renewable energy resources are represented in several sectors of the U.S. energy economy – and in NEMS – this paper will focus on renewable resources used for electric generation, and more specifically on wind resources. Wind and other renewable resources compete within the Electricity Market Module (EMM) capacity planning module for incremental capacity installation to satisfy growing demand for electricity. Alternatively, incremental capacity growth can occur if the new capacity or generation is able to economically displace existing capacity or generation, for example as a "fuel saver" or in response to government subsidy or regulation. The economics of capacity expansion are solved for each year, based on the mix of new and existing capacity and generation that meets projected load requirements and relevant power-sector regulations, at the least cost within each of 13 electricity market regions (based on the North American Electric Reliability Council, or NERC, regions or sub-regions). Load requirements are estimated on an 11-time-segment load duration curve, ensuring that needs for both base-load and peak generation resources are represented.

As a separate algorithm within NEMS, the dispatch of existing capacity is estimated based on marginal operating cost economics to satisfy a somewhat more detailed load duration curve representation. Renewable resources, including wind, that have zero or near-zero variable operating costs are not solved-for in the dispatch optimization algorithm, but rather operated on an as-available basis given assumptions about seasonal and diurnal resource output in each segment of the load duration curve.

2. Modeling Wind Technology in NEMS

The EMM directly uses assumptions regarding wind technology cost and performance to evaluate capacity expansion decisions. Wind technology capital cost and capacity factor vary both among regions within the model, as well as through time. Spatial variation is primarily a function of resource modeling, discussed in the following section. Temporal variation, however, is primarily (although not entirely) a function of the "learning-by-doing" algorithms in NEMS. In addition to the "direct" cost of wind technology represented in NEMS, capacity expansion decisions need to account for the intermittent output of wind and associated impacts on systems operations.

Technology Cost Learning -All technology options available to the EMM capacity expansion module are assumed to decline in capital cost as a function of growth in installed capacity. Such "learning-by-doing" or "experience curve" impacts are relatively well explored in the literature. Some literature also specifically addresses cost declines in wind energy technology[1]. Several factors, however, challenge implementation of the standard "experience curve" model with respect to wind technology. First, wind technology is in a global market, with the largest vendors and most of the installed capacity (and frequently the highest growth rates) located in Europe. NEMS is a U.S. model, and can neither forecast nor fully account for cost reductions from international markets. Second, as the cost of many components (blades, towers, transmissions/gear-boxes) is reduced through learning effects, turbine designers can choose to either maintain the components "as-is" and reduce system capital costs or can redesign the system with bigger/more efficient components at the same capital cost but with significantly improved performance. This latter design option may, in many cases, provide more value to the project owner, and in many respects appears to more accurately explain some cost trends in the wind technology market. Finally, improvements in engineering cost do not always translate into reductions in customer prices. Policies that create higher demand for products than vendors can accommodate, limitations on how fast industry can expand, or even international exchange rates can have (and perhaps have

[1] Namovicz, Chris. "Analysis of Cost Reductions in the U.S. Wind Industry." *Proceedings of WindPower 2005*. American Wind Energy Association. Denver, June 2005. Also see Durstewitz, et al. at http://www.iset.uni-kassel.de/extool/ExtoolExperienceCurve.htm and Neij, Lena, et al. *Experience Curves: A Tool for Energy Policy Programmes Assessment.* Environmental and Energy System Studies. Lund University. Lund, Sweden. 2003.

had) an impact on market prices beyond the inherent supply-and-demand clearing mechanisms built into the model. These factors also appear to be at play in recent observations of wind technology costs. NEMS does capture short-term production bottleneck costs, such as seem to be appearing in current wind technology markets through a short-term elasticity function. Applied to all generation technologies, this short-term elasticity function temporarily increases technology-specific capital costs if installation rates for new capacity exceed historically observed growth rates by a threshold amount.

The current "baseline" capital cost assumption for wind technology in NEMS of $1167/kw (2004$) is based on an analysis of U.S. wind project costs from 1999-2002, from the EIA Form 412 survey (now discontinued). The analysis that produced this estimate also suggested a significant stagnation in wind capital cost reductions from the late 1990's relative to the rather robust cost reductions seen from the early 1980's to the mid-1990's. NEMS currently assumes that wind capital costs will decrease by 1 percent for every doubling of installed capacity. Recent anecdotal and non-statistical data suggest a significant increase in wind capacity costs since 2002, with current installations reported in the $1500 to 1600/kW range. There is no firm explanation for this apparent "reverse learning," but plausible factors (likely working in some combination) include short-term increases in steel and concrete prices; unfavorable exchange rates; insufficient global and domestic manufacturing capability (exacerbated by short-term uncertainty in U.S. wind subsidy policy); and exercise of market power by the consolidating manufacturing industry. EIA effectively assumes that the causes are largely transient in nature and will have been largely mitigated by 2008.

Technology Performance Learning - Improvement in turbine performance, manifested through increasing plant capacity factors, can also improve the value of wind generating equipment to plant owners through the corresponding reduction in levelized cost (or rather, by allowing capital costs to be more quickly recovered through increased annual generation). Plant capacity factors are determined through a complex interplay of site-specific factors (climate, terrain, turbine-array spacing, and so forth), turbine design characteristics (rotor size relative to generator size, reliability, and the efficiency of blades, transmissions, and power electronics), and actual weather encountered by the installation on a year-to-year basis (related to climate, but reflecting more of the uncertainty of inter-annual variation in climate).

EIA Form 906 provides a reasonably reliable database of actual plant performance for most of the U.S. operating stock, with plant vintages generally identified from the Form 860 data (although plant repowers or upgrades are not identified within the data). While this allows for limited examination of capacity factor improvement trends – used to calibrate the capacity factor "learning" parameters in NEMS – more reliable results would require the addition of more dimensions to the analysis. Some data, such as geographically specific estimates of climate (using the PNL "Wind Class" scale as a proxy for climate) are available, and could plausibly be used to generate an improved understanding of the basic relationship between state-of-the-art climate estimators used in NEMS and real-world wind plant performance. Other data may also be available with some significant research effort (such as identifying actual technology used at each plant, characterizing actual terrain). Such additional research may also serve to inform the development of reasonable model representations of the tradeoffs between component cost reduction and reduction in either total system cost or improvement in plant performance.

Grid Interactions - It is sometimes said that the uncontrolled, intermittent nature of wind generation increases its cost to the system operator. While it is true that additional investment in mitigating technologies, such as gas turbines or energy storage, would be required to convert wind power into a dispatchable "generation commodity," such investments are seldom (if ever) explicitly made, nor are they generally required to accommodate wind on the grid. Rather, most effects of intermittency manifest themselves through reduced value of wind energy relative to operator-controlled resources. Over the past 5 years, much progress has been made in more accurately representing the actual value of intermittent wind generation on the regional grids modeled within NEMS. Intermittency impacts modeled within NEMS include the value of wind energy through the seasonal and diurnal match or mis-match to regional energy demands; the contribution of wind energy to capacity reserves for meeting regional reliability requirements; and the lost value to wind plant owners in surplus generation that occurs when wind power saturates the flexible dispatch portion of grid operations.

Energy produced during peak demand periods is worth more than energy produced during "shoulder" or off-peak periods. The operator of a wind plant, however, cannot control the plant to produce power at the highest value periods. In some regions, climatic conditions do, in general, tend to produce winds during peak load time-of-day or seasonal periods. In other regions, the winds tend to blow during periods of moderate or even low energy value. Even in regions with favorable wind/load match, the addition of increasing quantities of low-variable cost wind to the dispatch stack will displace the highest cost fuels first. This will eventually reduce the value of energy during that peak demand period, resulting in less per-unit revenue to wind plant owners. NEMS captures this interaction by modeling nine demand time periods (three seasons, each with three time-of-day periods) and the corresponding average wind output in each period for each of the 13 electric market regions in the model. This ensures that the model knows the value of electricity generated by wind (and other capacity expansion options) for making capacity expansion decisions.

System Reliability - In addition to valuing generation (energy), the grid operator also values contribution to meeting system reliability. To represent reliability requirements, each region in NEMS has an explicit or imputed system reserve margin – that is, a margin of total installed capacity above projected peak load. Although wind plants are not operator controlled, they can contribute to regional reserve margins, as there is a probability that a wind plant will be generating power during a period of system need, just as there is a probability that an operator-controlled plant will be out-of-service during such a period. Of course, the effective "unplanned outage" rate for a wind plant is generally much higher than that of a conventional resource, so its contribution to reserve margin, also called "capacity credit," is correspondingly less. The capacity credit of an isolated wind plant is generally equal to its capacity factor during the system's peak load period (that is, the top several hundred hours of load).

However, as more wind capacity is added to a system within a finite geographic area, it becomes increasingly likely that an "outage" at any given facility will be temporally correlated with an "outage" at a nearby (or even not-so nearby) plant. This tends to reduce the average capacity credit for a wind plant as more such facilities are added in a region. Based on limited data from a study of Colorado wind resources, NEMS uses a regional correlation factor to adjust wind capacity credits evaluated for capacity expansion. This representation could be improved with finer resolution data on regional wind (and load) patterns, and with region-specific temporal-spatial wind correlations.

In Denmark, which perhaps has the highest utility-service-area penetration of wind capacity and generation in the world, there are occasional periods where net load is relatively light, but winds are strong. As wind production ramps-up, dispatchable units are turned-down or cycled-off. However, much of the generating stock is not dispatchable, not able to be quickly shut-down, or not quickly restarted once off. Because Denmark is a small part of a larger electrical grid, it is usually able to balance its load by exporting surplus generation. However, NEMS effectively models isolated electricity balancing markets with limited options to export surplus generation. While NEMS assumes that most gas-fired capacity (turbines and combined-cycle turbines) can economically respond to relatively short-term wind power fluctuations, it assumes that larger steam plants (nuclear or coal) will have limited flexibility to economically (or safely) reduce output below minimum operating thresholds given an unscheduled excursion of wind power. Using regional wind correlation factors developed for the capacity credit algorithm noted above, NEMS calculates the fraction of wind energy that would be "shed" once the inflexible units reach minimum loading, and deducts this energy from annual capacity factors used to evaluate system cost.

3. Modeling Wind Resource Supply in NEMS

In addition to considering the cost of the wind technology itself, NEMS must also factor in the variation in cost of accessing the patchwork of domestic wind resources. While it is reasonable to surmise that the vast differences among each of the millions of different potential wind sites available will result in a significant gradation in the cost of developing each site, empirical evidence to determine the general shape of such a "wind resource supply curve" is generally lacking. Some factors are reasonably well estimated with climate and terrain models or historic transmission line locations; however, reliable estimates for costs imposed by factors such as the need to upgrade long-distance transmission corridors, the costs imposed by physical and infrastructure barriers at many sites, and the opportunity cost (value) of competing land uses for all of the available land are generally just beginning to be rigorously explored, or have not been substantively examined at all. Based on the sometimes limited data available, NEMS does provide estimates of the impacts on each of these factors.

Wind Plant Performance - Perhaps the best understood aspect of wind resource distributions is that of the impact of regional climate or wind regimes on plant performance. As noted in the previous section, NEMS utilizes a relatively detailed model of the regional distribution of "wind classes" (summary indicators of potential plant performance based on wind technology assumptions; wind classes are based on the gross power available on average, given estimated annual variation in wind speed). While engineering models are currently used to predict current and future plant performance within each wind class, little empirical analysis has been done to correlate the significant historic plant performance data with the currently available detailed geographic models of wind power potential.

Impacts on Development Costs - Unlike conventional fuels that can be transported from the mine or well to the point-of-conversion, wind must be converted at the site of origin, requiring transmission lines to transport the electricity to market. NEMS accounts for the cost of developing transmission feeder lines to get from resource areas to the existing grid. In addition, NEMS uses resource cost multipliers to account for the assumed increasing cost of developing wind lands as the best and lowest-cost sites are exploited. Originally calibrated based on several regional studies of economic wind potential, these factors are assumed to account for the cost of upgrading long-distance transmission networks to bring generation from the generally remote wind resources to load centers; the cost of developing land with difficult terrain or that which is increasingly removed from development infrastructure (such as major roads, rivers, or rails capable of transporting the bulky and heavy construction equipment); and the increasing cost of acquiring or developing land with significant competing market value or even non-market value (such as environmental or scenic value).

Based on the wind resource data used to determine plant performance, NEMS further groups each of the three wind classes modeled into three "distance-to-transmission" categories. Resources in each of these groups are assigned additional capital costs based on estimates of the cost to build new, appropriately sized transmission lines from the main collector bus at the plant site to the nearest existing transmission line 2.5 miles, 7.5 miles, or 15 miles away (that is, groupings of 0 to 5 miles, 5 to 10 miles, and 10 to 20 miles). It is further assumed that wind resources beyond 20 miles from existing transmission lines will not be exploited.

The cost of getting the wind from the local point-of-generation to a potentially distant load center is accounted for separately from the cost of simply interconnecting the site to the nearest transmission line. Even at the relatively low current levels of wind penetration on regional grids, long-distance transmission has already proven to be a significant issue for new wind development. Wind plants in Texas have had to curtail output during hours when regional trunk lines are at physical capacity, and Minnesota and California are currently examining ways to alleviate transmission congestion as more development is proposed in their best wind resource areas. Detailed models of wind and long-distance transmission markets have recently been developed, and EIA is currently examining the potential of such models to improve the representation of these costs in NEMS.

Developing a windy site requires the ability to ship bulky and/or heavy equipment and components directly to the site, and then assemble these components. To the extent that local roads or bridges cannot accommodate blade shipments in excess of 50 meters (over 160 feet) length or nacelle shipments of 50 tons or more, they must be upgraded, rebuilt, or (retroactively) repaired as a part of the plant development process. Furthermore, at sites farther from population centers, it may be necessary to bring in heavy construction equipment and skilled operators from some distance to complete the project. Very little, if any, literature exists to estimate the potential cost of these factors with respect to the relatively well described U.S. wind resource base.

At about 6 or 7 megawatts per square kilometer of net power potential, wind plants are necessarily spread-out over a significant land area. While most of the "resource area" occupied by the turbines is useful for other economic purposes (especially agricultural uses), wind plants must still compete for use of these land resources. In many cases, wind power may be the highest value use. However, the value of some lands for other types of development (such as urban or housing development) has limited and will limit wind power location options. Wind power development may also face non-economic development barriers from people that object to the potential for environmental or scenic impairment from these plants. Although these issues are frequently discussed in the popular literature, and some academic work has been done on limited aspects, little is known about the broader potential for these land value issues to affect the cost or permissibility of future wind development.

4. Conclusion

Because wind energy has gone from a relatively small niche technology to a fast growing and potentially significant contributor to domestic energy supply in such a~~s~~ short period of time, there have been few empirical studies to support the analysis of large-scale potential growth in wind energy market share. Early attention was given to the raw description of wind energy technology and resource potential, but until recently, little attention has been paid to ~~those~~ how these factors might change with a significant increase in wind technology production (manufacturing) market size, a very high share of power generation markets, and utilization of a significant portion of the domestic wind resource supply. In some cases, data is available, but rigorous analyses have not been conducted. In many cases, data is either unavailable, or not available in a readily exploitable format. Improved analysis of these wind technology and resource issues will support improvement of the existing model structures used to analyze wind markets in NEMS, as well as the development of new model structures to analyze areas of greater uncertainty.