The Wind Power Paradox

BENTEK Energy

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The Wind Power Paradox

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Questions?
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I. Executive Summary

For years the wind energy industry and a vast array of politicians have claimed that increasing the use of wind power to produce electricity will result in huge reductions in CO_2 and other emissions. These claims rest on the results of dispatch models that predict not only emissions, but also fuel costs and generation levels for individual utilities and utility grids.

The Wind Power Paradox finds that these claims are significantly overstated. This study, the first to systematically assess emission reduction performance based on actual generation and emissions data across a variety of regions, reveals that actual CO_2 reductions through wind generation are either so small as to be insignificant or too expensive to be practical.

The study results are summarized in Table 1. Actual emissions data reveal a wide range of emissions reductions from wind power depending on the region. SO_2 reductions range between 0.0 and 4.9 lbs/MWh, NO_x reductions are between 0.1 and 2.0 lbs/MWh, and CO_2 reductions are between and 0.1 and 1.0 tons/MWh depending on the region analyzed.

Table 1: Emissions Savings per MWh of Wind; Cost of Saving 1 Ton of CO_2 per Region

	SO_2 (lbs/MWh)	NO_x (lbs/MWh)	CO_2 (tons/MWh)	CO_2 ($/MWh/ton)
ERCOT	1.2	0.7	0.5	$71
BPA	0.1	0.2	0.1	$420
CAISO	0.0	0.1	0.3	$114
MISO	4.9	2.0	1.0	$33
U.S. Avg	2.2	1.1	0.6	$56
AWEA	5.7	2.3	0.8	$42

The regional differences reflect the generation source that is cycled to accommodate wind. In BPA and CAISO, wind generally displaces either hydropower or natural gas-fired generation. Hydropower has no associated emissions. NO_x and CO_2 emissions from natural gas-fired power generation are relatively low and SO_2 are virtually nonexistent. In ERCOT, coal generation is cycled along with natural gas generation, and thus emissions savings are higher. Coal-fired generation provides a much higher share of total power production in MISO, and as a result, wind power has a greater impact on emissions in that area. In all cases, however, the reductions are lower than the assumptions used by American Wind Energy Association (AWEA) and others in traditional analyses based on dispatch models. It is also important to note that while the benefits of wind generation in MISO are greater than in the other regions, they are likely to diminish over time as more natural gas-fired generation is introduced to the region to displace less efficient coal-fired units in response to new EPA directives.

Table 1 also indicates the cost of saving one ton of CO_2 in each region if wind energy costs are valued solely on the federal government tax credit that is provided for each MW of electricity generated by wind.[1] Based on the tons of CO_2 actually avoided as a result of wind generation, it does not appear that wind power is a cost-effective solution for reducing CO_2 if carbon is valued at less than $33 per ton.

These results derive from an analysis of detailed data on wind generation and emissions from plants in four regional power areas — the Electric Reliability Council of Texas (ERCOT), Bonneville Power Administration (BPA - Pacific Northwest region), the California Independent System Operator (CAISO) and the Midwest Independent System Operator (MISO). This report estimates the reduction in SO_2, NO_x and CO_2 due to wind generation in those territories, utilizing more than 300,000 individual hourly observations for the years 2007 through 2009. The results for each region are compared to the savings claimed by AWEA and the average emission rate of thermal generation units across the U.S.

[1] Currently, the federal government tax credit for wind energy is $22 per MWh pre-tax and $34 per MWh after-tax.

II. Introduction

Over the past decade wind has become the "apple pie" of energy policy. Many in the U.S. and around the world have embraced wind energy as the principal renewable energy source by which mankind can slay the twin dragons of hydrocarbon consumption and production of greenhouse gases (GHG).

Over the past 18 years the U.S. federal government, many states and some local governments have devised numerous programs to encourage the development of renewable energy. The federal government provides direct financial subsidies for renewable technologies via production tax credits. Many states have adopted a more indirect approach by implementing Renewable Portfolio Standards (RPS), which require utilities to purchase various levels of power generated from renewable energy sources. California has the highest RPS requirement – 33% by 2020 – and 32 other states have implemented formal RPS programs. Sixteen of those states require 20% or more of total power sales to come from electricity generated from renewable energy sources by 2025.

During 2009 and 2010 there were repeated discussions in Congress about establishing a national RPS, more evidence that wind and solar energy remain at the forefront of U.S. energy policy.

Wind energy has become the most pervasive of the renewable energy technologies. Since 2005 more than 28,000 MW of wind generation capacity has been built in the U.S. compared to 2,000 MW for all other forms of renewable energy. In 2010, about 92,277 GWh, or more than 2% of total U.S. generation, came from wind. Wind power also is distributed throughout most of the United States. Five states have more than 2,000 MW of wind generation capacity, and several regional transmission systems, covering multiple states, have significant wind power capacity as well. Wind and solar generation have forced hydrocarbon-based power resources off the generation grid, and this has led researchers and policymakers to assume that emissions have declined accordingly.

Given the proliferation of wind energy generation facilities, it is time to test this assumption. Ample generation and emissions data exist to test the presumption that adding wind power to the U.S. energy portfolio will significantly reduce emissions. For this report, "significant" is defined as sufficient to justify the requisite investment of public dollars as valued by the federal government production tax credit. In other words, is the cost of the wind energy tax credit to the taxpayer equal to or greater than the value of the CO_2 emissions reduction from wind energy? An examination of actual performance data allows for an assessment of the actual reductions of $S0_2$, NO_X and CO_2 that resulted from the addition of wind generation. It also provides a starting point for assessing whether actual emissions reductions are sufficient to justify the associated commitment of federal tax dollars through the production tax credit.

Accordingly, the objective of this study is to assess the SO_2, NO_X and CO_2 savings from wind generation that have been achieved in ERCOT, BPA, CAISO and MISO. BENTEK, in conjunction with Dr. Daniel Kaffine from the Colorado School of Mines (CSM), developed a reduced form econometric model of the interaction among wind, coal and natural gas-fired generation within each region and the resulting change in SO_2, NO_X and CO_2 emissions that occurred as wind energy generation increased.[2] This analysis is based on hourly generation data provided by the Independent System Operators (ISO) in each of the four areas and actual hourly emissions data reported by utilities to the U.S. Environmental Protection Agency (EPA) through the Continuous Emissions Monitory System (CEMS).

Background

This new analysis follows another wind study released by BENTEK in 2010 that identified cycling issues in ERCOT and Public Service Company of Colorado's (PSCo) operating area. That report, titled "How Less Became More," concluded that emissions reductions thought to be achieved by wind generation in ERCOT and PSCo were either minimal or nonexistent in those territories. The report was the first to

[2] Reduced-form models are used to simplify the complex relationships between variables without making too many assumptions about those relationships.

use detailed empirical data rather than estimates hypothesized in various dispatch models to assess the emissions impact of adding wind power to these areas. The analysis received a number of important criticisms:

1) While there is ample wind generation data in ERCOT to clearly link wind generation to cycling of coal units, the data in PSCo is insufficient because it is limited to a few days; PSCo is unwilling to make hourly wind generation data publically available.
2) The study compared emissions on a “wind event” day to emissions on a “Stable Day.” A “Stable Day” is a day in which generation is most stable at each coal facility. This comparison was criticized for overstating wind generation-driven emissions estimates.
3) The report was funded by IPAMS (now known as Western Energy Alliance), a trade organization for the oil and gas industry. The report was dismissed by some because of its funding source.
4) The emissions impacts resulting from operating wind generation instead of natural gas-fired generation were not addressed in the report, as the stable day methodology could not be applied to natural gas-fired generation. Natural gas generation almost by definition does not have a “stable day” as it is designed to be frequently cycled for many reasons.

This feedback was incorporated into the current study. This report addresses these critiques in the following manner:

1) Analysis is conducted on areas in which full datasets of wind generation and thermal emissions and generation are available. PSCo is largely dropped from this analysis, except in several examples in which adequate data is available.
2) The stable-day methodology was replaced with a regression-based approach. In conjunction with Dr. Kaffine, BENTEK developed a regression methodology to determine the impacts of wind on emissions.
3) BENTEK funded this research with its own resources.
4) The study includes the interaction among wind, coal and natural gas generation in the assessment of emissions impacts.

The goal of this report is to provide fundamental data and analysis so that policymakers and market participants can make more informed energy decisions, particularly related to wind power and more cost-effective ways to reduce emissions from power generation.

Data

Multiple data sources underlie this analysis. Thermal generation and emissions data is sourced from the Environmental Protection Agency's (EPA) Continuous Emission Monitoring System (CEMS) program, a reporting requirement of the Clean Air Act. [3] This program continuously monitors boiler-level hourly emissions, generation and fuel consumption at every coal, oil and natural gas power plant in the United States that is more than 25 MW in capacity (1,542 facilities, 4,921 boilers). This sample represents the vast majority (in excess of 96%) of electricity generation from thermal units (excluding nuclear) in the nation. Hourly temperature data also is utilized to capture the fluctuations in demand throughout the day. This data is sourced from NOAA and is population-weighted for each region in the analysis.[4] Finally, hourly wind generation data is sourced from the respective ISO balancing authorities.[5] [6] [7] [8]

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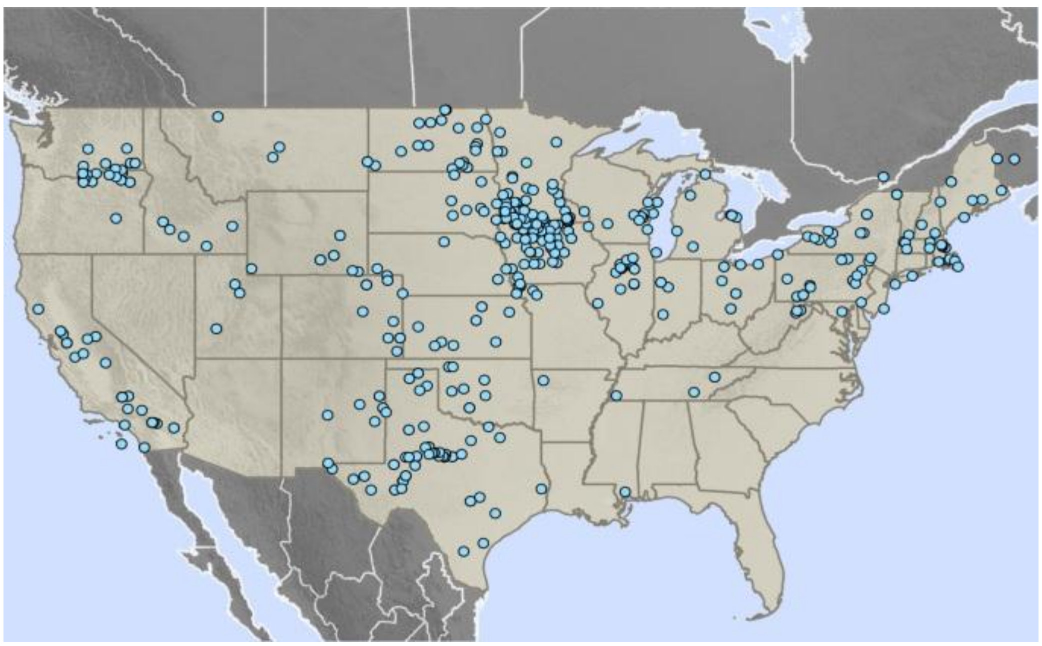
[3] http://camddataandmaps.epa.gov/gdm/index.cfm
[4] http://www.ncdc.noaa.gov/oa/ncdc.html
[5] ERCOT: http://planning.ercot.com/data/hourly-windoutput/

[6] MISO: http://www.midwestmarket.org/publish/Folder/25228f_10631e11216-7fe30a48324a?rev=11
[7] CAISO: http://www.caiso.com/1817/181783ae9a90.html
[8] BPA: http://www.bpa.gov/corporate/windpower.html

III. Wind Becomes a Significant Component of the Power Fleet

In 2000, wind powered only a negligible 0.15% of total U.S. electricity demand. Today it provides more than 2.0% of total U.S. electricity demand, with more than 36,000 MW of installed wind turbine capacity and another 6,000 MW in development.

Figure III-1: U.S. Installed Wind Capacity

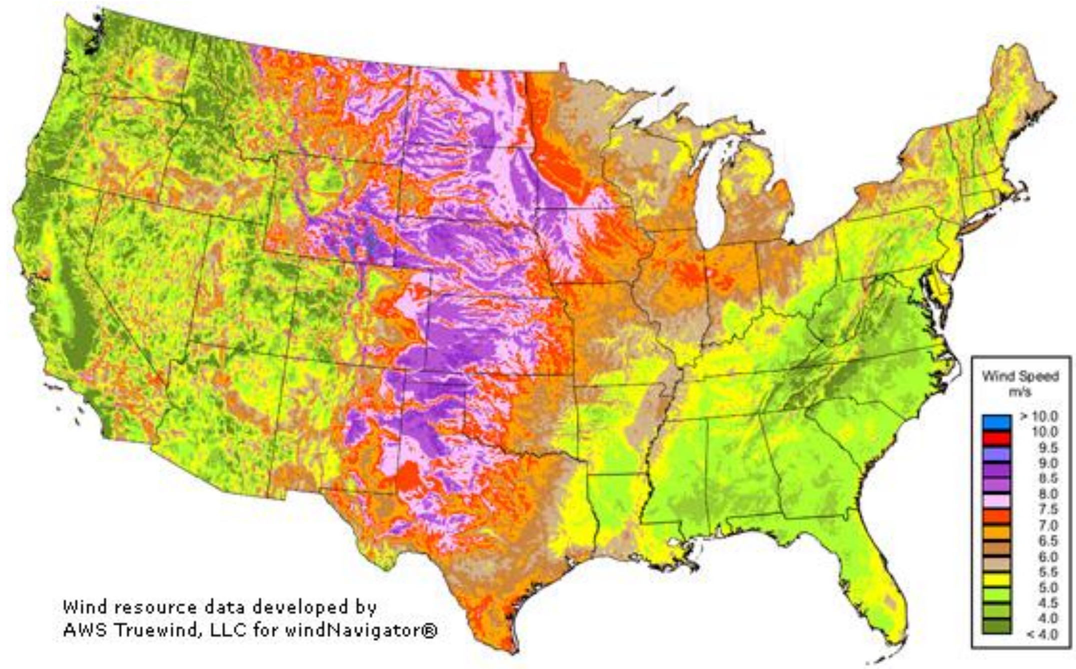


In general, wind farms are sited in areas where wind energy can actually be captured at rates that are economically viable. Figure III-1 shows that wind generators have mostly been developed in the Great Plains (including Texas and Oklahoma), the Northwest, the Northeast and California.

The National Renewable Energy Laboratory (NREL) has performed extensive analysis on U.S. wind resources to determine the best areas for wind generation. This analysis focuses on how wind performed at the 80-meter level, approximately the height of most modern commercial turbines. Figure III-2 is a graphical depiction of this data.

The existence of the purple and red shaded areas in the Midwest indicates the location of the strongest and most available wind resources.

Figure III-2: NREL Wind Resource Map[9]



Not surprisingly, as is reflected in Figure III-1, the highest concentration of wind generation resources is in these areas.

NREL also conducted analysis to understand the efficiency of wind turbines in each state. Using the wind resource data, NREL identified the potential installed capacity for 80-meter wind turbines and the utilization rates. This full dataset is presented in Appendix A in Table XI-1. Overall, NREL estimates there is the potential for nearly 10,500,000 MW of wind turbine capacity at an average utilization rate of 40%. The regions with the highest wind resources also reflect the highest utilization rates. For example, NREL estimates that Nebraska wind facilities will have an estimated 44% utilization rate compared to Alabama, with an estimated 32% utilization rate.[10]

Installing this much wind turbine capacity would represent a significant power generation source for the U.S. At an average 40%

[9] (NREL, Wind Maps)
[10] Utilization rate = actual energy generated / potential energy generated

utilization rate, 10,500 GW of wind capacity would generate 4,215 GW of electricity every hour, which the Energy Information Administration (EIA) says is nearly 10 times the average hourly electricity demand in the U.S.[11]

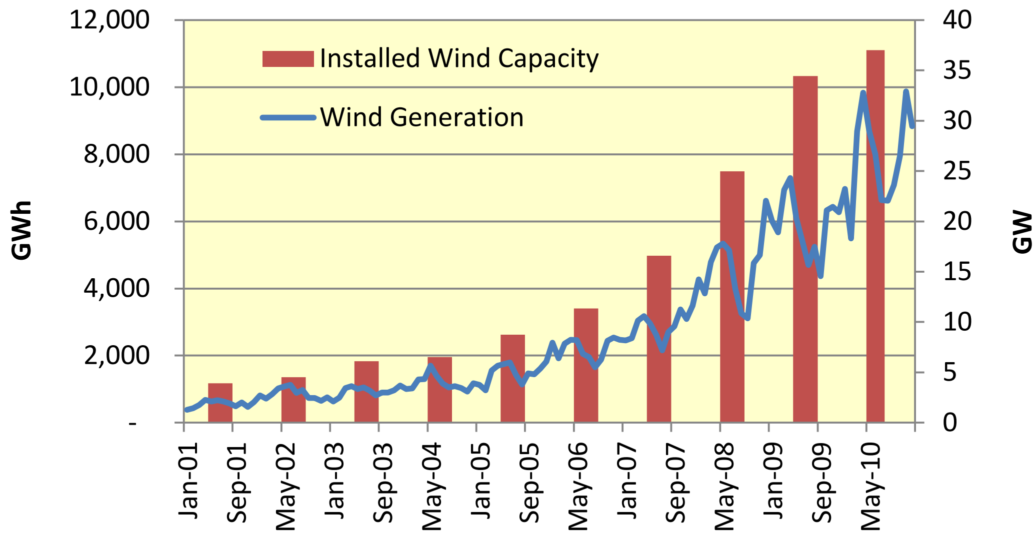
Since the middle part of the past decade energy policy has supported wind energy development. Policy action has taken place at both the state and federal level, and as a result, wind generation in 2009 met more than 1% of U.S. electricity demand for the first time.

Establishing Renewable Portfolio Standards (RPS) is the primary policy action that has been taken by states to promote wind energy development, and 29 states had RPS obligations at the end of 2010. These standards typically mandate that utilities operating in the state obtain some percentage of their energy sales requirements from renewable sources. In some cases the mandates specify renewable energy types, but usually utilities are free to choose from whatever renewable source they choose to meet the standard.

The federal production tax credit is the primary means used by the federal government to encourage wind and other renewable power development. Wind power has gained significant ground as a result of these policy encouragements in part because it is a cheap and scalable renewable energy source (see Figure III-3).

[11] Over the past 3 years, U.S. electricity demand has averaged 421 GW per hour. (Energy, Retail Sales of Electricity to Ultimate Customers)

Figure III-3: U.S. Wind Generation and Wind Turbine Capacity[12]



Between 2001 and 2010, wind turbine capacity increased by 844% from 3,918 MW to 36,998 MW. Actual generation from wind turbines increased during the past decade from 6,737 GWh in 2001 to 70,761 GWh in 2009. The acceleration of wind generation capacity development in 2005-2007 reflected passage of the federal Production Tax Subsidy and RPS in CO, HI, MD, NY, RI, DC, NM and DE in addition to major RPS revisions in NM, CT, MN, NJ, NV, TX, PA, CA and AZ. Table XI-2 in the appendix captures the RPS enacted by each state.

Further expansion and utilization of wind power continues to be a significant component of most energy policy debates. States are pushing RPS levels to new heights (California recently increased its goal to 33% by 2020), and U.S. legislators and policymakers continue to discuss a national RPS which would require each state to meet renewable energy goals.

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[12] (Energy, Electric Power Monthly 2009 - Monthly Data Tables), (Energy, Electric Power Annual 2008 - State Data Tables)

IV. Studies Question the Assumptions Underlying Wind Energy's Policy Appeal

> *"The models and techniques needed to study the impacts of wind integration and improved wind speed forecasting models are still being developed."*[13] *– Thomas A. Imbler, VP Commercial Ops, Xcel Energy*

The allure of wind energy has been largely driven by the belief that the resource offers emissions-free electricity. Alone, the resource produces no emissions when generating a unit of electricity. It was thought that introducing this resource would dramatically reduce emissions from traditional thermal resources (coal, oil and natural gas). However, when integrated into a system of other resources, which are forced to react to the variability of wind generation, wind generation creates stresses on other units that directly reduce the efficiency of operation.

Previous research on integrating wind generation into the power grid used emissions estimates based on the average composition of U.S. power generation by fuel type. The U.S. power generation mix in 2010 resulted in 4.1 lbs of SO_2, 1.7 lbs of NOx and 0.9 tons of CO_2 for a given MWh of generation. The models that were used assumed that introducing 1 MWh of wind generation to the system would accordingly reduce emissions by these amounts.

BENTEK's analysis finds that methodology overstates the actual emissions savings rates of wind, largely due to the factors outlined in Chapter VII.

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[13] (Rebuttal Testimony and Exhibits of Thomas A. Imbler on Behalf of Public Service Company of Colorado, 2008)

Research conducted by Moore et al. (Moore, 2010) found that in order to attribute emissions reductions to wind generation, models must identify the specific generation units (and the associated emissions of those generation units) that are actually being offset by wind generation output. Moore's findings were further supported by Cullen (Cullen, 2010), who used plant-level emissions data in ERCOT to estimate the emission savings associated with wind generation between 2005 and 2007. Cullen found that wind generation saved 3.15 lbs. of SO_2, 1.05 lbs. of NO_x and 0.79 tons of CO_2 per MWh of wind generation. Cullen's methodology was based on the assumption that the average emissions from the power plants that were turned off during wind power events were eliminated.

As outlined in Chapter VII, this approach does not capture the actual emissions savings on the system. The efficiency of generation units degrades as the units are cycled to accommodate for wind generation. Liik et al. (Liik, 2003) supports this conclusion, finding that accommodating wind generation is emissions-intensive due to the need to cycle traditional generation resources.

Two papers recently published further support this conclusion. One paper by Callaway and Fowlie (Callaway, 2009) and another report by Novan (Novan, 2010) find that assuming an average emissions reduction rate is not sufficient to accurately capture emissions reduction through wind generation. Additionally, both papers identify that utilizing dispatch models to assume which units would react to wind generation is insufficient to estimate wind generation-driven emissions reductions.

A widely distributed and utilized paper from the National Renewable Energy Lab's (NREL) Western Wind Integration Study (WWIS), commissioned by the Department of Energy (DOE), found that generation systems could technically support the integration of 30% wind and 5% solar. The NREL analysis does not examine the actual operating abilities of power plants in the footprint area (*p. 317 of WWIS*).[14] Information including the actual maximum generation output (capacity), fuel type, plant location and transmission were not part of the analysis.

[14] (National Renewable Energy Lab, 2010)

The analysis assumed that all coal, gas, oil, nuclear and hydro plants operate in the same way in the footprint. Implicitly, this assumption also meant that NREL utilized dispatch models for its analysis, a concern that both Callaway (Callaway, 2009) and Novan (Novan, 2010) note in their respective studies.

The analysis in this report addresses the findings from these studies and others. It relies on utilizing actual hourly data points from each region for every hour of power plant operation. This approach avoids assumptions associated with dispatch models and avoids using average emissions rates.

V. Cycling

> *"Integrating intermittent, volatile electricity into the grid can cause a surge or a sag that can lead to brownouts or blackouts. So grid operators, like Xcel Energy, must balance the wind-generated electricity with electricity online, ready and available to the system. In order to do that, plants that are already operating and connected to the grid must suddenly and rapidly increase or decrease their output to maintain balance. In some cases, this means that plants that are offline must be brought online quickly. The rapid starts and stops or increases and decreases in output are called 'cycling.'"*[15] *- Aptech*

The quote from a study by Aptech, an engineering consultancy working for Xcel Energy, describes a phenomenon that is critical to understanding the true impact on emissions from wind energy. This phenomenon to date has been largely missing from wind integration studies.

The Aptech studies attempted to estimate the emissions savings from wind generation, but overlooked or made assumptions regarding issues related to cycling. The studies generally assumed that natural gas would absorb the volatility from wind generation; natural gas turbines were assumed to be the principal backup power source used to accommodate wind energy.

In fact, data from ERCOT reveals that coal units also are frequently cycled to accommodate wind. Figure V-1 details total generation output by fuel source in the ERCOT operating area on a 15-minute basis over a seven-day period. The purple area depicts wind generation. The total of generation from all sources equals demand in ERCOT. Figure V-1 indicates that, for the most part, wind blows in the early morning hours when total demand is low (indicated by the circles). Figure V-1 also shows that when the wind blows in these early

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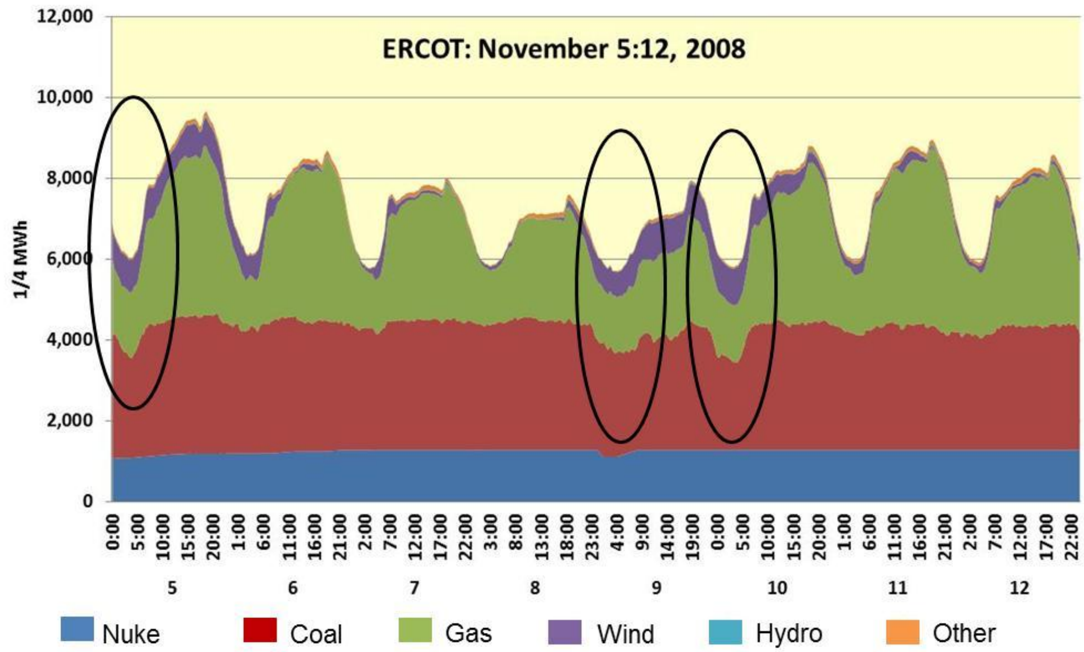
[15] (Aptech)

morning hours, coal generation and natural gas generation are reduced to accommodate wind. The sudden up or down fluctuation in generation will be referred to as "cycling" throughout the remainder of this report.

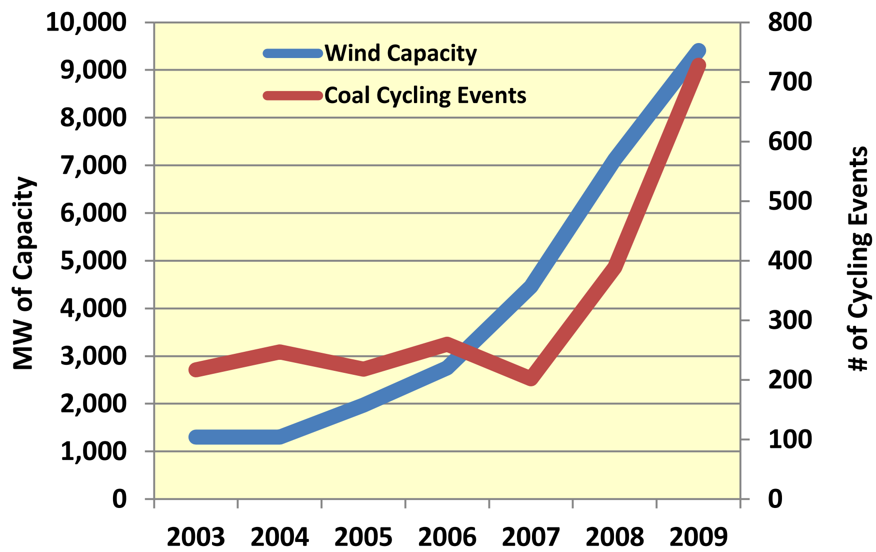
Figure V-1: ERCOT Generation Stack Nov. 5:12, 2008



The cycling of coal generation shown in Figure V-1 frequently occurs in ERCOT and is defined quantitatively as a period during which total coal-fired generation output declines by more than 5% hour-over-hour at the beginning of these events and climbs by more than 5% hour-over-hour at the end of these events. Several more charts showing additional examples of this type of cycling are presented in the Appendix under Figure XI-1.

Historically, coal plants were designed to serve as baseload generation plants, operating most efficiently when run at a relatively constant high utilization rate (generally greater than 70%). In ERCOT, however, the frequency and magnitude of cycling has increased dramatically with the incorporation of wind generation. Coal cycling events due to wind generation in ERCOT are quantified by identifying instances in which total coal generation output changed more than 5% coincident with a similar change in wind generation. Figure V-2 compares the growth of wind generation capacity in ERCOT and the number of coal cycling instances based on the 5% threshold. Beginning in 2006 when wind capacity reached the 4,000 MW level, cycling of coal units spiked upward and has continued to increase.

Figure V-2: ERCOT Wind Capacity & Coal Cycling Events



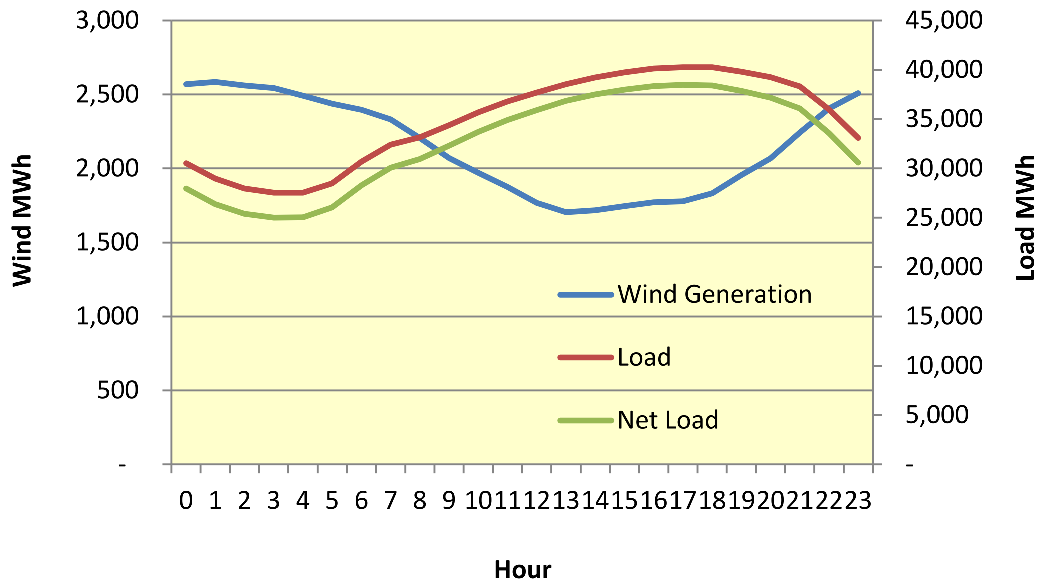
Aptech performed an analysis of cycling for Xcel Energy. Its findings were similar to BENTEK's ERCOT analysis. "When significant amounts of unmanaged wind-generated electricity are introduced into the system, cycling events will increase at baseload plants,"[16] Aptech stated.

As wind capacity increased in ERCOT between 2003 and 2007, the amount of wind generation was not significant enough to dip into the coal generation stack at night. However, as wind turbine capacity surpassed roughly 5,000 MW, the instances of coal cycling events increased nearly 400% from 2007 to 2009. As more wind is added to the system, coal cycling instances will likely increase further.

ERCOT coal generation is cycled in response to wind generation due to the inherent nature of wind patterns in the area. Wind generation reaches peak output during early morning hours, as detailed in Figure V-3.

[16] (Aptech)

Figure V-3: Average Hourly Wind Generation & Load in ERCOT, 2009[17]



On average, there is a nearly 35% decline in wind generation output from the night hours to the middle of the day. As wind generation is reaching peak output, total load in ERCOT is declining to its lowest levels. The Net Load line in Figure V-3 represents total load net of wind generation output, capturing the demand level that the remaining fuel sources are required to fulfill.

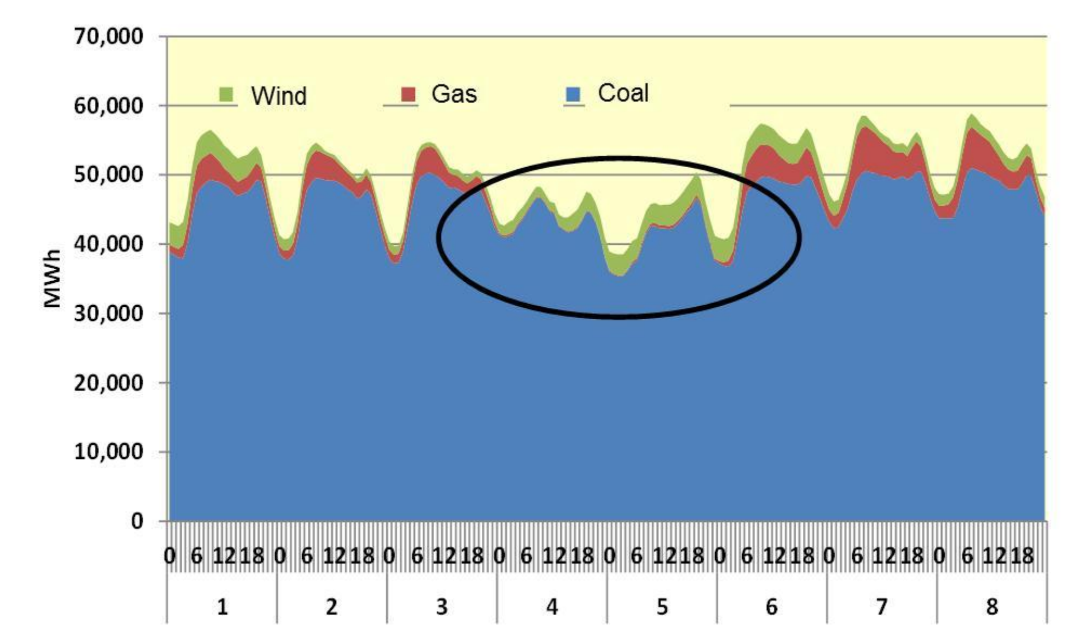
Wind integration studies assume that natural gas units will be the primary generation used to absorb the changes in wind generation output. In contrast to standard coal-fired baseload units, gas-fired generation units are designed to meet unpredictable and varied demand.

However, at night in ERCOT when the wind blows, both natural gas combined cycle and combustion turbine units are already at relatively low generation levels because they are relatively more expensive to operate than coal and nuclear plants. In many cases, and especially in the shoulder season, natural gas generation sources are operating at levels below which they cannot be dispatched without violating system reliability standards. Additionally, transmission constraints often impact the units that will be cycled.

[17] (ERCOT)

As shown in Figure V-1, in ERCOT both coal and gas units are cycled in order to accommodate wind generation. Figure V-4 shows similar interaction in MISO for the first eight days of April 2009. The relatively small portion of total generation provided by gas was cycled down for just over two days to accommodate wind generation, but even with this reduction, coal units had to be cycled as well. Coal generation in MISO has historically been cycled in a load-following capacity; these coal units are designed to load-follow more efficiently than coal units in ERCOT. However, thermal units were still cycled in order to accommodate wind generation.

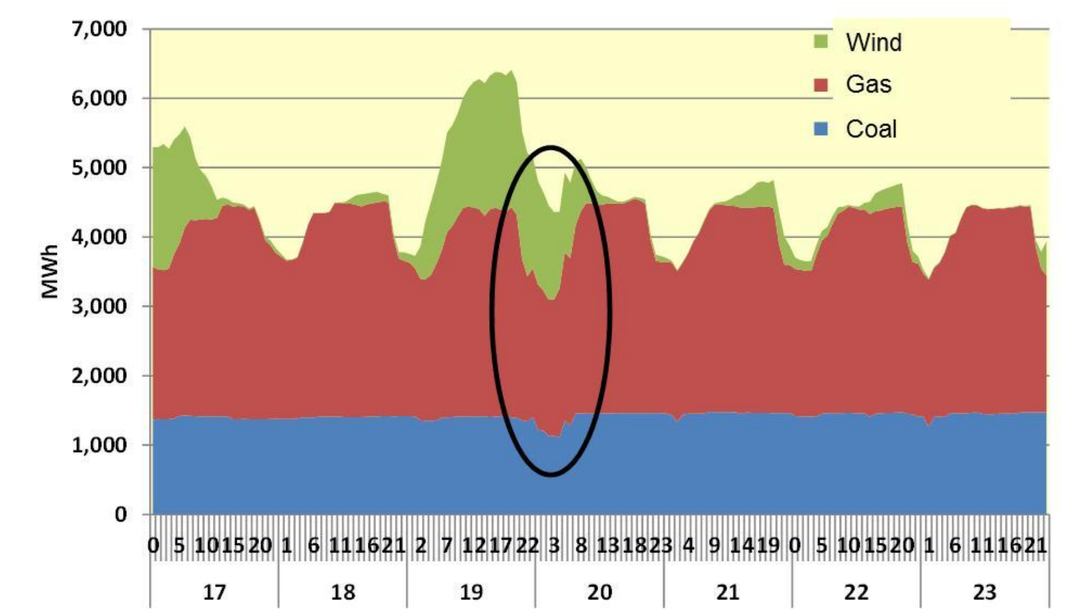
Figure V-4: MISO Generation Stack, April 1:8, 2009



Coal cycling is evident in the BPA territory. In contrast to MISO, gas-fired and hydro generation accounts for a much larger portion of the generation mix, 10.8% and 45.5% on average, respectively. [18] Accordingly as shown in Figure V-5, when wind generation is available, gas-fired generation declines. Nevertheless, as shown for Sept. 19 and 20, there are times when the volume of wind requires BPA to cycle its coal-fired generation. While the fuel consumption impacts are different, dispatching wind generation requires thermal assets to cycle in all of the areas studied.

[18] (BPA, 2009)

Figure V-5: BPA Generation Stack, September 17:23, 2009



VI. Impacts of Cycling

> *"The aim [of this study] is to show that the fuel economy and emissions reduction in the power systems consisting mainly of thermal power plants are not proportional with the electricity production of wind turbines. Participation of thermal power plants in the compensation of fluctuating production of windmills eliminates a major part of the expected positive effect of wind energy."*[19] *– Liik, Oidram, Keel*

Wind generation forces thermal generation units to cycle, making the generation system less environmentally and operationally efficient. All electricity generation facilities are designed with an ability to increase and decrease generation output. The rate at which operators can increase or decrease generation from a specific unit is called the "ramp rate." Every generation unit has a design ramp rate. Natural gas plant ramp rates are relatively large, more than 80% of capacity per hour. Coal unit ramp rates are relatively low, near 20% of capacity per hour. Optimal operation of the units requires that the operator keep the cycling impacts well within the ramp rate specifications of each unit.

To understand the impact of cycling, think of an automobile. A car obtains optimal gas mileage when it is operated at a consistent speed. When a car enters stop-and-go traffic, combustion efficiency and fuel use efficiency decreases. Thermal power plants operate similarly.

The impacts of stop-and-go operation are more significant at coal facilities than at natural gas facilities. Because most natural gas combined cycle and combustion turbine units are designed to accommodate cycling, the efficiency degradation on these units is mitigated. However, coal facilities have typically been designed as baseload generators and are not designed to accommodate variable generation requirements. Changing the way coal plants operate in

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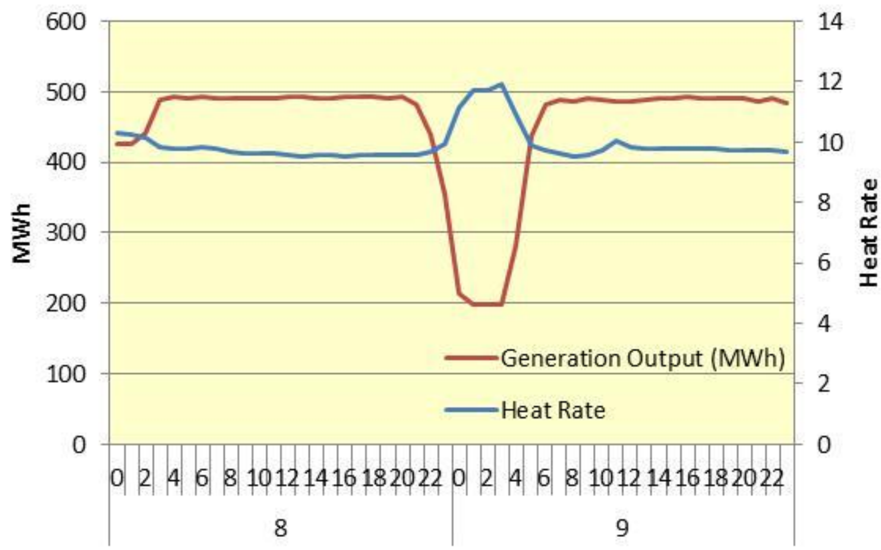
[19] (O. Liik, 2003)

order to accommodate wind generation has the similar efficiency impact experienced when operating a car on the highway versus a car in the city. In the city, more fuel is consumed per unit of output, and therefore, efficiency declines. Cycling thermal facilities in response to stochastic variation in wind generation decreases the efficiency of these facilities.

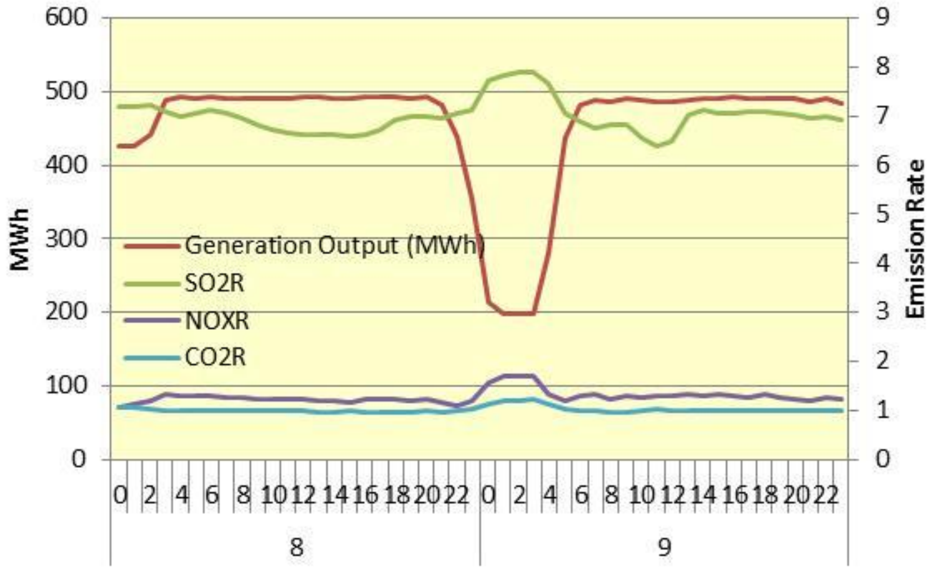
The efficiency degradation due to cycling is widespread across thermal facilities in areas where significant amounts of wind generation are integrated. Figure VI-1 below captures the generation output and heat rate of the Gibbons Creek coal-fired generation plant in Texas during January 2009.

Figure VI-1: Gibbons Creek Steam Electric Station (ERCOT), January 8:9, 2009



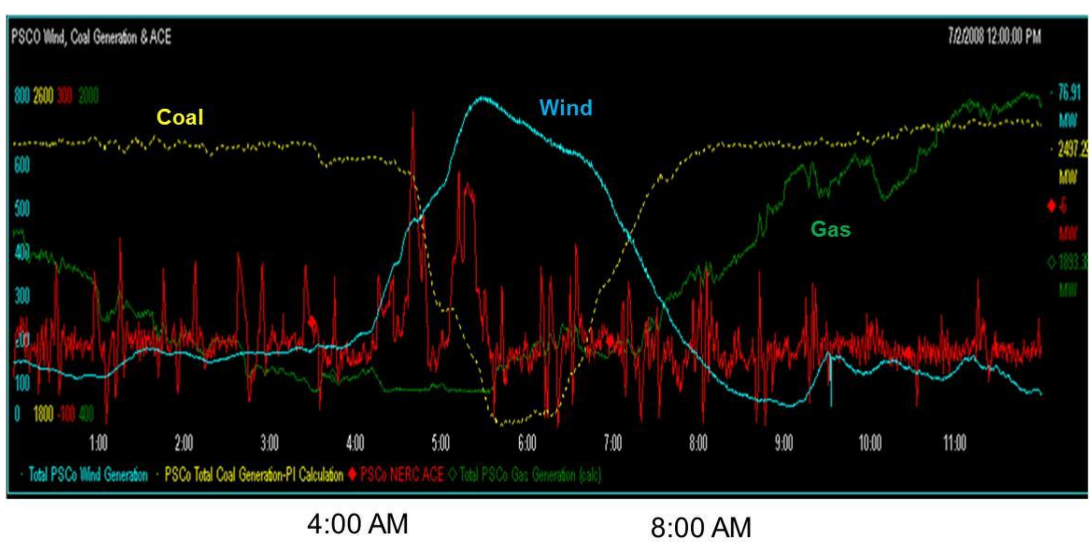
When the facility was cycled (generation suddenly fell) in order to absorb changes in wind generation, the heat rate (MMBtus of energy consumed per hour divided by the MWs produced) increased by more than 20%. The rising heat rate negatively impacts emissions rates. Figure VI-2 captures the changes in emissions rates at the plant over the same timeframe. SO_2, NO_X and CO_2 emissions rates all increased during the wind event because the heat rate at the plant changed.

Figure VI-2: Gibbons Creek Steam Electric Station (ERCOT), January 8:9, 2009 Emissions Rates



Cycling of coal facilities can cause a second, more significant type of inefficiency to occur. The following example is sourced from training materials distributed internally at PSCo, a subsidiary of Xcel Energy, to inform dispatchers of potential hazards associated with wind generation. Figure VI-3 is a snapshot of one day on PSCo's system when wind generation adversely impacted coal generation.

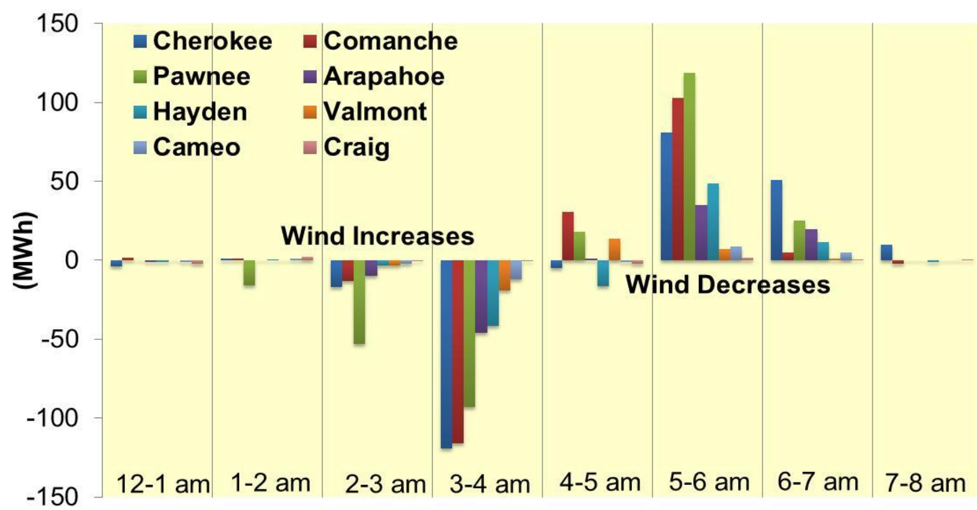
Figure VI-3: Wind Event on PSCo System (July 2, 2008)



On July 2, 2008, during the morning hours, wind generation ramped up from 150 MWh of output to 800 MWh of output in less than two hours. Typically operators dispatch units based on cost of operation; more expensive units are dispatched down before less expensive units. However, gas generation on PSCo's system was already at such a low level that it could not be reduced without sacrificing reliability – transmission limits also are a limiting factor for availability of units to meet changes in wind generation. Consequently, PSCo was forced to reduce coal generation from 2,500 MWh to 1,800 MWh in a very short timeframe. As wind generation dropped to roughly 150 MWh by 8 a.m., coal generation was ramped back up to 2,500 MWh to meet increasing load levels on PSCo's system.

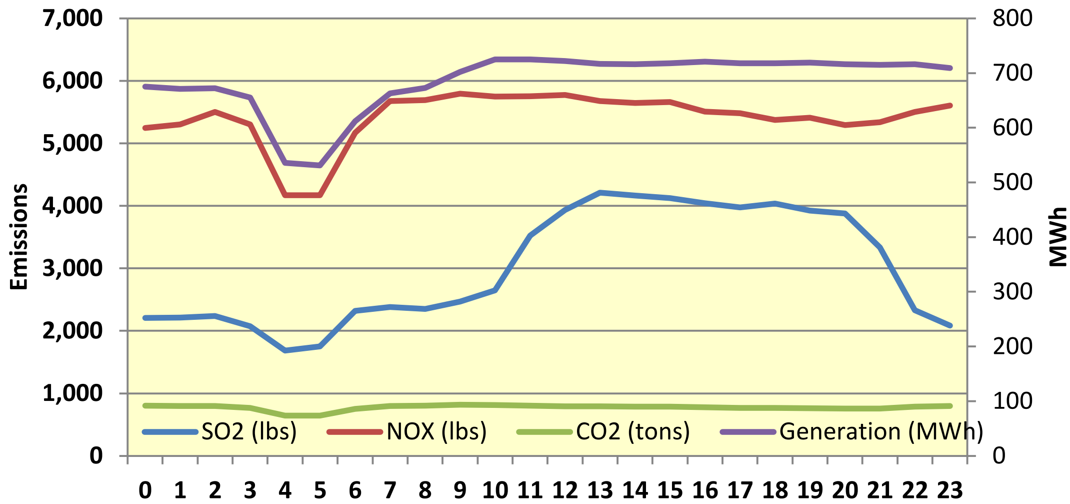
Generation at several coal plants was reduced in order to accommodate wind generation on the system. The hour-to-hour change of generation output at the facilities operated by PSCo on July 2, 2008, is captured in Figure VI-4.

Figure VI-4: Hour-to-Hour Change in Generation (July 2, 2008)



The Cherokee, Comanche and Pawnee coal facilities provided the most flexibility for PSCo on July 2, 2008. Complications arose at the Cherokee facility hours after the cycling event, problems attributed to wind generation (the unit would not have cycled had wind generation not been present). Figure VI-5 captures emissions and generation output at Cherokee on July 2, 2008.

Figure VI-5: Emissions and Generation Output at Cherokee on 7/2/2008



Between the hours of 2 a.m. and 7 a.m. generation output at Cherokee was offset by wind generation. There are associated fuel and emissions savings with the lower level of generation throughout this timeframe, as indicated by the dips in NO_x, SO_2 and CO_2 in Figure VI-5. However, complications at the facility for hours after the cycling event negated any SO_2 and NO_x emissions savings. In fact, SO_2 and NO_x emissions ended up higher for the day because the unit was cycled to accommodate wind generation.

After the cycling event, generation levels at Cherokee settled at roughly 720 MWh, 7% higher than prior to the cycling event. However, NO_x levels increased 10% after the cycling event and SO_2 levels increased 90%. CO_2 emissions remained steady after the cycling event.

These types of events must be accounted for when quantifying emissions reductions due to wind generation and comparing them to other energy sources. Complications arose at Cherokee on July 2. Efforts to balance the boilers using natural gas ended up plugging SO_2 reduction units, thereby eliminating their effectiveness. Repairs were made to the units, but took most of the day to complete, and emissions spiked during the interim period.

Cycling thermal facilities degrades coal plant efficiency and the degradation worsens under extreme ramp rate scenarios. Arthur Campbell of MIT describes the phenomenon as follows:

> *"The countervailing force, which may increase emissions, acts through a change in the efficient (least cost) mix of non-renewable generation when wind provides a fraction of electricity. If this mix involves more GHG intensive generating technologies then this will act to offset the emission gains due to the output from wind."*[20]

Offsetting one MWh of generation at a thermal facility with wind generation does not result in an equivalent amount of emissions savings when compared to normal, or average, emissions rates at a particular site because of the system integration inefficiencies that it precipitates.

[20] (Campbell, 2008)

VII. The Wind Generation Paradox

> *"There is no evidence that industrial wind power is likely to have a significant impact on carbon emissions. The European experience is instructive. Denmark, the world's most wind-intensive nation with more than 6,000 turbines generating 19% of its electricity, has yet to close a single fossil fuel plant. It requires 50% more coal-generated electricity to cover wind power's unpredictability, and pollution and carbon dioxide emissions have risen (by 36% in 2006 alone)."*[21] *– Trebilcock*

Wind generation creates a paradox. Wind blows naturally, and causes no CO_2, NO_X, SO_2 or any other form of pollution except, of course, particulate pollution in the form of dust. It seems entirely logical that, if one ignores pollution created in the process of manufacturing wind generation equipment, adding wind generation to a power generation system would reduce system-wide emissions since the pollutant-emitting coal and natural gas units would be run less often.

This theory, however, is not supported by this analysis. Wind energy must operate within a complex generation system, comprised of multiple generation sources with widely varying flexibility. The intermittent nature of wind causes cycling of other thermal power plants on the system, making them more inefficient. This inefficiency reduces the overall system-wide emissions benefits attributable to wind. System-wide emissions reductions fall well short of expectations. This is the wind energy paradox.

Model Approach

To assess the emissions savings from wind generation BENTEK estimated emissions reductions due to wind generation using a

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[21] (Trebilcock, 2009)

multivariate model that incorporates hourly and plant specific data on wind generation, thermal power generation, emissions and temperatures. The model was applied to the CAISO, MISO, BPA and ERCOT operating areas.

In order to identify the emissions reductions due to wind generation in each operating area, the exogenous, stochastic variation in wind must be examined. The model below captures the systematic response of thermal generation emissions to hourly fluctuations in wind generation. The model is discussed in detail in the appendix under Equation 1: Emissions Model.

$$E_{irt} = \alpha_{ir} + \beta_{ir} W_{rt} + \gamma_{1ir} T_{rt} + \gamma_{2ir} T_{rt}^2 + \delta_{ir} X_t + \epsilon_{irt}.$$ [22]

The model identifies the emission reduction that results from adding an incremental MWh of wind generation to the system. The model incorporates the characteristics of the actual generation stack and associated emissions, local temperatures, day of the week, month and year.

- E_{irt} = emissions of pollutant *i* in region *r* and time *t*
- $Alpha_{ir}$ = constant regression term for pollutant *i* in region *r*
- $Beta_{ir}$ = the change in emissions due to a MWh change in wind generation
- W_{rt} = wind generation in MWh in region *r* at time *t*
- T_{rt} = temperature in degrees F in region *r* at time *t (this is a proxy for demand)*
- e_{irt} = the idiosyncratic unobserved error term
- X_t = vector of time-controlling dummy variables, representing year, month, day of week and hour

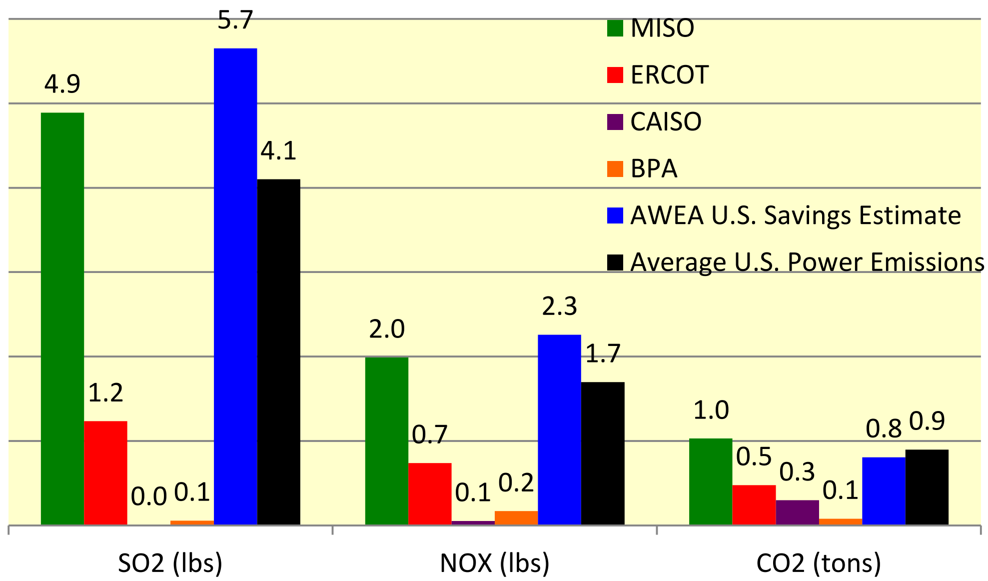
The model results were statistically significant. Table XI-3 in the appendix reports the summary statistics output of each model across the balancing authorities analyzed in this study.

[22] Equation 1: Emissions Model, discussed in the Appendix

Emission Reduction Findings

BENTEK estimated emission savings for the ERCOT, BPA, CAISO and MISO areas for 2008-2010. The results are shown in Figure VII-1 and are compared to the asserted savings that would result from using wind industry estimates, which are generally accepted in the policy community.

Figure VII-1: Wind Generation Emission Savings per MWh by Territory vs. Average U.S. Power Emissions



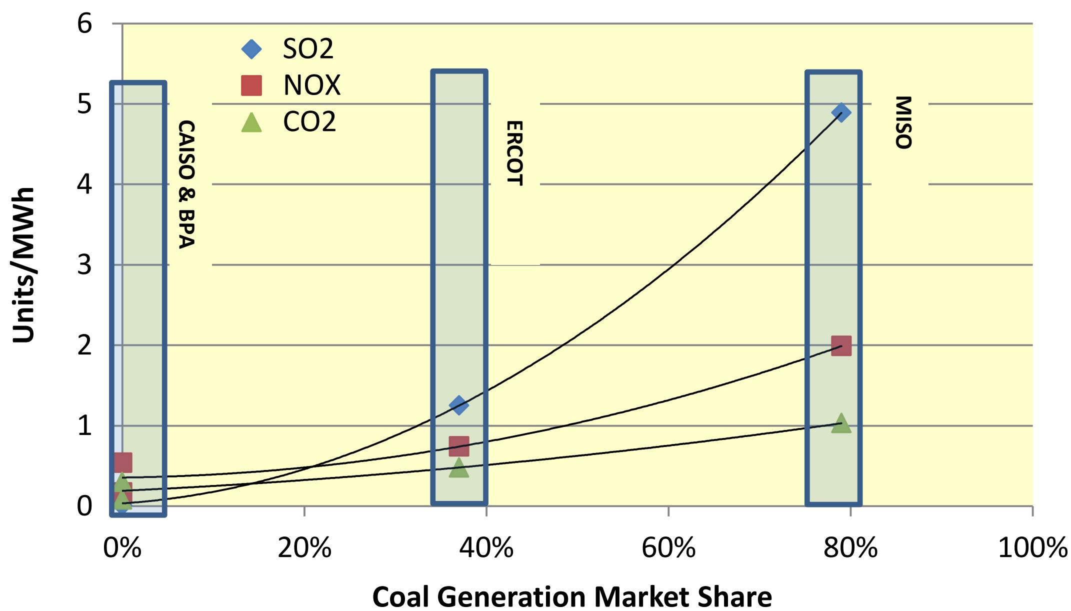
Wind generation-driven CO_2 emission savings vary from 0.081 tons per MWh in BPA to 1.025 tons per MWh in MISO. NO_x emission savings are between 0.17 pounds per MWH to 1.995 pounds per MWh. Emission savings for SO_2 range from 0.008 pounds per MWh to 4.89 pounds per MWh. Compared to wind industry estimates, actual emission savings are less than expected.

Figure VII-1 leads to two overarching conclusions: First, the emissions savings that result from adding an incremental MWh of wind vary depending on the power supply composition of the service territory. Savings are higher in the MISO area where coal constitutes a very large portion of the generation stack (approximately 80%). Conversely, in areas where coal plays a minimal generation role (CAISO and BPA) an increment of wind generates very negligible emissions savings.

The second major conclusion is that savings are relatively small compared to other estimates and accepted policy assumptions. Again, the disparity is less pronounced in areas such as MISO where coal is more prevalent, but even in MISO. SO_2 savings are 23% less than estimated by the AWEA approach while CO_2 savings in MISO are slightly higher than expected using the AWEA estimation method.

The emissions savings vary significantly from territory to territory due to the differences in the generation stack between each territory. Figure VII-2 plots the percentage of coal-generation market share against the emission savings for each territory.

Figure VII-2: Wind Generation Emissions Savings vs. Coal Generation Market Share



As the percentage of coal generation market share increases, so do the emission savings. This is due to more coal generation being offset to allow for wind generation. However, this interaction presents its own problems. As more coal units are cycled, reliability is degraded, efficiency declines and maintenance costs rise.

Coal-fired generation assets in the MISO operating area represent 79% of total generation. Wind generation mostly offsets coal-fired generation, which has higher emissions rates than natural gas fired generation. In comparison, there is little to no coal-fired generation in the CAISO or BPA operating areas. Natural gas and hydro generation units are used to accommodate wind generation. Due to the low emissions rates of these units (no emissions in the case of hydro), there is very little emissions savings in BPA or CAISO. ERCOT has a relatively balanced mix of natural gas and coal generation assets, which explains why emissions savings in this region fall between those in BPA/CAISO and MISO.

Wind generation emission savings will likely fall in coal-dominated areas such as MISO. EPA regulations covering the release of SO_2, NO_x and mercury will discourage the use of coal-fired power plants for electricity. This interaction will result in the reduction of potential savings for wind generation as natural gas units are brought online to replace coal-fired generation.

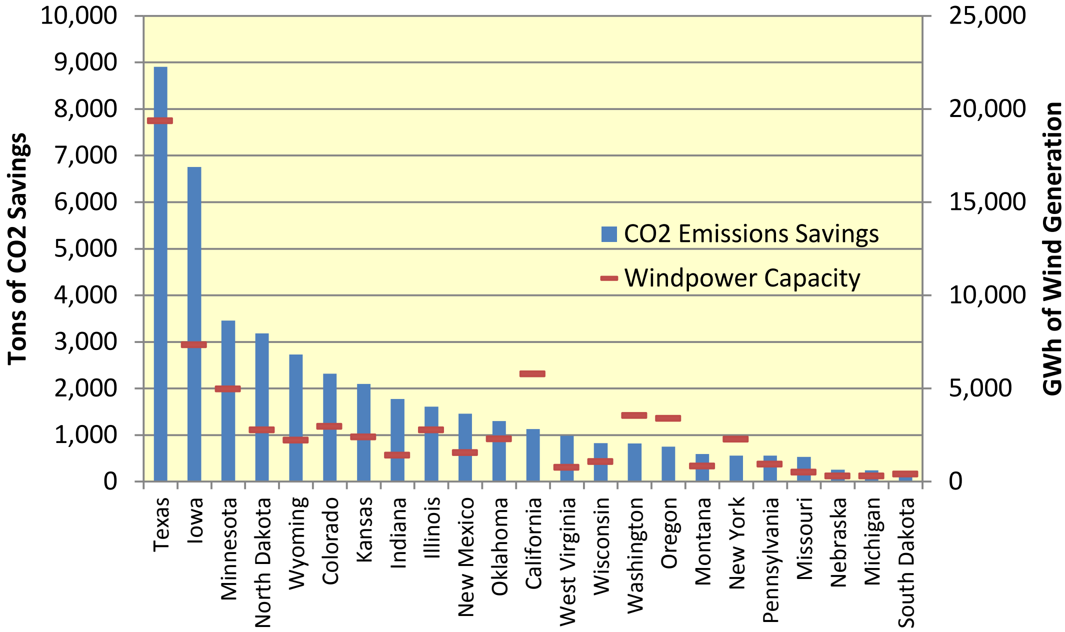
A sufficient amount of wind generation data for other balancing areas is unavailable. Nevertheless, the results from the four regions above allow for a reliable extrapolation of wind-induced emissions savings across the remaining U.S. states. Units of emissions savings per MWh are estimated for each state using the relationship developed in Figure VII-2 by using coal market share as the primary input.[23] Total wind generation data by state, which is provided by the EIA, is utilized in order to calculate total emissions savings and emissions savings rates.[24]

Figure VII-3 captures the actual estimated CO_2 emissions savings by state during 2009 based on the amount of wind generation and the coal market-share relationship developed in Figure VII-2. This data reflects both capacity utilization and wind resource availability by region.

[23] $E_{SO2} = 6.809C^2 + 0.769C + 0.034$, $E_{NOX} = 2.450C^2 + 0.134C + 0.36$, $E_{CO2} = 0.666C^2 + 0.537C + 0.19$

[24] (Department of Energy)

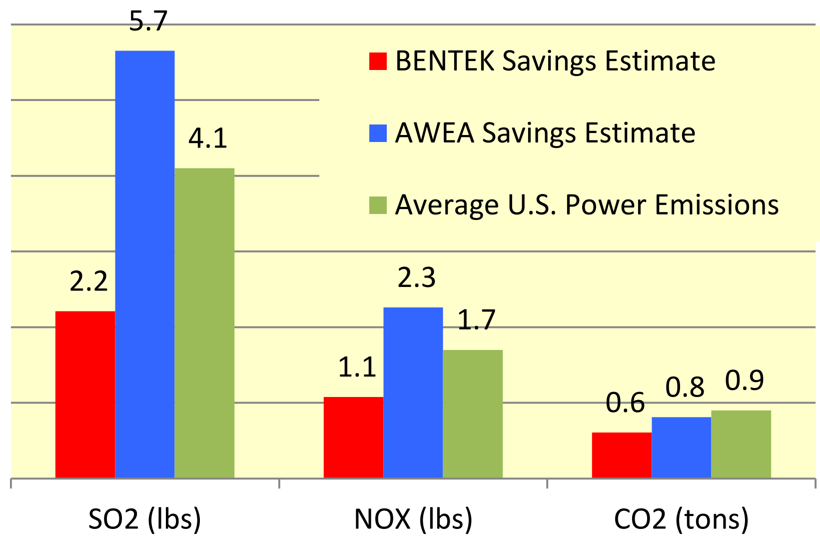
Figure VII-3: Actual CO_2 Emissions Savings by State & Total Wind Generation, 2009



Several conclusions can be drawn from Figure VII-3 where the blue bars indicate thousand tons of CO_2 savings and the red bars indicate GWh of wind generation by state in 2009. Even though total wind generation in Iowa was 62% less than Texas, total CO_2 savings were only 24% less. This is due to the market share of coal in Iowa being higher than in Texas. The same logic applies to California and Colorado - even though there is nearly twice as much wind generation in California than in Colorado, the CO_2 savings in California are half that of Colorado.

Using the approach from Figure VII-3 a U.S. CO_2 emissions savings rate can be derived. The calculation sums the total calculated avoided CO_2 emissions in Figure VII-3 and divides that value by total wind generation across the U.S. The output of this calculation is shown in Figure VII-4.

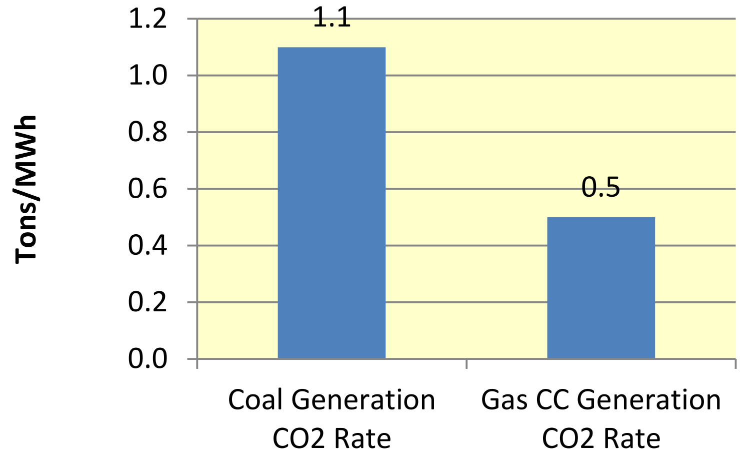
Figure VII-4: U.S. Emissions Savings per MWh of Wind Generation vs. Average U.S. Power Emissions



These results imply that CO_2, SO_2 and NO_x estimations from some previous studies are far above the actual savings rates. The national averages also mask the fact that emissions savings vary widely by region due to the type of generation in each region. Environmental planners must understand this as plans to meet emissions goals are outlined.

The CO_2 emissions reduction aspects of this study suggest that goals of environmental planners can be met through current generation technologies, including replacing coal-fired generation with natural gas. Based on actual emissions from coal and gas plants across the U.S., Figure VII-5 captures the average CO_2 emissions rate of coal-fired generation and natural gas-fired combined cycle generation.

Figure VII-5: CO_2 Emissions Rates of Coal and Natural Gas Combined Cycle Generation



The difference between the CO_2 emissions rate of coal and gas combined cycle facilities is 0.6 tons/MWh. Replacing coal-fired generation with natural gas combined cycle generation would result in the same CO_2 emissions savings rate as the national average for wind generation.

VIII. The Costs of Wind Generation

> *"Wind energy easily costs more than it yields, not only in monetary terms, but also in non-sustainable energy use and thus it will easily increase rather than decrease CO_2 emissions."*[25] *– K. de Groot & C. le Pair*

Although the emissions benefits from wind are quantifiable, the costs are more difficult to ascertain. In the end, ratepayers are paying for these costs either through federal or local tax mandates or electricity rate increases, often both. These costs need to be understood by policymakers who mandate the use of renewable energy and by the utilities that plan for the integration of these assets. According to the analysis conducted above, the emissions savings that result from using wind in the BPA, CAISO, ERCOT and MISO are minimal. The question addressed in this chapter is whether they are sufficient to justify their costs simply defined as the underlying Production Tax Credit offered by the federal government. Use of wind energy entails many other costs and these will be discussed in this chapter as well. However, conclusive data on these costs other than the Production Tax Credit is not available at this time.

Renewable Electricity Federal Production Tax Credit (PTC)

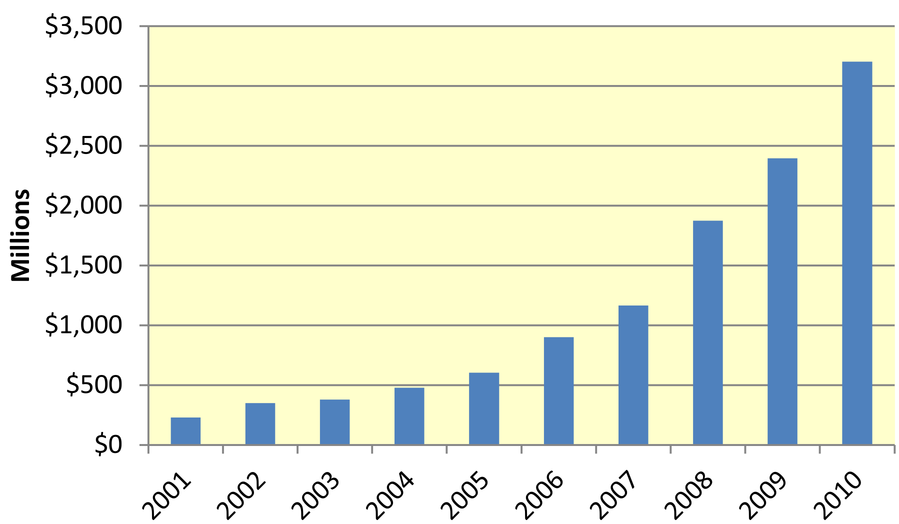
Federal mandates have encouraged the growth of the U.S. renewable energy sector through tax breaks and subsidies. One of the most influential mandates is the Renewable Electricity Federal Production Tax Credit (PTC). Enacted in 1992, this tax credit offers renewable operators tax credits for the amount of electricity generation on a per-unit basis. Wind, geothermal and closed-loop biomass generation facilities receive a tax credit of 2.2 cents per kWh generated ($22/MWh). Other eligible technologies receive 1.1 cents per kWh. This credit applies to both commercial and industrial sectors. In order to be eligible for the tax credit, operators must have begun construction of the facility before Dec. 31, 2013. Operators are compensated

[25] (Pair, 2009)

through this credit for the first 10 years after the date the facility goes into service.[26]

Monthly wind generation data from the EIA combined with the tax credit allows for a high-level understanding of the monthly cost to subsidize wind generation across the U.S. Figure VIII-1 shows this data on a monthly basis in millions of dollars. Since January 2001, wind generation operators have received a total of more than $11 billion in federally subsidized compensation. In the early stages of the program, monthly costs to the government were typically below $20 million and on an average basis ranged from $13 million to $22 million. By 2010, however, the program cost increased with a total annual expenditure of $3.2 billion. It is important to recognize that these costs build upon themselves because the subsidy extends for 10 years from the date the plant becomes operational.

Figure VIII-1: Annual Cost of Federal Production Tax Credit for Wind Generation



Implied Costs of Saving CO_2 through Wind Generation

Several legislative efforts over the past two years have attempted to limit the amount of CO_2 emissions from stationary sources and to create a market in which CO_2 can be traded. Recent efforts include the Waxman-Markey bill proposed by Reps. Henry Waxman (D-CA) and Ed Markey (D-MA). The bill was passed by the U.S. House of

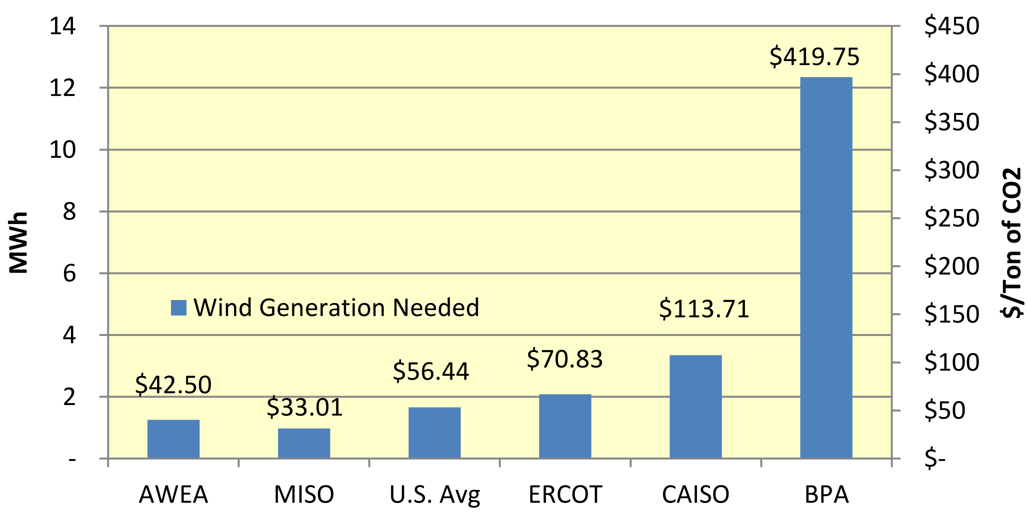
[26] (DSIRE, 2010)

Representatives in June 2009. Another bill was proposed by Sens. John Kerry (D-MA) and Joe Lieberman (I-CT). The goal of these legislative efforts was to reduce the amount of carbon emissions in the U.S. by imposing additional costs on carbon-intensive industries.

The cost per ton of carbon dioxide was also forecasted in these bills. Estimates suggested that one ton of CO_2 would likely be priced between $11-$15 in 2012 and $22-$28 in 2025. These rates would increase the cost of electricity, but would likely decrease the amount of CO_2 emitted annually by electricity generators. Our analysis shows the cost to reduce one ton of CO_2 through wind generation is significantly higher than the costs stipulated in the cap-and-trade legislative efforts.

Currently, the PTC offers a tax credit of $22 per MWh to wind generation operators. Because this is a tax credit, the true cost of the subsidy should be evaluated as pre-tax. To do this the $22/MWh value needs to be divided by one, minus the tax rate (35%), or 65%. The resulting pre-tax value of the production tax credit is ~$34 per MWh. If wind generation offsets 1 ton of CO_2 per MWh, then the cost of reducing CO_2 emissions by one ton is $34. In order to estimate the cost to reduce 1 ton of CO_2 with wind generation, the savings rate of CO_2 emissions in each territory is applied to the cost of the PTC. Figure VIII-2 captures this data for each region.

Figure VIII-2: Social Cost to Offset 1 Ton of C02 through Wind Generation



The cost to reduce one ton of CO_2 emissions in ERCOT through wind generation is $70. This drops to $33 in MISO, increases to $114 in CAISO and tops out at $420 in BPA. On average, the cost of offsetting CO_2 through the production tax credit is $56 per ton. These costs far exceed the costs per ton of CO_2 stipulated by any of the recent carbon cap legislation.

This analysis indicates that it is not cost-effective to reduce CO_2 emissions using wind generation if carbon is valued at the rates proposed by the Waxman-Markey legislation. Carbon must be valued 50-100% higher in MISO for wind power to be a cost-effective alternative. In BPA, carbon must be valued nearly 13 times higher than the 2025 maximum carbon price proposed in Waxman Markey for wind to be cost effective.

Other Wind Generation Cost Components

Several studies have cited numerous additional costs that are not generally quantified or discussed when calculating the cost of wind generation. The data to properly quantify these costs is not available to the public, and utilities are asking for rate increases to cover many of these unexpected costs.

- **Increased Maintenance Costs Due to Cycling.** Cycling coal and natural gas power units also impacts maintenance and other operating costs, in addition to efficiency degradation during operation. This is particularly damaging for coal plants, which are not designed to be cycled at a high rate and magnitude. The costs associated with cycling power plants in response to variable generation output from wind assets is not well understood by utilities currently integrating wind generation into their generation portfolios. It is widely understood that there is a positive, linear relationship between system costs and the frequency of unit cycling. The costs of integrating wind generation due to cycling will continue to rise, and the cost will likely be passed on to the ratepayer.

- **Fuel Costs Due to Backup Generation**. Many studies have noted the necessity of backup generation sources to allow for the unpredictable nature of wind generation. These backup sources are thermal facilities that are kept in standby mode in order to react within seconds to changes in wind generation. However, fuel is required to keep these resources available, thereby generating emissions to allow for wind generation (Beenstock,[27] Puga[28]). As wind generation capacity continues to increase, more backup generation assets will be needed to keep the grid in balance. While this likely will be a linear relationship, it is an incremental cost to wind generation.

- **Incremental Flexible Capacity Costs.** Flexible generation capacity is a necessity for wind generation operators that lack access to external electricity markets to purchase power in an on-demand scenario. PSCo in Colorado is increasingly finding itself in this situation. In testimony given in June 2008 to the Colorado Public Utilities Commission, Thomas Imbler, president of Commercial Operations for PSCo, noted that, "We may reach a saturation point in which additional wind turbines exceed the capacity of our thermal units to compensate for a rapid reduction in wind production."[29] In order to incorporate significant amounts of wind generation, PSCo believes that either current generation units will have to be altered to have higher ramping capabilities or new generation assets with high ramping abilities will have to be built in order to compensate for the variability in wind generation.

- **Negative Electricity Prices.** Volatile supply of any commodity creates volatile prices. This is happening in the West pricing zone of ERCOT as wind generation has been introduced. However, in this case, there is such oversupply that electricity prices actually go negative for long periods of time. Figure VIII-3 captures ERCOT's four pricing zones May 21-23, 2009, and the hourly wind generation that accompanied the pricing scenarios.

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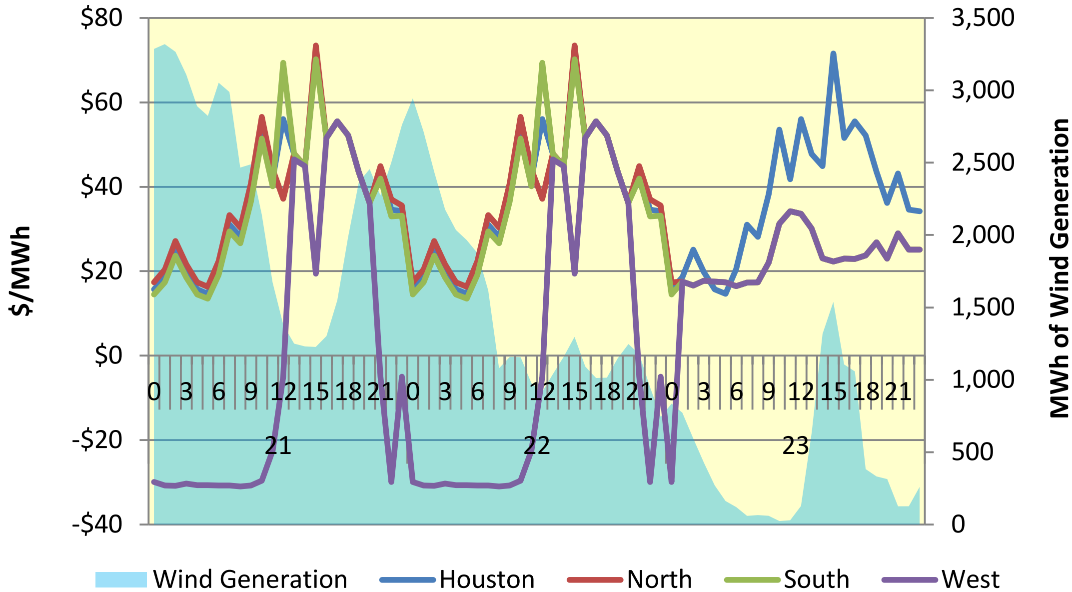
[27] (Beenstock, 1995)
[28] (Puga, 2010)
[29] (Rebuttal Testimony and Exhibits of Thomas A. Imbler on Behalf of Public Service Company of Colorado, 2008)

Figure VIII-3: Electricity Prices and Wind Generation in ERCOT, May 2009

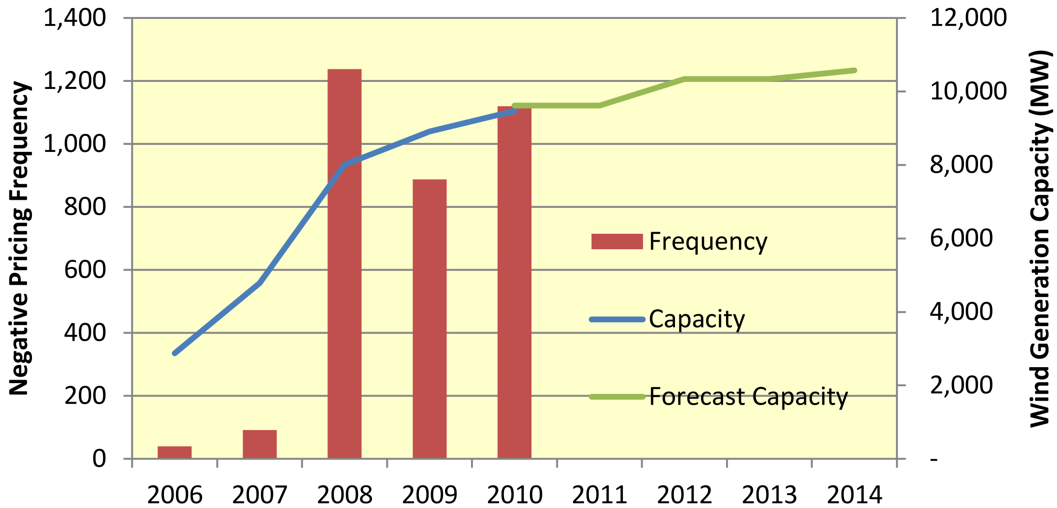


Supply of wind generation on May 21 and May 22 was at such high levels that it caused the West ERCOT pricing point to go negative. For hours at a time prices were sustainably near -$30/MWh. At one point on May 21, wind generation supply subsided, causing prices to return to a normal range. As wind generation died throughout May 22 and 23, West prices returned to a normal level, priced at parity with the North and South zones for the remainder of the time series.

Prices go negative because of the Federal Production Tax Credit that operators receive. Notice that the hourly settle price in the West does not deviate far from $30/MWh, which is the tax-free adjusted amount that wind generation operators receive per MWh.

The frequency of negative pricing increased as the installed capacity of wind generation rose between 2006 and 2010. Figure VIII-4 plots the number of hours when prices averaged less than $0.00/MWh at the ERCOT West pricing point on an annual basis. Installed wind generation capacity in ERCOT is also plotted.

Figure VIII-4: ERCOT West Negative Price Frequency vs. Installed Wind Capacity



As installed wind capacity rose between 2006 and 2010 so did the frequency of negative pricing occurrences. This should continue going forward and be more widespread because of the nodal market that is in place.

Negative prices do not support competitive markets. Quantifying the cost of this impact is difficult as it affects the entire ERCOT power system. Electricity prices in general are signals to consumers and investors. ERCOT will be challenged to attract potential generation asset investors with negative prices in the region. This is a signal to both wind farm and thermal plant builders that the ERCOT market may not be as profitable as once thought.

- **Transmission lines.** Typically, power generation sources are placed in areas where the units are able to serve certain local demand. However, as East Shore Partners notes, “Prime wind installation locations are also often far away from load centers (consumption areas), resulting in material incremental transmission construction costs for it to be utilized (as opposed to repowering existing, older facilities). At $4-$5 million per mile, or more, this represents a major incremental cost that would be mostly avoided if a utility were able to instead opt for repowering existing generation."[30] These costs would be massive for regions required to meet renewable energy standards but with few domestic resources available.

Even in states such as Texas, which has prolific wind resources, there are transmission problems. In a transmission study conducted in 2007, ERCOT found that, "The continued rapid increase in the installation of new wind generation in West Texas is expected to result in congestion on multiple constraints and West to North transfers until new bulk transmission lines are added between West Texas and the rest of the ERCOT system… Nearly all of the anticipated congestion in the West weather zone is associated with the massive increase in wind generation capacity in ERCOT." [31] Estimated costs for the transmission projects range between $2.95 billion for 12,053 MW of wind generation capacity and $6.38 billion for 24,859 MW of wind generation capacity.[32]

The costs per MWh for these transmission installations can be calculated. Assuming that the utilization rate of wind in ERCOT is 30% and there is a 20-year lifespan of the installed capacity:

> 12,053 MW * 30% utilization * 24 hours * 365 days * 20 years = 633,505,680 MWh of wind generation →$2,950,000,000/633,505,680 MWh = $4.66/MWh of wind
>
> 24,859 MW * 30% utilization * 24 hours * 365 days * 20 years = 1,306,589,040 MWh of wind generation →6,380,000,000/1,306,589,040 MWh = $4.88/MWh of wind

Between the low and high case for wind capacity and transmission costs, the incremental cost of wind generation due to transmission lines alone in ERCOT is between $4.66/MWh and $4.88/MWh.

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30 (East Shore Partners, Inc., 2010)
31 (ERCOT, 2007)
32 (ERCOT, 2008)

IX. Conclusion

The results of this study suggest that wind energy constitutes a significant paradox: Generation of power from wind, per se, yields no emissions. However, integration of wind power into a number of complex utility systems has led to little or no emissions reductions on those systems, and has significantly increased costs to power producers, grid operators and electricity consumers.

Several specific conclusions can be drawn from this research.

1. Utilities are forced to cycle coal and natural gas-fired generation capacity in order to accommodate intermittent wind generation. Cycling significantly decreases efficiency at the facilities, thereby increasing the emissions rates.

2. Emissions savings due to wind generation vary by territory and are heavily dependent on what type of fuel is being offset by wind generation. In the case of BPA, hydro generation is offset by wind generation. As there are no associated emissions with hydro, very little emissions are saved through wind generation in this area. An operating area where coal fuels a higher proportion of its generation base, such as MISO, achieves more emissions savings benefits by using more wind.

3. If a ton of carbon is valued at the levels associated with the legislation proposed by Waxman-Markey and Lieberman, none of the regions observed in this study saved enough CO_2 by substituting wind generation for hydrocarbon generation to achieve a positive per ton of carbon reduced cost. In all regions, placing a value equal to the Production Tax Credit of $22 per MWh produced on the generation needed to save one ton of CO_2, yields a total cost of carbon reduction well in excess of $50 per ton.

4. The same CO_2 benefits that wind generation currently achieves also can be met by re-firing coal facilities with natural gas. The difference in the CO_2 emissions rate between coal- and gas-fired facilities is the same as the actual emissions savings from

currently installed wind power across the nation, or about 0.6 tons/MWh CO_2. The economics and reliability of natural gas-fired generation suggest that achieving CO_2 emissions reductions through re-firing coal plants with natural gas is more favorable than using wind generation. Switching to gas avoids many of the costs associated with wind, including transmission, billions of dollars in tax credits, maintenance costs due to cycling and other variables mentioned above.

5. As natural gas market share continues to eat away at coal-fired generation, the potential emissions savings due to increased wind generation will decline. The convergence of low, stable natural gas prices, increasing coal costs and impending EPA environmental legislation that will tighten SO_2, NO_x, mercury and other emissions will increase the market share of natural gas-fired generation across the U.S. As this happens, total power generation-related emissions rates will decline. As the generation share associated with gas increases, the CO_2 savings associated with an incremental MWh of wind will decline and the cost of using wind to achieve the savings will increase. Wind will become an increasingly expensive way to reduce emissions.

6. It appears that many of the federal and state policy efforts to reduce CO_2 and other emissions from power plants are based on models that do not present an accurate picture of the cost of wind generation. The intermittent nature of wind energy causes utilities to cycle other hydrocarbon-based generation units, thereby reducing the savings potential from wind. Wind can only be an effective tool to reduce emissions if it is developed on a scale that enables it to become a baseload technology, and thus enables utilities to do away with their hydrocarbon-fueled capacity while producing reliable power for their customers.

   Policymakers must rely on results and analysis of actual emissions and other power data rather than on modeled estimates and assumptions. Making policy based on modeled data and assumptions hinders or prevents the energy industry from attaining clean air goals while also raising costs for energy consumers and power companies.

X. Works Cited

The works cited section contains publications which were helpful in both identifying the relationships presented herein and supporting conclusions drawn throughout the study.

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XI. APPENDIX

Table XI-1: NREL Estimated Potential Wind Turbine Capacity & Utilization Rate[33]

(NREL, Wind Potential 80M)	**Capacity (MW)**	**Utilization Rate**	**State**	**Capacity (MW)**	**Utilization Rate**
Alabama	118	32%	Nebraska	917,999	44%
Arizona	10,904	32%	Nevada	7,247	33%
Arkansas	9,200	33%	New Hampshire	2,135	36%
California	34,110	35%	New Jersey	132	32%
Colorado	387,220	38%	New Mexico	492,083	38%
Connecticut	27	31%	New York	25,781	33%
Delaware	10	31%	North Carolina	808	34%
Florida	0	32%	North Dakota	770,196	44%
Georgia	130	33%	Ohio	54,920	32%
Idaho	18,076	33%	Oklahoma	516,822	40%
Illinois	249,882	35%	Oregon	27,100	34%
Indiana	148,228	34%	Pennsylvania	3,307	33%
Iowa	570,714	41%	Rhode Island	47	37%
Kansas	952,371	44%	South Carolina	185	31%
Kentucky	61	33%	South Dakota	882,412	44%
Louisiana	410	31%	Tennessee	309	33%
Maine	11,251	34%	Texas	1,901,530	39%
Maryland	1,483	33%	Utah	13,104	32%
Massachusetts	1,028	37%	Vermont	2,949	35%
Michigan	59,042	33%	Virginia	1,793	34%
Minnesota	489,271	39%	Washington	18,479	34%
Mississippi	0	N/A	West Virginia	1,883	35%
Missouri	274,355	34%	Wisconsin	103,757	33%
Montana	944,004	32%	Wyoming	552,073	40%
U.S. Total	**10,458,945**	**40%**			

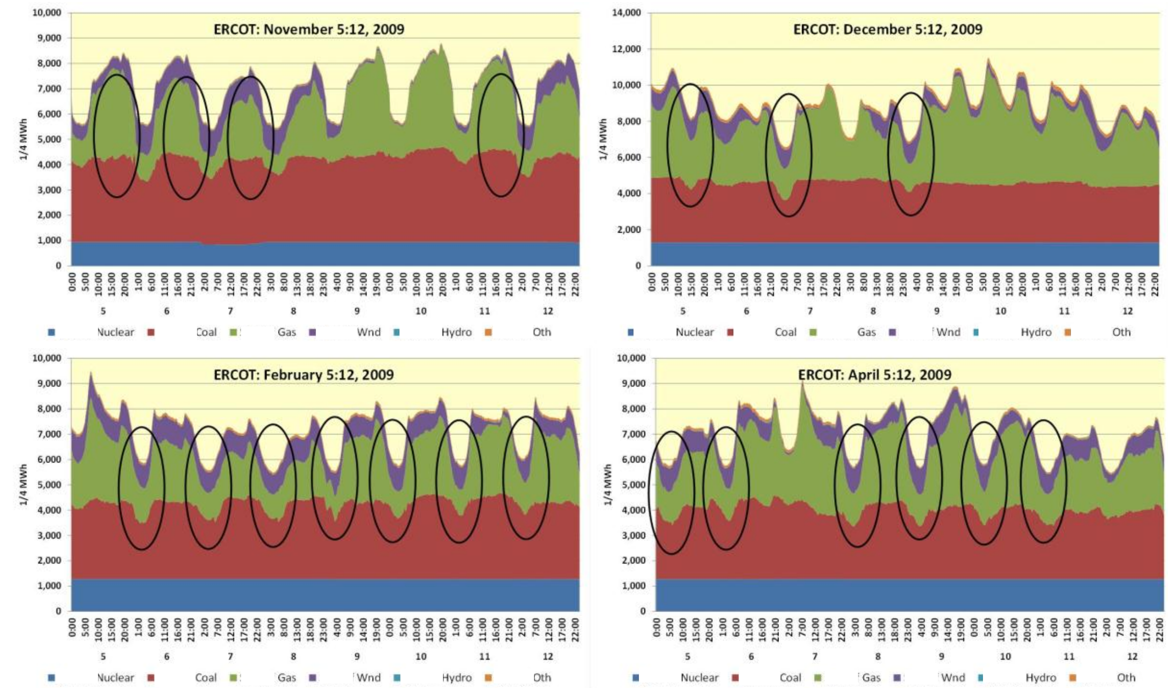
[33] (NREL, Wind Potential 80M)

Table XI-2: Renewable Portfolio Standards by State[34]

State	Amount	Year	State	Amount	Year
Arizona	15%	2025	New Jersey	22.50%	2021
California	33%	2020	New Mexico	20%	2020
Colorado	20%	2020	Nevada	20%	2015
Connecticut	23%	2020	New York	24%	2013
District of Columbia	20%	2020	North Carolina	12.50%	2021
Delaware	20%	2019	North Dakota*	10%	2015
Hawaii	20%	2020	Oregon	25%	2025
Illinois	25%	2025	Pennsylvania	8%	2020
Massachusetts	15%	2020	Rhode Island	16%	2019
Maryland	20%	2022	South Dakota*	10%	2015
Maine	40%	2017	Texas	10,000 MW	2025
Michigan	10%	2015	Utah*	20%	2025
Minnesota	25%	2025	Vermont*	10%	2013
Missouri	15%	2021	Virginia*	12%	2022
Montana	15%	2015	Washington	15%	2020
New Hampshire	23.80%	2025	Wisconsin	10%	2015

34 (Energy, States with Renewable Portfolio Standards)

Figure XI-1: ERCOT Wind Days



Equation 1: Emissions Model

The explanation below is adopted from Kaffine, McBee, Lieskovsky (2011):

The model presented below captures the relationship between total emissions *Eirt* of pollutant *i* in territory *r* at hour *t* against the total hourly wind generation *Wrt* (in MWh), average hourly temperature *Trt* and its square *T²rt*, and a vector of other control variables *Xt:*

$$E_{irt} = \alpha_{ir} + \beta_{ir} W_{rt} + \gamma_{1ir} T_{rt} + \gamma_{2ir} T_{rt}^2 + \delta_{ir} X_t + \epsilon_{irt}.$$

Bir, the coefficient of interest, captures the marginal change in emissions in each territory due to wind generation. This coefficient captures the amount of emissions reduces in pounds/pounds/tons for SO2, NOX and CO2 for each MWh of wind generation in a given territory.

Other control variables need to be introduced in order to account for ongoing trends throughout the study period which, if left unaccounted, would result in an erroneous interpretation of *Bir*. Temperature is a strong representative of total load, which can impact the amount of wind generation allowed onto a system. Additionally, day of week and monthly fixed effects are introduced to account for changes of which temperature may represent total load. Hourly fixed effects are included to represent both differences of load during a given day (at a given temperature) and to account of the diurnal wind variation over the course of the day. On average, wind generation is strongest in the early morning hours when electricity demand and emissions are lowest.

Month-year fixed effects are included to account for changes in wind generation capacity throughout the study timeframe.

Table XI-3: Estimation Results for Emissions Reductions from Wind Generation by Territory

Territory	ERCOT			MISO			CAISO			BPA		
Pollutant	SO_2 (lbs)	NOX (lbs)	CO_2 (tons)	SO_2 (lbs)	NOX (lbs)	CO_2 (tons)	SO_2 (lbs)	NOX (lbs)	CO_2 (tons)	SO_2 (lbs)	NOX (lbs)	CO_2 (tons)
Wind (MWh)	1.235**	-0.739**	-0.484**	-4.8900**	-1.995**	-1.025**	-0.008	-0.054*	-0.299**	-0.059*	-0.170*	-0.08**
	(0.183)	(0.042)	(0.029)	(0.924)	(0.280)	(0.103)	(0.007)	(0.027)	(0.074)	(0.008)	(0.055)	0.026**
Temp (F)	-814.1**	1226**	-798.6**	5670**	-1897**	-810.8**	-15.79**	-126.7**	-473.0**	-11.5*	-9.99*	-32.8***
	(94.42)	(25.20)	(12.98)	(339.7)	(154.0)	(51.58)	(6.747)	(22.53)	(47.00)	26.0	15.0	6.23***
$Temp^2$	6.564**	10.39**	6.692**	63.04**	19.00**	9.115**	0.122**	1.164**	4.213**	0.213*	0.124*'	0.320***
	(0.742)	(0.204)	(0.107)	(3.775)	(1.501)	(0.569)	(0.047)	(0.202)	(0.424)	(0.29)	(0.13)	0.051***
Hour FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Month-Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
DOW FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	26280	26280	26280	15520	15520	15520	8760	8760	8760	17,464	17,464	17,464
R^2	0.63	0.82	0.92	0.87	0.95	0.88	0.12	0.43	0.8	0.08	0.72	0.85

Table 4: National Emissions Savings 2009

	Coal	Wind Gen	Emission Savings Rate			Total Emission Savings		
	Share %	(MWh)	SO2	NOX	CO2	SO2	NOX	CO2
Alabama	0.39	0	1.358	0.776	0.499	0	0	0
Alaska	0.09	3,062	0.166	0.389	0.246	0	1	1
Arizona	0.44	9,555	1.666	0.88	0.551	16	8	5
Arkansas	0.35	0	1.162	0.711	0.464	0	0	0
California	0.01	5,764,637	0.042	0.357	0.195	241	2,055	1,127
Colorado	0.63	2,942,133	3.179	1.398	0.787	9,354	4,113	2,315
Connecticut	0.08	0	0.136	0.381	0.236	0	0	0
Delaware	0.59	0	2.842	1.282	0.737	0	0	0
Florida	0.25	0	0.642	0.539	0.364	0	0	0
Georgia	0.54	0	2.433	1.141	0.674	0	0	0
Hawaii	0.14	213,224	0.265	0.419	0.276	56	89	59
Idaho	0.01	227,028	0.039	0.356	0.193	9	81	44
Illinois	0.46	2,761,152	1.856	0.945	0.583	5,126	2,609	1,609
Indiana	0.93	1,403,192	6.615	2.591	1.263	9,282	3,636	1,771
Iowa	0.72	7,331,391	4.119	1.723	0.922	30,198	12,629	6,756
Kansas	0.69	2,385,107	3.813	1.617	0.879	9,094	3,856	2,096
Kentucky	0.93	0	6.6	2.586	1.261	0	0	0
Louisiana	0.25	0	0.666	0.546	0.369	0	0	0
Maine	0	260,121	0.037	0.356	0.192	10	93	50
Maryland	0.55	0	2.532	1.175	0.689	0	0	0
Massachusetts	0.27	3,798	0.72	0.564	0.38	3	2	1
Michigan	0.66	289,188	3.512	1.513	0.835	1,016	437	242
Minnesota	0.56	4,956,987	2.588	1.195	0.698	12,830	5,922	3,460
Mississippi	0.26	0	0.72	0.564	0.38	0	0	0
Missouri	0.81	498,515	5.129	2.073	1.063	2,557	1,034	530
Montana	0.58	810,815	2.808	1.27	0.731	2,277	1,030	594
Nebraska	0.69	288,681	3.772	1.602	0.873	1,089	463	252
Nevada	0.2	0	0.459	0.48	0.324	0	0	0
New Hampshire	0.14	28,466	0.283	0.424	0.281	8	12	8
New Jersey	0.08	19,150	0.143	0.383	0.239	3	7	5
New Mexico	0.73	1,543,715	4.265	1.773	0.943	6,584	2,737	1,456
New York	0.1	2,258,904	0.17	0.39	0.248	383	882	559
North Carolina	0.55	0	2.513	1.169	0.687	0	0	0
North Dakota	0.87	2,756,289	5.803	2.308	1.154	15,994	6,361	3,182
Ohio	0.84	15,474	5.429	2.178	1.104	84	34	17
Oklahoma	0.45	2,271,590	1.784	0.92	0.571	4,052	2,090	1,297
Oregon	0.06	3,372,284	0.098	0.37	0.222	332	1,249	750
Pennsylvania	0.48	921,137	1.975	0.985	0.602	1,819	907	555
Rhode Island	0	0	0.034	0.355	0.19	0	0	0
South Carolina	0.34	0	1.105	0.692	0.454	0	0	0
South Dakota	0.39	392,308	1.384	0.785	0.504	543	308	198
Tennessee	0.52	51,747	2.292	1.093	0.652	119	57	34
Texas	0.35	19,350,879	1.141	0.703	0.46	22,070	13,611	8,909
Utah	0.82	64,497	5.193	2.095	1.072	335	135	69
Vermont	0	11,589	0.034	0.355	0.19	0	4	2
Virginia	0.37	0	1.223	0.731	0.475	0	0	0
Washington	0.07	3,538,936	0.123	0.377	0.232	437	1,335	821
West Virginia	0.96	742,439	7.071	2.751	1.323	5,250	2,042	982
Wisconsin	0.62	1,059,126	3.143	1.386	0.782	3,329	1,467	828
Wyoming	0.91	2,213,820	6.39	2.513	1.233	14,147	5,563	2,729
United States	0.44	70,760,936	2.242	1.086	0.612	158,649	76,858	43,318

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