Emissions savings from wind power generation: Evidence from Texas, California and the Upper Midwest*

Daniel T. Kaffine[†], Brannin J. McBee[‡], and Jozef Lieskovsky[§]

May 2011

Abstract

Wind power has the potential to reduce emissions associated with conventional electricity generation. Using detailed, systemic hourly data of wind generation and emissions from plants in ERCOT (Texas), CAISO (California), and MISO (Upper Midwest), we estimate the SO_2, NO_x and CO_2 emissions offset by wind generation in those territories. Our estimation strategy implicitly captures both the marginal unit of generation displaced by wind on the electrical grid, and the marginal emissions reduction from that displaced unit. Our results reveal substantial variation in emissions reduction by territory, which appear to be strongly driven by differences in the existing generation mix. While the environmental benefits from emissions reductions in the Upper Midwest roughly cover government subsidies for wind generation, environmental benefits in Texas and California fall short. Finally, we provide back-of-the-envelope calculations for the average national reductions in emissions per megawatt-hour of wind energy.

*We thank Bentek Energy for collection and organization of several data sources used. George Taylor, Mark Lively, Yahya Anouti, Tom Tanton, and CSM Seminar participants provided useful comments and corrections. All remaining errors are our own.

†Assistant Professor, Division of Economics and Business, Colorado School of Mines, 329 Engineering Hall, Golden CO, 80401; corresponding author (tel. 303.384.2430 e-mail: dkaffine@mines.edu).

‡Energy Analyst, Research and Development, Bentek Energy LLC, bmcbee@bentekenergy.com

§Director of Research, Research and Development, Bentek Energy LLC, jlieskovsky@bentekenergy.com

1 Introduction

Production of electricity from wind energy has risen rapidly in the last decade, with installed capacity doubling every three years in the United States (World Wind Energy Association 2009) and wind generation accounting for 2% of world consumption. As of 2009, the United States, China and Germany were the world leaders in installed wind power generation capacity, with 35 gigawatts (GW), 26 GW and 26 GW of capacity respectively, with another 50 GW of capacity installed across the European Union. Technological advances in wind turbine design, control and siting have led to falling costs per megawatt-hour (MWh) and increased the penetration of wind energy into the power sector. In addition, government subsidies and policies have also played an important role in encouraging wind power production. For example, in the United States, a majority of states have implemented Renewable Portfolio Standards mandating that a percentage of total state electricity generation be derived from renewable sources, and the federal government provides a Production Tax Credit of $22 dollars per MWh to wind power producers.

Government support for wind power development is primarily predicated on the environmental benefits of avoided emissions, such as sulphur dioxide (SO_2), nitrogen oxides (NO_x), and carbon dioxide (CO_2). It is these avoided emissions that form the focus of our study.[1] In particular we ask, what is the emissions savings rate for SO_2, NO_x and CO_2 per MWh of wind power produced, and how does that savings rate vary across regions with different

[1] Clearly there are other considerations beyond emission savings that can influence the nature and degree of government intervention in energy markets. For example, negative externalities from upstream production activities or reliability costs associated with accommodating wind's volatility on the grid (Bonneville Power Authority (BPA) has introduced a 0.6 cents/MWh wind integration charge).

existing generation mixes? To answer these questions, we consider more than 50,000 hourly observations of wind generation and emissions from the territories of the Electric Reliability Council of Texas (ERCOT), California Independent System Operator (CAISO) and the Midwest Independent System Operator (MISO).

Electricity generation in the United States relies heavily on fossil fuel sources. As of 2010, coal accounts for 44% of total generation while natural gas accounts for 25% of total generation, compared to 18% for nuclear, 8% for hydropower, 2% for wind power, and $< 1\%$ each for solar, geothermal and biomass.[2] Average emission rates in the United states for coal-based generation are 13 lbs/MWh of SO_2, 6.0 lbs/MWh of NO_x, and 1.1 tons/MWh of CO_2; average emission rates for natural gas-based generation are substantially below those of coal, at 0.10 lbs/MWh of SO_2, 1.7 lbs/MWh of NO_x, and 0.57 tons/MWh of CO_2.[3] If a MWh of wind replaced a MWh proportional to the US generation mix, emissions of 5.7 lbs of SO_2, 3 lbs of NO_x and 0.63 tons of CO_2 would be avoided under average emission rates.

However, there is reason to believe that calculating the emissions savings from wind by replacing an average unit of generation and using average emission rates is an incorrect methodology. Several studies have noted that wind energy requires backup generation, such as gas, to account for the intermittency of stochastic wind power generation (Beenstock 1995; Puga 2010) even at low levels of wind penetration (Decarolis and Keith 2006).[4]

[2] From Energy Information Administration (EIA) http://www.eia.doe.gov/cneaf/ electricity/epm/tablees1a.html. Percentages do not sum to 100% due to independent rounding.

[3] From U.S. EPA, eGRID 2000 (http://www.epa.gov/cleanenergy/energy-and-you/affect/air-emissions.html). It should be noted that average emission rates can vary substantially by region and by plant.

[4] The stochastic nature of wind itself is exacerbated by the fact that wind power generation is proportional to the *cube* of wind speed. Thus a doubling/halving of wind speed leads to an eightfold increase/decrease in generation.

Other studies have considered the use of hydropower (Benitez et al. 2008) or compressed air storage (Decarolis and Keith 2006; Denholm et al. 2005; Sioshansi 2011) as non-fossil backup generation when wind power production declines. Back-of-the-envelope calculations by Lang (2009) incorporating emissions from natural gas backup generation suggest that CO_2 emissions savings may be very small (less than 0.1 tons/MWh).

In addition to concerns about backup generation, other studies have stressed the fact that rather than displacing a representative unit of power generation, wind is likely to displace generation from higher marginal cost sources that can easily accommodate wind power on the grid - most likely natural gas. Moore et al. (2010) stress the importance of the emissions profile of the marginal power plant in terms of measuring emissions savings, while Campbell (2009) presents a theoretical exercise and notes that emissions may increase if wind intermittency leads to increases in carbon-intensive accommodating sources. In a careful econometric study, Cullen (2010) uses plant-level generation data from ERCOT 2005-2007 to estimate the marginal change in generation at each plant per MWh of wind generated in ERCOT. He finds that for every 1 MWh of wind power generated, 0.72 MWh of gas and 0.28 MWh of coal are displaced.[5] Applying average plant emission rates to the marginal change in generation by plant, Cullen calculates that 3.15 lbs of SO_2, 1.05 lbs of NO_x, and 0.79 tons of CO_2 were avoided per MWh of wind power.

Yet, average plant emission rates may not appropriately reflect the actual emissions savings from wind generation. Liik et al. (2003) raise the concern that rapid ramping of fossil fuel plants (known as cycling) to accommodate wind is emissions-intensive, implying that

[5] By contrast, the mix of generation in ERCOT is 47% gas and 38% coal during the 2005-2007 time period.

marginal emission rates are the appropriate measure of emissions savings. Their operations research simulation model suggests that emissions savings may be completely eroded in some scenarios due to cycling-related emissions. A recent study by Bentek Energy LLC (2010) raises similar concerns about emissions associated with cycling. Engineering simulations of gas turbines in Katzenstein and Apt (2009) find that while 80% of hypothetical CO_2 savings can be achieved, only 30-50% of expected NO_x savings will be realized due to cycling.

These concerns have even led some to claim that wind power produces no emissions savings. For example, Michael J. Trebilcock states: “There is no evidence that industrial wind power is likely to have a significant impact on carbon emissions.” (Trebilcock 2009). Given the widely varying assumptions and findings in the papers above, there is clearly a need for a careful analysis of actual changes in emissions associated with wind generation. Such an analysis must capture both the marginal unit of generation displaced by wind as well as the marginal emissions from that displaced generation. This study helps to fill this crucial gap in the literature, and provides emission savings estimates based on large sample empirical data that will be of use to policymakers and future researchers.

Our study is in line with two recent economics papers (Callaway and Fowlie 2009; Novan 2010) that stress the fact that emissions savings are unlikely to be constant over space, time, or even at a single plant, and therefore methods that rely on assuming average or constant emissions savings are likely to be incorrect.[6] Callaway and Fowlie (2009) use observed CO_2 emissions and generation to identify the marginal operation emissions rate (MOER) in New England and New York from 2004-2007. This MOER represents the predicted amount of

[6] Both Callaway and Fowlie (2009) and Novan (2010) provide useful reviews of the existing emission savings estimation strategies and their limitations. Briefly, these can be grouped into average emission methods, dispatch model methods, and load following methods.

CO_2 that would be offset by a MWh of wind power; they find substantial variation in the MOER over the course of the day.[7] Building on Callaway and Fowlie (2009), Novan (2010) develops a theoretical model demonstrating that subsidies correlated with emissions savings will induce more efficient siting decisions by wind farm developers than the current policy of production subsidies. As this result is driven by the fact that emissions savings per unit of production are not constant, he estimates emissions savings in ERCOT to highlight the variability in emission savings rates even within a single territory. In particular, he shows that emissions savings per unit of wind power vary considerably with the load level, due to the fact that at low levels of load, coal is the marginal fuel, while at high levels of load, gas is the marginal fuel.

Building on the insights from Cullen (2010), Callaway and Fowlie (2009) and Novan (2010), we estimate the emissions savings from wind generation across several Independent System Operator (ISO) territories in the United States. We exploit exogenous variation in hourly wind generation levels to identify the effect of wind generation on total hourly emissions of SO_2, NO_x, and CO_2. Thus, our reduced-form estimation implicitly captures both the marginal unit of generation displaced by wind, as well as the marginal emissions reduction from that unit. In total, our rich data set contains over 50,000 hourly measurements of wind generation and emissions across Texas, California, and the Upper Midwest. We

[7] It should be noted that Callaway and Fowlie (2009) do not have actual wind generation data for New York and New England. Mesoscale climate modeling is used to produce wind speed profiles which are then used to predict wind generation. This spatial and temporal wind generation in turn is mapped against the estimated MOER to predict emission reductions. A key assumption of this approach is that a change in wind power is equivalent to an equal and opposite change in demand, which is likely to be true when variation in wind generation is roughly in line with variation in demand. This assumption may be strained as wind capacities increase and the potential for increasingly large variation in wind generation increases the aggressiveness of cycling to accommodate intermittency.

focus on ERCOT 2007-2009 (Texas), CAISO 2009 (California), and MISO 2008-2009 (Upper Midwest) for two reasons: first, they contain a significant portion (roughly 60%) of total wind capacity and generation in the United States, and second, these territories vary substantially in terms of their existing fossil fuel generation mix. MISO's generation is dominated by coal, CAISO's generation is dominated by gas, and ERCOT's generation is roughly an even mix of both. This variation in existing generation will prove crucial in determining the emissions savings from wind generation in each territory.

We find that emissions savings across territories are less than the hypothetical savings based on average emission rate analysis. Nonetheless we do find that emissions savings from wind generation are statistically different than zero for most pollutants and vary substantially across territories. In coal dominated MISO, we find emissions savings of 4.9 lbs/MWh for SO_2, 2 lbs/MWh for NO_x, and 1 ton/MWh for CO_2. By contrast in CAISO, where wind typically offsets gas generation, we find emissions savings of 0.0 lbs/MWh for SO_2, 0.05 lbs/MWh for NO_x, and 0.3 tons/MWh for CO_2. Generation in ERCOT is roughly evenly balanced between coal and gas, and we find that emission savings in ERCOT fall in between MISO and CAISO, with emissions savings of 1.2 lbs/MWh for SO_2, 0.7 lbs/MWh for NO_x, and 0.5 tons/MWh for CO_2. These results suggest that emissions savings are strongly driven by differences in existing generation mix - coal-intensive territories experience larger reductions in emissions due to wind generation.

Consistent with Novan (2010), hour-by-hour estimates of emissions savings also vary substantially by time of day, as the generation mix and operation within a territory change over the course of a day. This further confirms the importance of considering the marginal unit of generation displaced by wind and highlights the fact that average emission rates are an inappropriate measure of emission savings. We note that while the emission savings benefits of wind power are roughly equal to the PTC subsidy in MISO, benefits fail to cover the subsidy in ERCOT and CAISO. Finally, based on the relationship between emissions savings rates and coal-shares in ERCOT, MISO and CAISO, we provide back-of-the-envelope calculations of predicted national average emissions savings in the US.

2 Accommodating wind on the electricity grid

In contrast to other goods, electricity requires instantaneous matching of supply and demand. As a general rule, lower marginal cost sources of generation (coal and nuclear) are utilized by the grid first, followed by higher marginal cost sources (typically gas) as the load increases.[8] While requiring substantial initial capital investment, wind is a near-zero marginal cost source of generation, and electricity generated by wind power is almost always taken by the grid when available. As a result, intermittent production of wind power requires rapid adjustment of fossil generation in response to increases or decreases in wind generation. Figure 1 displays the ERCOT generation mix from November 5th through November 12th in 2008. This figure reveals substantial variation in wind power produced at any given point in time. During high load periods (middle of the day), substantial gas generation is online, and variation in wind power is accommodated by gas cycling. By contrast, during low load periods (overnight), limited gas generation is available, and variation in wind power is accommodated by coal cycling (as evidenced by the drop in coal generation relative to the

[8] It should be noted that coal and nuclear generation are designed to operate at a relatively constant level of output to meet baseload demand. Peak demand is frequently met by gas generators which are designed to operate at more variable levels of output and can be cycled quickly.

base level output during periods of large overnight wind generation).

A key contribution of Cullen (2010) (and echoed in Callaway and Fowlie (2009) and Novan (2010)) is recognizing that the unit of generation used to accommodate wind is not a proportional unit of the generation mix, which, given the heterogeneity in emissions by generation source, will have important implications for emissions savings. So while gas and coal represent 43% and 37% of actual generation in ERCOT, Cullen (2010) finds that wind power is accommodated primarily by gas, 72%, with the remainder, 28%, accommodated by coal. In other words, for every MWh of wind power that is supplied to the grid, on average 0.72 MWh of gas and 0.28 MWh of coal is taken off the grid. Accounting for this marginal unit of accommodation is crucial, as the environmental profile of average coal and gas generation are very different, with coal producing ten times as much NO_x, over twice as much CO_2, and vastly more SO_2. In sum, the marginal unit of accommodation does not equal the average unit of generation - a crucial feature that any estimation strategy of emissions must account for.

It is also important to account for the marginal emissions associated with the unit of generation displaced by wind power. As noted in Liik et al. (2003), the ramping up and down of gas and coal generation in response to stochastic variation in wind generation effectively increases the emissions per MWh from coal and gas. Just as automobiles are most fuel-efficient (and thus have the least emissions-per-mile) when driven steadily at approximately 55 mph, coal-fired and gas-fired plants will have lower emission rates when operated steadily at their designed level of output. Thus, as seen in figure 1, when coal plants are cycled down to accommodate wind, those plants will be operating at an inefficient level of output, raising emissions rates. Therefore, while Cullen (2010) captures the marginal unit of generation used to accommodate wind, the reliance on average emission rates from that accommodating unit may overestimate the emissions savings from wind generation. By contrast, our study (as well as Callaway and Fowlie (2009) and Novan (2010)) captures the feature that marginal emissions saved per MWh of wind generation is unlikely to be equal to the average emissions for the accommodating unit of generation.

3 Data

Our dataset consists of over 50,000 hourly observations of total wind generation in MWh and total emissions in pounds of SO_2 and NO_x and tons of CO_2 in ERCOT (2007-2009), MISO (2008-2009), and CAISO (2009). When properly identified, changes in aggregate wind generation can be causally linked to changes in aggregate SO_2, NO_x and CO_2 emissions within each territory.

3.1 Emissions

Hourly emissions data is sourced from the Environmental Protection Agency's (EPA) Continuous Emission Monitoring Systems (CEMS) program, which requires coal and gas power units with over 25 MW of capacity to submit hourly data on SO_2, NO_x and CO_2 emissions.[9] These emission reports are required by the EPA to monitor compliance with emission regulations, and strict quality assurance standards are in place to guarantee the accuracy of

[9] Units subject to CEMS requirements are mandated to report continuous hourly emissions based on either direct gas measurements or continuous fuel feed monitoring and mass balance calculations.

emission measurements.[10] However, emissions per territory are not explicitly reported under CEMS. To determine which units operated in a given area, each unit is spatially referenced using latitude/longitude against the spatial footprint of each operating territory, obtained through the operating territory's website. Units that fall under the spatial footprint of the territory are assumed to provide generation to the corresponding territory and the emissions from that plant are included in the territory's total emissions. Thus, an observation consists of the total hourly emissions of each pollutant by territory, representing the sum of emissions from all units.

3.2 Wind generation

The hourly wind generation data is acquired from each operating territory (ERCOT, MISO, CAISO) and represents total electricity generation from wind turbines operating in the territory. This publicly available data, directly reported by the operating territory, is posted on the operators' websites.[11] It should be noted that the availability of hourly wind generation data is the primary limiting factor of our analysis, both in terms of the time period and territories over which data is available. Wind generation data is available for ERCOT from 2007, for MISO from 2008, and for CAISO from 2009. We collected this

[10] For example, under the Acid Rain Program, reported SO_2 emissions by plant are checked against allowance holdings. See http://www.epa.gov/airmarkt/emissions/continuous-factsheet.html for further details on CEMS. While CO_2 is currently an unregulated pollutant, units are still required to submit hourly CO_2 emission data.

[11] ERCOT wind generation data is available at http://planning.ercot.com/data/hourly-windoutput/, MISO wind generation data is available at http://www.midwestmarket.org/publish/Folder/25228f_10631e11216_-7fe30a48324a, and CAISO wind generation data is available at http://www.caiso.com/1817/181783ae9a90.html.

data for each of these three territories through December 31st, 2009.[12] The 50,000 hourly observations of wind generation in our dataset thus provide a detailed look at actual wind generation levels across the three territories. Furthermore, the three territories we study account for over 60% of total wind capacity and generation in the United States.

3.3 Temperatures

Temperature is a key determinant of electricity demand and thus emissions (Valor et al. 2001). Temperature data for all territories is taken from the National Oceanic and Atmospheric Administration's (NOAA) hourly temperature database, which is available through subscription to NOAA's hourly surface data. A population-weighted average is created for each operating territory utilizing the major population centers within the territory's footprint. These average hourly temperatures are used throughout the analysis.

3.4 Summary statistics

Table 1 reports summary statistics regarding hourly emissions, wind generation and temperature for ERCOT, MISO and CAISO over the years of available data for each territory. During the 2007-2009 period, average yearly total generation in ERCOT was 306.3 million MWh, with wind power representing 4.7% of total generation. Coal accounted for 37% of

[12] In addition, hourly wind generation data was obtained from the Bonneville Power Authority (http://www.bpa.gov/corporate/WindPower) for 2008-2009, and from the Public Service Company of Colorado (PSCO) for January 2009. However, BPA frequently exports wind generation to neighboring territories, significantly complicating efforts to estimate emissions reductions. PSCO does not publicly provide wind generation reports, and the January 2009 values were captured from a graph via image processing. Despite the limitations of these two datasets, analysis was performed on these territories as robustness checks of our results for MISO, ERCOT and CAISO.

total generation and gas accounted for 43% of generation. ERCOT average emission rates across all forms of generation was 2.63 lbs/MWh for SO_2, 0.72 lbs/MWh for NO_x, and 0.64 tons/MWh for CO_2.

During the 2008-2009 period, average annual total generation in MISO was 566.2 million MWh, with wind power representing 2% of total generation. MISO relies primarily on coal generation with 80% of total generation coming from coal and only 2.7% from gas. In coal-dominated MISO, average emission rates are substantially higher than in ERCOT, at 5.74 lbs/MWh for SO_2, 2.15 lbs/MWh for NO_x, and 0.86 tons/MWh for CO_2.

In 2009, total generation in CAISO was 178.6 million MWh, with wind power accounting for 3.2% of total generation.[13] CAISO has no coal plants in their territory, while 35% of total generation came from gas. Due to the lack of coal plants, average emission rates in CAISO were much cleaner than ERCOT or MISO, at 0.00 lbs/MWh for SO_2, 0.37 lbs/MWh for NO_x, and 0.16 tons/MWh for CO_2. The heterogeneity in emission rates and generation sources across these three territories will prove important in understanding the emission savings from wind emissions.

4 Empirical strategy

Our identification strategy hinges on exploiting the exogenous and stochastic variation in hourly wind power generation. The reduced-form model presented below captures the systematic response of conventional generation (and thus emissions) to hourly fluctuations in

[13] It should be noted that this measure of total generation, as reported by CAISO, also includes net imports, which constitute over a quarter of the reported total generation. The total generation reported above for ERCOT and MISO also include net imports, though they are much smaller as a percentage than CAISO (1% and 5% respectively).

wind generation. Total emissions E_{irt} of pollutant i in territory r at hour t are separately regressed by territory against total hourly wind generation in each territory W_{rt} (in MWh), average hourly temperature T_{rt} and its square T_{rt}^2 in each territory, and a vector of other control variables X_t:

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

The coefficient of interest is β_{ir}, which represents the marginal change in emissions in each territory due to a change in wind generation.[14] Thus, for every MWh of wind generation produced in hour t in territory r, this coefficient represents the reduction in lbs/lbs/tons of SO_2/NO_x/CO_2.[15]

The remaining covariates control for trends in wind generation and emissions that may be correlated, leading to erroneous interpretations of β_{ir}. Due to heating and cooling needs, temperature is a strong driver of electricity demand and emissions and thus is explicitly included as a covariate along with the square of temperature, to account for non-linearities (Valor et al. 2001). The remaining covariates in the vector X_t are fixed effects to account for other sources of variation in emissions. Hourly fixed effects are included to account for

[14] This coefficient represents the average marginal effect of wind power in the territory during the time period when data was available (ERCOT 2007-2009, MISO 2008-2009, CAISO 2009). While the estimated coefficients provide a clear view of the emission savings by territory in the specified time periods, it is important to note that these coefficient estimates are subject to the generation mix, wind capacity, and other relevant factors as they existed during those years. As such, structural estimation or simulated dispatch models may be more appropriate for estimating future emissions savings from wind. Nonetheless, the reduced-form estimates reported below provide insight into actual emission savings and can serve as a useful baseline for follow-up studies.

[15] Standard errors for all estimations reported below correct for heteroscedasticity and autocorrelation. Newey-West standard errors are reported with a 5-day lag for SO_2, 1-day lag for NO_x, and 3-day lag for CO_2.

diurnal wind variation over the course of the day, which can be correlated with changes in the electricity demand profile. On average, winds are strongest in the early morning hours when electricity demand and emissions are at their nadir, and therefore failing to control for this hourly variation would lead to an overestimate of the emissions reductions from wind.

Over the sample period, wind capacity steadily increased, which may be correlated with changes in demand and emissions driven by macroeconomic effects unrelated to wind generation. To account for these longer-run trends, month-year fixed effects are included, leading to identification of the effect of wind generation on emissions through within-month variation.[16] Finally, though wind generation is not correlated with the day of the week, day-of-week fixed effects are included to capture within-week variation (primarily between weekdays and weekends) in electricity demand and emissions.

5 Results

5.1 Hourly estimates

The estimates of the emission savings from wind generation in ERCOT, MISO, and CAISO are presented in table 2. The reported coefficients in the first row can be interpreted as the lbs/lbs/tons of $SO_2/NO_x/CO_2$ emissions reduced per MWh of wind generation. The first three columns represent the emissions savings by pollutant due to wind power in ERCOT from 2007-2009. Each MWh of wind generation in ERCOT on average reduced SO_2 by 1.235

[16] Alternative specifications with month and year fixed effects or flexible polynomial time trends yielded estimates nearly identical to those presented below, as did estimations with month-hour fixed effects. In addition, estimations were run with heating-degree day and cooling-degree day specifications instead of temperature, generating coefficients and standard errors that differed only trivially from those reported below.

lbs, NO_x by 0.739 lbs, and CO_2 by 0.484 tons.[17] [18] All coefficients are very statistically significant. The next three columns represent emission savings in coal dominated MISO from 2008-2009, where each MWh of wind generation in MISO reduced SO_2 by 4.890 lbs, NO_x by 1.995 lbs, and CO_2 by 1.025 tons. Again, all coefficients are statistically significant and are larger than the estimated emissions savings in ERCOT. By contrast, in gas dominated CAISO, we find emissions savings in 2009 of 0.008 lbs/MWh for SO_2, 0.054 lbs/MWh for NO_x, and 0.299 tons/MWh for CO_2, with significant coefficient estimates for NO_x and CO_2. Coefficients for the effect of temperature on emissions are also reported. Coefficients for the linear and quadratic temperature terms are significant across pollutants and territories, and as expected, reflect a U-shaped relationship between temperature and emissions with minimums occurring around 45-60 °F.

The estimated emission savings in ERCOT using average plant emission rates found in Cullen (2010) provide a useful reference point. Cullen calculates that 3.15 lbs of SO_2, 1.05

[17] Novan (2010) estimates ERCOT emissions savings rates over the same 2007-2009 time period. While adopting a similar identification strategy, there are several specification differences of note. First, changes in hourly emissions (ΔE) are regressed against changes in hourly wind generation (ΔW). Second, Novan uses measures of heating and cooling degrees across 9 sub-regions of Texas (based on deviations from an exogenously specified 65 °F), as opposed to the flexible polynomial in temperature used here. Finally, quarter-year and hour-quarter fixed effects are used to control for the diurnal and seasonal variation noted above, as opposed to month-year and hourly fixed effects. Despite the differences in specification, Novan (2010) finds ERCOT 2007-2009 savings rates of 1.545 pounds of SO_2/MWh, 0.828 pounds of NO_x/MWh, and 0.569 tons of CO_2/MWh, which are very similar to the values reported here. As these two studies were developed independently, the general agreement in estimated emissions savings rates is encouraging and demonstrates the robustness of our findings.

[18] The inclusion of fixed-effects in our model primarily controls for changes in demand (load) at different times of day and over different seasons. As a robustness check, we also include ERCOT load as a right-hand side regressor. Under this specification, we find emission savings of 1.270 pounds of SO_2/MWh, 0.790 pounds of NO_x/MWh, and 0.521 tons of CO_2/MWh, slightly larger but statistically indistinguishable from the estimates presented in table 2.

lbs of NO_x, and 0.79 tons of CO_2 were avoided per MWh of wind power in ERCOT from 2005-2007. By contrast, our estimates for ERCOT (2007-2009) above (as well as estimates in Novan (2010)) find substantially smaller emission savings rates of 1.235 lbs/MWh for SO_2, 0.739 lbs/MWh for NO_x, and 0.484 tons/MWh for CO_2. This difference is likely driven by emissions associated with cycling - as noted in Katzenstein and Apt (2009), only 30-50% of expected NO_x savings will be realized due to emission increases from cycling gas turbines. It should be noted that this comparison may actually understate the reduction in emission savings caused by cycling, as it compares emission savings rates from Cullen's 2005-2007 estimates against our 2007-2009 estimates. Re-estimating our model with 2007 data only, we find smaller SO_2 reductions of 0.88 lbs/MWh, NO_x reductions of 0.41 lbs/MWh, and CO_2 reductions of 0.38 lbs/MWh. Increased emission savings rates in ERCOT in 2009 likely stem from increases in wind capacity and generation that required increased accommodation by coal generation.[19]

Before concluding the discussion of hourly estimates of emissions savings, one concern worth discussing is the import and export response to wind generation in a territory. The particular concern is that, if import and export decisions are adjusted in response to changes in wind generation (for example, reducing imports or increasing exports of generation when wind levels are high), estimated emissions savings will be underestimated (biased towards zero) as the changes in emissions will occur at thermal plants outside the territory's operating footprint. How concerned should we be about this potential downward source of bias?

[19] In addition to hourly emissions data for ERCOT, we also obtained hourly coal MWh generation for 2007-2009. Estimates of the displacement of coal by wind power in 2007 versus 2009 suggest that more coal was displaced as wind capacity grew, which concurs with findings in Bentek Energy LLC (2010) that the number of wind-induced coal cycling events in ERCOT doubled from 2007 to 2009.

ERCOT is relatively isolated from the rest of the national electrical grid, and as such we might expect limited import or export response to changes in wind generation. Analysis by Cullen (2010) and Novan (2010) estimate that changes in aggregate imports (Cullen) and emissions at plants which export to ERCOT (Novan) in response to changes in wind generation are small and statistically insignificant. In contrast to ERCOT's isolation, CAISO is substantially connected to neighboring territories and is very import dependent, with roughly a quarter of their load met by imports. Perhaps the small emissions savings in CAISO could be explained by the fact that CAISO adjusts its hourly import levels in response to wind power generated. To test this hypothesis, we obtained hourly net import levels in the CAISO territory and estimated imports against wind generation (utilizing the same controls as the emission estimation in equation 1). Estimated changes in imports due to wind generation were small (-0.05 MWh of imports per MWh of wind) and statistically insignificant (p-value = 0.50), suggesting that CAISO is not adjusting import levels in response to wind generation.[20]

Finally, MISO is less import-dependent than CAISO but more-so than ERCOT. We obtained hourly import and export data (including the name of the exporting or importing territory) for MISO to test for any import or export response to wind generation levels. We find some evidence of a response of net imports to wind generation, with a reduction of 0.15 MWh of net imports per MWh of wind generation (p-value = 0.01). While the bulk (80%) of the import response is from hydro and nuclear-dominated territories (Manitoba Hydro Electric Board (MHEB), Ontario's Independent Electricity System Operator (IESO), east-

[20] This is consistent with CAISO documents which state that import scheduling occurs ahead of time and in blocks of one hour. Such a system may be too inflexible to adjust in response to wind intermittency.

ern interconnection region (WAUE) of the Western Area Power Administration (WAPA)), to the extent that reductions in exports to MISO from these areas implies that thermal generation may be offset elsewhere, the emission saving estimates for MISO may be slightly underestimated.

5.2 Daily aggregate estimates

The previous section exploited the hourly exogenous variation in wind generation to estimate the emission savings rate per MWh of wind generation in ERCOT, MISO and CAISO. As noted above, one potential concern for misestimation is that the emissions savings occurred outside the ISO footprint where the wind power was generated. Another potential concern is that there may be dynamic effects of wind generation, such that wind power generated at time t affects emission at some later $t+n$ time period. For example, a strong morning wind event displaces substantial thermal generation, which would then require emissions-intensive ramping (which may spill over into the following hours) as the wind event diminished. Alternatively, the cycling of thermal plants in response to large levels of wind generation may negatively affect emission control technologies, resulting in increased emissions after wind generation levels have diminished. If such dynamic effects were occurring, our estimates of emission savings associated with wind would be too large.

As a simple exploration of whether or not such dynamic effects are of serious importance, hourly wind generation and emissions are aggregated into daily aggregate totals by pollutant and by territory. Such an aggregation will capture any spillover emission effects over the course of the day. The daily aggregate results are presented in table 3, and the coefficients can again be interpreted as the lbs/lbs/tons of $SO_2/NO_x/CO_2$ emissions reduced per MWh of wind generation. The estimated daily aggregate coefficients across territories and pollutants are statistically indistinguishable from the hourly estimates presented in table 2. While this does not rule out dynamic effects of wind generation, these results do suggest that any dynamic effects are either infrequent enough or small enough in magnitude to not affect the daily aggregate estimates of emission savings from wind.[21]

5.3 Emissions savings rates across territories

The importance of the generation mix can be seen by comparing estimates of emission savings across territories. Figure 2 displays emission savings per MWh against the percentage share of coal generation in each territory (fit with a quadratic polynomial). Each pollutant exhibits an upward trend with respect to coal share, with emissions savings from SO_2 displaying the steepest increase. The stronger dependence of SO_2 emission savings on coal share is driven by the fact that coal is the only source of SO_2, while NO_x and CO_2 are also produced by gas. Each pollutant also exhibits a convex response to coal share. Territories with low to moderate coal share typically have a substantial number of gas plants, and it is these gas plants that are used to accommodate wind on the grid, and thereby relatively smaller emission savings are generated. As coal share increases and gas share decreases, the ability of gas to accommodate wind is also diminished, which in turn implies that base load coal is cycled more frequently to accommodate wind, increasing emission savings.

[21] A related concern is that the volatility of wind generation could have emission consequences that spill over multiple hours. While beyond the scope of this paper, exploring the effects of wind generation volatility on emission savings may be an important line of research as the volatility of wind power will increase in the future as wind capacity increases.

As a crude check on our findings, we also estimated BPA 2008-2009 emissions savings and PSCO December 2009 emissions savings from wind power, despite the difficulties with these datasets. Like CAISO, BPA has a very low coal share (hydropower represents two-thirds of BPA generation), and we find similarly low emissions savings of 0.059 lbs of SO_2, 0.170 lbs of NO_x, and 0.081 tons of CO_2 per MWh of wind.[22] By contrast, PSCO has coal and gas shares of generation that are similar to ERCOT, and for December 2009, we find emissions savings very similar to ERCOT of 0.900 lbs of SO_2, 0.752 lbs of NO_x, and 0.398 tons of CO_2 per MWh of wind (all statistically significant despite the limited sample).

As noted above, over the course of a day, the share of each generation type (coal vs. gas) as well as the contribution of each plant to the total generation profile varies considerably. Figures 3-5 plot the emission savings by pollutant for each territory by hour.[23] Figures 3-5 demonstrate that the marginal emissions savings are not constant over the course of the day, which is driven by differences in the fuel mix of generation as well as differences in emission

[22] These numbers are the estimated changes in emissions within the BPA footprint due to wind generation, which should be interpreted with some caution. BPA exports a substantial amount of their generation, particularly during the late spring and early summer months when heavy snowpack melt-off leads to large amounts of hydropower generation and thermal plants are run at minimum levels or completely shut down. Hourly import/export data was obtained from BPA and net exports were regressed against hourly wind generation for 2008-2009 (using all controls from equation 1). We find that net exports increased by a statistically significant 0.320 MWh per MWh of wind generation. If we combine our point estimate of emissions savings with the estimate of exports, we can determine a plausible upper-bound on total possible CO_2 emission savings from wind power in BPA. Given the region of the country, if fossil generation is offset by these exports, it will likely be natural gas with an assumed 0.5 tons/MWh of CO_2 emissions. Thus, multiplying 0.5 tons of CO_2 emissions per MWh from gas by the 0.320 MWh exports per MWh of wind, and adding that to the 0.081 tons of CO_2 emissions saved per MWh of wind in BPA's territorial footprint yields upper-bound emissions savings of 0.241 tons of CO_2 per MWh of wind power in BPA.

[23] Each point represents a separate regression. 216 by-hour regressions were run in total, with each estimation including temperature, temperature squared, day-of-week fixed effects, and month-year fixed effects.

rates across plants within a fuel type. These hourly results are generally consistent with the estimations in Novan (2010) of emissions savings against load (see figure 2 in Novan (2010)). Novan finds that SO_2 emission savings rates fall monotonically as load increases, consistent with the decreased SO_2 emissions savings during mid-day in figure 3 when demand is at its highest level and variation in wind generation is accommodated primarily by gas. By contrast, NO_x and CO_2 emissions savings rates initially decline as load increases, but then rise as load increases further. Figures 4 and 5 display somewhat higher emissions savings rates for NO_x and SO_2 during overnight periods (lowest demand) and mid-day (highest demand).

5.4 Calculating a national emissions savings rate

The above results demonstrate that a strong dependence exists between emissions savings rates and the existing generation mix. In this section, a back-of-the-envelope calculation of the national emissions savings rate is undertaken. As our data already includes 60% of the nation's wind generation, our task is to determine the emission savings for the remaining 40% of wind generation outside of MISO, ERCOT and CAISO. In figure 2, emission savings rates against the coal share in each territory were fit with a quadratic polynomial. We propose to use 2009 coal shares for each state to predict emissions savings rates for that state based on this quadratic polynomial.[24] Total emission savings for state s and pollutant i are then simply the predicted emissions savings rate based on coal share E_{is} times total state

[24] The emissions savings equations in figure 2 for each pollutant E_i as a function of coal share C are as follows: $E_{SO2} = 6.809C^2 + 0.769C + 0.034$, $E_{NOX} = 2.450C^2 + 0.134C + 0.36$, $E_{CO2} = 0.666C^2 + 0.537C + 0.19$. While we fully acknowledge the limitations of this crude proxy approach, nonetheless this procedure should provide a useful back-of-the-envelope calculation of emission savings.

wind generation in 2009 W_s.[25] Total national emissions savings for pollutant i are then calculated as $\sum_s E_{is} W_s$, and the national emissions savings rate is equal to total national emissions savings divided by total national wind generation $\sum_s W_s$.

Table 3 displays the results of this exercise. For each state, the coal share of generation, wind generation, predicted emissions savings rate by pollutant, and total emissions savings by pollutant are reported. In 2009, the top three states in total wind power generation were Texas, Iowa and California. By contrast, the top three states for SO_2 reduction were Iowa, Texas, and North Dakota, while the top three states for NO_x and CO_2 reductions were Texas, Iowa and North Dakota. Due to its 87% coal share, North Dakota generated the third largest predicted emissions reductions across all three pollutants despite ranking ninth in total wind generation. West Virginia and California present a useful comparison for highlighting the importance of the existing generation mix in terms of emissions savings. Predicted NO_x and CO_2 reductions in West Virginia were similar to those of California, while SO_2 reductions were twenty times larger. This occurred despite the fact that California generated over seven times as much electricity from wind power as West Virginia. This result is driven by the fact that California generates virtually no power from coal, while West Virginia generates 97% of its power from coal. While the potential for substantial wind power in West Virginia is somewhat limited, states such as Kansas, Nebraska, North Dakota, Iowa, Wyoming, and New Mexico rank in the top 10 for potential wind power and have coal shares of roughly

[25] The fraction of total electricity generation produced by coal was obtained from the EIA Electric Power Annual Report (1990-2009 Net Generation by State by Type of Producer by Energy Source (EIA-906, EIA-920, and EIA-923)) at http://www.eia.gov/cneaf/electricity/epa/epa_sprdshts.html. Total wind generation was obtained from the EIA Renewable Energy Consumption and Electricity Preliminary Statistics 2009: Table 6 at http://www.eia.doe.gov/cneaf/alternate/page/renew_energy_consump/rea_prereport.html.

70% or more.[26]

The final row of table 3 reports the back-of-the-envelope calculated emissions savings rate and total emission savings in the US. Wind power in 2009 is predicted to have reduced SO_2 emissions by 159 million pounds, NO_x emissions by 77 million pounds, and CO_2 emissions by 43 million tons. The national average emission savings rates were calculated to be 2.2 pounds of SO_2, 1.1 pounds of NO_x, and 0.6 tons of CO_2 per MWh of wind energy. As these emission savings rates are substantially below the emission savings rates in the several high-wind potential, high-coal share states noted above, this raises the possibility that a subsidy linked to emissions savings (or a proxy such as coal share) could have generated greater emissions reductions for the same total subsidy expenditure, relative to the production-based subsidy currently in place (Novan 2010).

5.5 Benefits of avoided emissions from wind power

A key issue of policy interest is the benefits of avoided emissions due to wind power. If unpriced emissions were the only market failure associated with conventional power generation, basic externality theory suggests that the optimal subsidy per MWh of wind power would be equal to the marginal social benefit of avoided emissions per MWh.[27] Such a subsidy would

[26] From the National Renewable Energy Lab's estimates of resource potential in the US at http://www.windpoweringamerica.gov/wind_maps.asp.

[27] In reality, there are likely many additional market failures and externalities (both positive and negative) associated with wind power. These market failures could include reliability and integration costs of wind power (for example, the 0.6 cents per MWh integration charge levied in BPA), upstream externalities associated with coal and natural gas extraction, reductions in particulates and mercury, learning-by-doing and research and development spillovers, and noise and visual disamenities associated with turbines. However, as much of the current focus on alternative energy development revolves around emissions savings (primarily CO_2), the discussion below will focus on the marginal social benefits of wind power associated with emissions reductions.

provide incentive for wind developers to internalize the social benefits of clean energy, leading to an efficient level of wind power production. Currently however, the federal Production Tax Credit subsidy is set at \$22 per MWh of wind power, regardless of the actual emissions savings from a given MWh of wind power. How does this existing subsidy compare to the hypothetical optimal subsidy?

While we have estimated the emissions savings per MWh in Texas, California, and the Upper Midwest, valuation of those avoided emissions is a difficult task. To facilitate comparisons with other studies, we adopt the assumptions and central estimates in Cullen (2010) for the marginal social benefit of emissions avoided. Assuming \$433 dollars per ton permit prices for SO_2 and \$5,000 dollars per ton permit prices for NO_x, figure 6 plots the emissions saving benefits per MWh in each territory as the marginal social damage of CO_2 varies.[28] The horizontal dashed line represents the \$22/MWh PTC.

One interpretation of figure 6 is that the intersection of the PTC line and the marginal benefit curve for each territory represents the marginal social damage per ton of CO_2 required for the emissions savings benefits to equal the current PTC. In coal-heavy MISO, emissions savings benefits will equal the federal production subsidy at \$16 dollars per ton of CO_2 (or at \$22 dollars per ton if SO_2 and NO_x reductions provide no social benefit). By contrast, in ERCOT and CAISO, substantially larger values of the marginal social damage of CO_2

[28] Cullen (2010) assumes that the marginal social damage of the regulated pollutants (SO_2 and NO_x) is equal to the market permit price, while acknowledging that such an assumption is subject to criticism. The vertical intercept in figure 6 represents the marginal benefits of avoided emissions for these regulated pollutants. However, if the cap on SO_2 and NO_x is appropriately set, the social cost of the regulated pollutants are efficiently internalized, generating no social benefits from reductions. If one assumes SO_2 and NO_x reductions provide no social benefit, then the marginal benefits of avoided emissions curve for each territory in figure 6 should be shifted downward such that the vertical intercept is equal to zero.

would be required to equal the production subsidy - roughly \$42 dollars per ton in ERCOT (\$46 per ton if regulated pollutant reductions provide no social benefit), and over \$70 dollars a ton in CAISO.

Finally, figure 6 also plots the predicted emissions savings benefits for the US based on the back-of-the-envelope calculations in the previous section. A marginal social damage of \$31 dollars per ton of CO_2 would be required (\$36 per ton in the absence of benefits from SO_2 and NO_x reductions) to equal the Production Tax Credit for the US as a whole. For comparison, the US Interagency Working Group On Social Cost Of Carbon selected \$21 dollars per ton of CO_2 as their central estimate of the social cost of carbon.[29] It should be noted that even if the marginal benefits of avoided emissions exceeded the production subsidy, that does not imply that wind power production subsidies are the most cost-effective instrument for emissions reductions.[30]

6 Conclusions

In the preceding sections, we provided estimates of emissions savings from wind power in Texas, California and the Upper Midwest. Our reduced form approach leverages the exogenous variation in hourly wind production to identify the impact of wind power on system-wide

[29] See "Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866" at http://www.epa.gov/oms/climate/regulations/scc-tsd.pdf and Greenstone et al. (2011) for further details on methodologies and assumptions. The central estimate assumed a 3% discount rate - at a 5% discount rate, the social cost of carbon was \$5 dollars per ton of CO_2.

[30] Fischer and Newell (2008) develop a calibrated numerical analysis to rank alternative mechanisms for climate mitigation, and renewable production subsidies rank fifth in terms of cost-effectiveness out of the six policies considered. Not surprisingly, a direct emissions pricing mechanism such as a tax or tradable permit emerged as the most cost-effective instrument.

emissions. Looking to the future, accommodation of wind onto the grid will become an increasingly important issue, as wind was the second largest new source of installed capacity in the US in 2008 and 2009. This paper has provided strong evidence that the emissions savings corresponding to this growth in wind power will vary substantially depending on the fuel source displaced by wind. In particular, the share of coal in the existing generation mix strongly influences emissions savings from wind. This suggests that there may be benefits to adjusting the existing Production Tax Credits to reflect the regional emission savings (or a proxy thereof) from a MWh of wind power.

Based on current trends, several competing forces will influence emissions savings from wind power in the future. First, gas is the leading source of new generation capacity in the US, due to decreasing fuel costs relative to coal as well as concern about stronger EPA regulation of coal plants. This would tend to increase the gas offset by wind power and reduce the emission savings associated with wind (although of course electricity generation from gas itself is less emissions-intensive than coal). Second, as wind capacity grows, the ability of existing gas generation to accommodate wind power will diminish, leading to increased cycling of coal plants (as seen in ERCOT), potentially increasing emissions savings. Finally, increasing wind capacity will likely require an increase in ramping of thermal generation, as the magnitude of shifts in wind speed is amplified into larger swings in aggregate wind generation. This increased cycling of thermal generation (in magnitude and potentially frequency) may erode the emissions savings per MWh of wind power as thermal generation is utilized less efficiently to accommodate wind. While it is unclear which of these effects will win out, it is clear that the resulting emission savings of wind power will depend critically on the factors highlighted in this paper. As such, this paper provides a transparent framework for updating and refining emission savings estimates as data on wind generation in more territories and across longer time periods becomes available.

References

Beenstock, M. (1995). The stochastic economics of windpower. *Energy Economics 17*(1), 27–37.

Benitez, L., P. Benitez, and G. Van Kooten (2008). The economics of wind power with energy storage. *Energy Economics 30*(4), 1973–1989.

Bentek Energy LLC (2010). How less became more: Wind, power and unintended consequences in the Colorado energy market. Technical report, Bentek Energy LLC.

Callaway, D. and M. Fowlie (2009). Greenhouse gas emissions reductions from wind energy: Location, location, location? *Working paper*.

Campbell, A. (2009). Government support for intermittent renewable generation technologies. *MIT Department of Economics, Working Paper 6*, 1381–1402.

Cullen, J. (2010). Measuring the environmental benefits of wind-generated electricity. *Working Paper*.

Decarolis, J. and D. Keith (2006). The economics of large-scale wind power in a carbon constrained world. *Energy Policy 34*(4), 395–410.

Denholm, P., G. L. Kulcinski, and T. Holloway (2005). Emissions and energy efficiency assessment of baseload wind energy systems. *Environmental Science and Technology 39*, 1903–1911.

Fischer, C. and R. G. Newell (2008). Environmental and technology policies for climate mitigation. *Journal of Environmental Economics and Management 55*(2), 142–162.

Greenstone, M., E. Kopits, and A. Wolverton (2011). Estimating the social cost of carbon for use in U.S. federal rulemakings: A summary and interprtation. *NBER Working Paper 16913*.

Katzenstein, W. and J. Apt (2009). Air emissions due to wind and solar power. *Environmental Science and Technology 43*(2), 253–258.

Lang, P. (2009). Cost and quantity of greenhouse gas emissions avoided by wind generation. *Working Paper*.

Liik, O., R. Oidram, and M. Keel (2003). Estimation of real emissions reduction caused by wind generators. In *International Energy Workshop, June 24-26, IIASA*.

Moore, M., G. Lewis, and D. Cepela (2010). Markets for renewable energy and pollution emissions: Environmental claims, emission-reduction accounting, and product decoupling. *Energy Policy 38*(10), 5956–5966.

Novan, K. M. (2010). Shifting wind: The economics of moving subsidies from power produced to emissions avoided. *Working paper*.

Puga, J. (2010). The importance of combined cycle generating plants in integrating large levels of wind power generation. *The Electricity Journal 23*(7), 33–44.

Sioshansi, R. (2011). Increasing the value of wind with energy storage. *The Energy Journal 32*(2), 1–30.

Trebilcock, M. (2009). Speaking Truth to Wind Power. *CD Howe Institute 22*, 209.

Valor, E., V. Meneu, and V. Caselles (2001). Daily air temperature and electricity load in Spain. *Journal of Applied Meteorology 40*, 1413–1421.

World Wind Energy Association (2009). World wind energy report 2009. Technical report, World Wind Energy Association.

Table 1: Hourly wind power generation and emissions by territory

		Mean	Standard Deviation	Maximum	Minimum
ERCOT	Sulphur dioxide	91.9	13.1	141	42.5
	Nitrogen oxides	25.2	6.13	62.5	10.8
	Carbon dioxide	22.3	4.63	38.9	11.0
	Wind generation	1.63	1.20	6.04	0
	Temperature	67.4	17.3	107	18
MISO	Sulphur dioxide	371	69.6	580	198
	Nitrogen oxides	139	43.7	260	63.8
	Carbon dioxide	56.6	8.50	83.9	32.8
	Wind generation	1.32	0.96	5.40	0
	Temperature	49.2	19.5	89.2	-11
CAISO	Sulphur dioxide	0.04	0.06	0.84	0.01
	Nitrogen oxides	0.76	0.40	4.84	0.17
	Carbon dioxide	3.17	1.36	9.37	0.49
	Wind generation	0.65	0.48	1.86	0
	Temperature	61.0	8.56	89.9	29.8

Notes: Variables are reported as follows: SO_2 and NO_x in thousands of pounds, CO_2 in thousands of tons, wind power in thousands of MWh, and temperature in degrees Fahrenheit. ERCOT values represent 26,280 observations from 2007-2009, MISO values represent 15,520 observations from 2008-2009, and CAISO values represent 8760 observations from 2009.

Table 2: Estimation results for emissions reductions from wind generation by territory - hourly

	ERCOT			MISO			CAISO		
Pollutant	SO_2 (lbs)	NO_x (lbs)	CO_2 (tons)	SO_2(lbs)	NO_x (lbs)	CO_2 (tons)	SO_2(lbs)	NO_x (lbs)	CO_2 (tons)
Wind (MWh)	-1.235**	-0.739**	-0.484**	-4.890**	-1.995**	-1.025**	-0.008	-0.054*	-0.299**
	(0.183)	(0.042)	(0.029)	(0.924)	(0.280)	(0.103)	(0.007)	(0.027)	(0.074)
Temp (° F)	-814.1**	-1226**	-798.6**	-5670**	-1897**	-810.8**	-15.79*	-126.7**	-473.0**
	(94.42)	(25.20)	(12.98)	(339.7)	(154.0)	(51.58)	(6.747)	(22.53)	(47.00)
Temp^2	6.564**	10.39**	6.692**	63.04**	19.00**	9.115**	0.122**	1.164**	4.213**
	(0.742)	(0.204)	(0.107)	(3.775)	(1.501)	(0.569)	(0.047)	(0.202)	(0.424)
Hour FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Month-Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
DOW FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	26280	26280	26280	17520	17520	17520	8760	8760	8760
R^2	0.63	0.82	0.92	0.87	0.95	0.88	0.12	0.43	0.80

*Notes: Dependent variables: SO_2 emissions (pounds), NO_x emissions (pounds), and CO_2 emissions (tons). Newey-West standard errors in parentheses (5/5/2.5 day lags for SO_2, 1/6/2.5 day lags for NO_x, and 3/5/5 day lags for CO_2 by ERCOT/MISO/CAISO territories.) ERCOT values represent hourly 26,280 observations from 2007-2009, MISO values represent 15,520 hourly observations from 2008-2009, and CAISO values represent 8760 hourly observations from 2009. * indicates 5 percent significance, ** indicates 1 percent significance.*

Table 3: Estimation results for emissions reductions from wind generation by territory - daily aggregates

		SO_2 (lbs)	NO_x (lbs)	CO_2 (tons)
	Wind (MWh)	-1.283**	-0.675**	-0.515**
		(0.302)	(0.076)	(0.044)
ERCOT				
	Observations	1095	1095	1095
	R^2	0.70	0.89	0.93
	Wind (MWh)	-5.061**	-2.037**	-1.100**
		(1.227)	(0.365)	(0.140)
MISO				
	Observations	730	730	730
	R^2	0.89	0.97	0.89
	Wind (MWh)	-0.008	-0.026	-0.268**
		(0.001)	(0.031)	(0.082)
CAISO				
	Observations	365	365	365
	R^2	0.13	0.53	0.84
	Temperature	Yes	Yes	Yes
	Month-Year FE	Yes	Yes	Yes
	DOW FE	Yes	Yes	Yes

*Notes: Dependent variables: SO_2 emissions (pounds), NO_x emissions (pounds), and CO_2 emissions (tons). Temperature controls include average daily temperature and average daily temperature squared. Newey-West standard errors in parentheses (5/5/2.5 day lags for SO_2, 1/6/2.5 day lags for NO_x, and 3/5/5 day lags for CO_2 by ERCOT/MISO/CAISO territories.) ERCOT values represent 1095 daily observations from 2007-2009, MISO values represent 730 daily observations from 2008-2009, and CAISO values represent 365 daily observations from 2009. * indicates 5 percent significance, ** indicates 1 percent significance.*

Table 4: Calculated national emissions savings 2009

	Coal share	Wind gen. (MWh)	Emission savings rate SO_2	NO_x	CO_2	Total emissions savings SO_2	NO_x	CO_2
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	0.880	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	6.600	2.586	1.261	0	0	0
Louisiana	0.25	0	0.666	0.546	0.369	0	0	0
Maine	0.00	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	0.720	0.564	0.380	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	0.720	0.564	0.380	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	1.270	0.731	2,277	1,030	594
Nebraska	0.69	288,681	3.772	1.602	0.873	1,089	463	252
Nevada	0.20	0	0.459	0.480	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	0.10	2,258,904	0.170	0.390	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	0.920	0.571	4,052	2,090	1,297
Oregon	0.06	3,372,284	0.098	0.370	0.222	332	1,249	750
Pennsylvania	0.48	921,137	1.975	0.985	0.602	1,819	907	555
Rhode Island	0.00	0	0.034	0.355	0.190	0	0	0
South Carolina	0.34	0	1.105	0.692	0.454	0	0	0

continued on next page

Table 4 – continued from previous page

	Coal	Wind gen.	Emission savings rate			Total emissions savings		
	share	(MWh)	SO_2	NO_x	CO_2	SO_2	NO_x	CO_2
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	0.460	22,070	13,611	8,909
Utah	0.82	64,497	5.193	2.095	1.072	335	135	69
Vermont	0.00	11,589	0.034	0.355	0.190	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	6.390	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

*Notes: Coal share represents the fraction of total state electricity generation produced from coal in 2009. Wind gen. represents total wind generation in the state for 2009. Emission savings rate is the predicted rate based on state coal share of generation and the relationship depicted in figure 2. SO_2 and NO_x emissions savings rates are reported in pounds per MWh of wind, and CO_2 emissions savings rate is reported in tons per MWh of wind. Total emissions savings are the calculated state emission savings based on total wind generation and predicted emission savings rate, expressed in thousands of pounds for SO_2 and NO_x, and thousands of tons for CO_2. * - For the United States entry: Coal share represents the fraction of total national electricity generation produced from coal. Wind gen. represents total wind generation in the country for 2009. Emission savings rate is given by total emission savings across all states divided by total wind generation across all states. Total emissions savings represent the sum of state emission savings.*

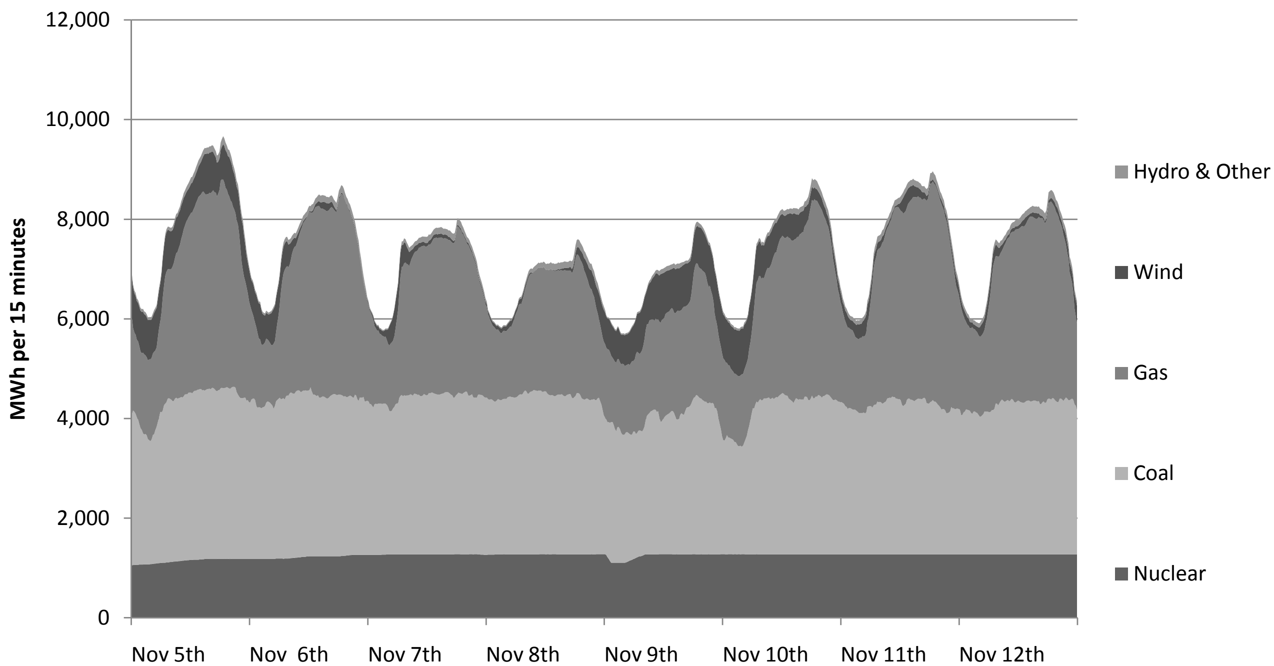

Figure 1: Generation mix in ERCOT (November 5-12, 2008)

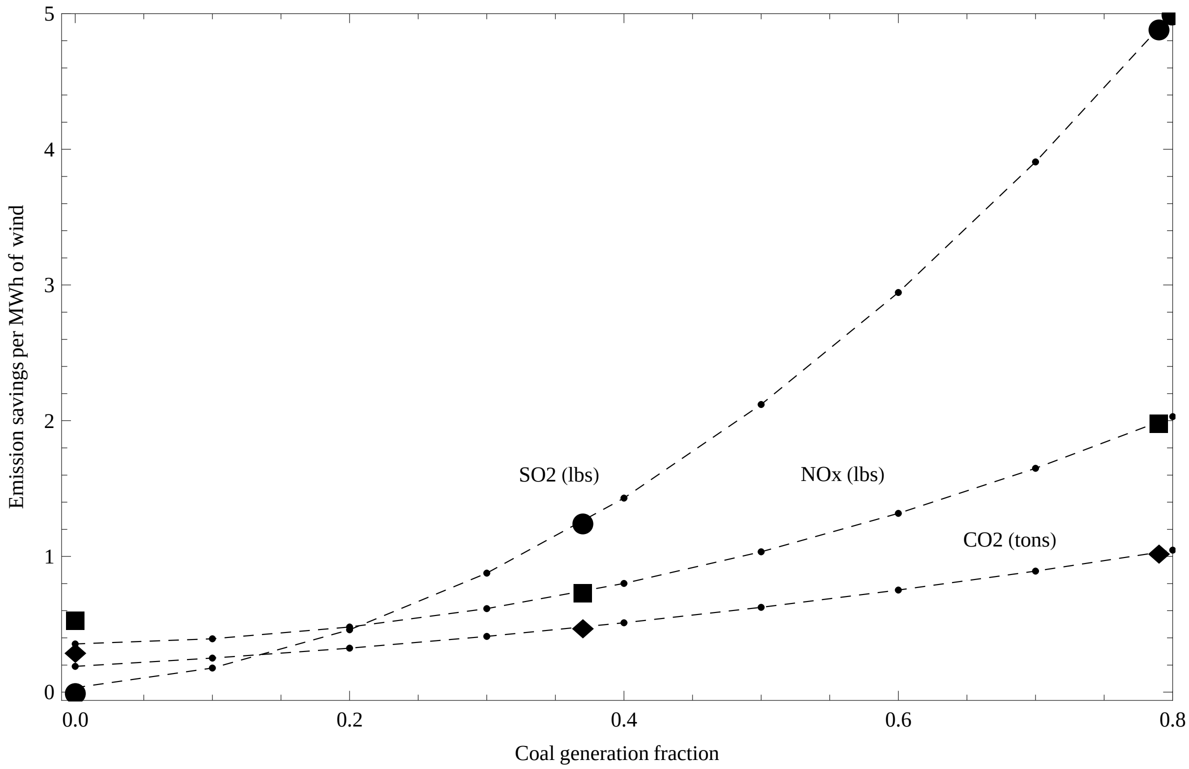

Figure 2: Emissions savings per MWh of wind power against the fraction of coal generation. Plotted points indicate estimated emissions savings rates by pollutant in CAISO, ERCOT, and MISO (left-to-right). Plotted lines represent fitted quadratic polynomials for each pollutant.

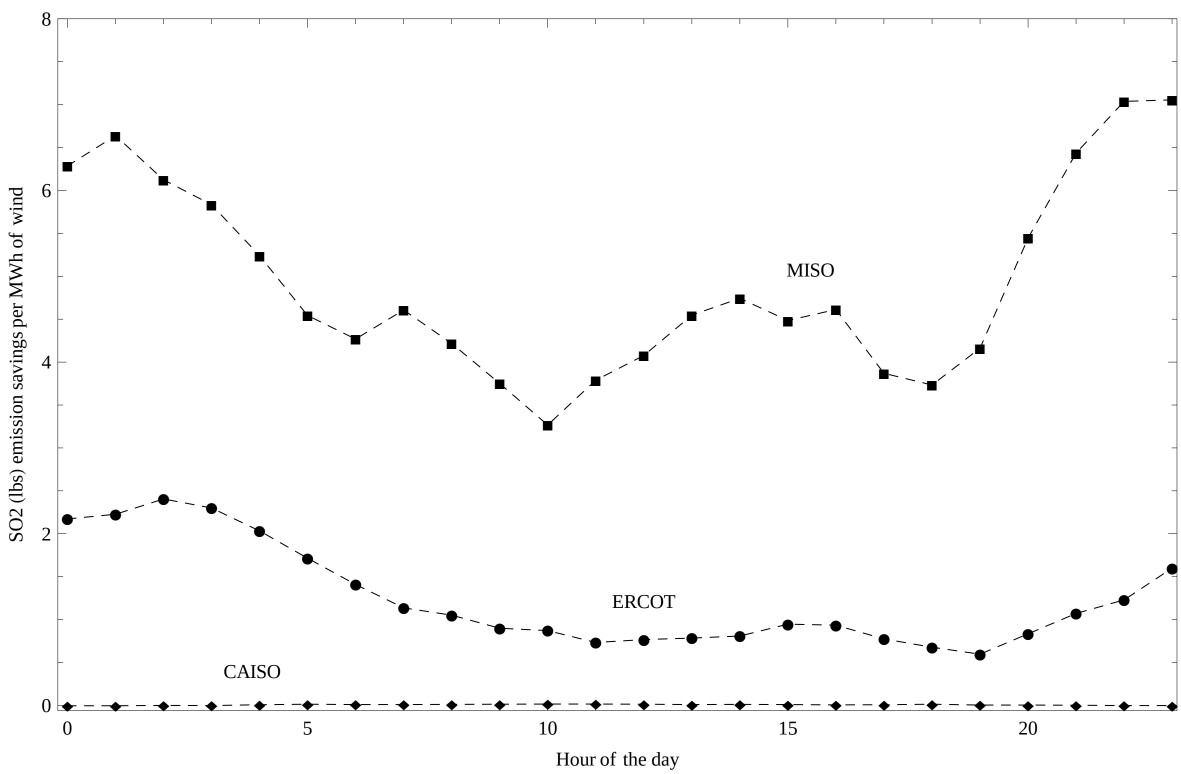

Figure 3: Hour-by-hour SO_2 emission savings per MWh of wind power by territory

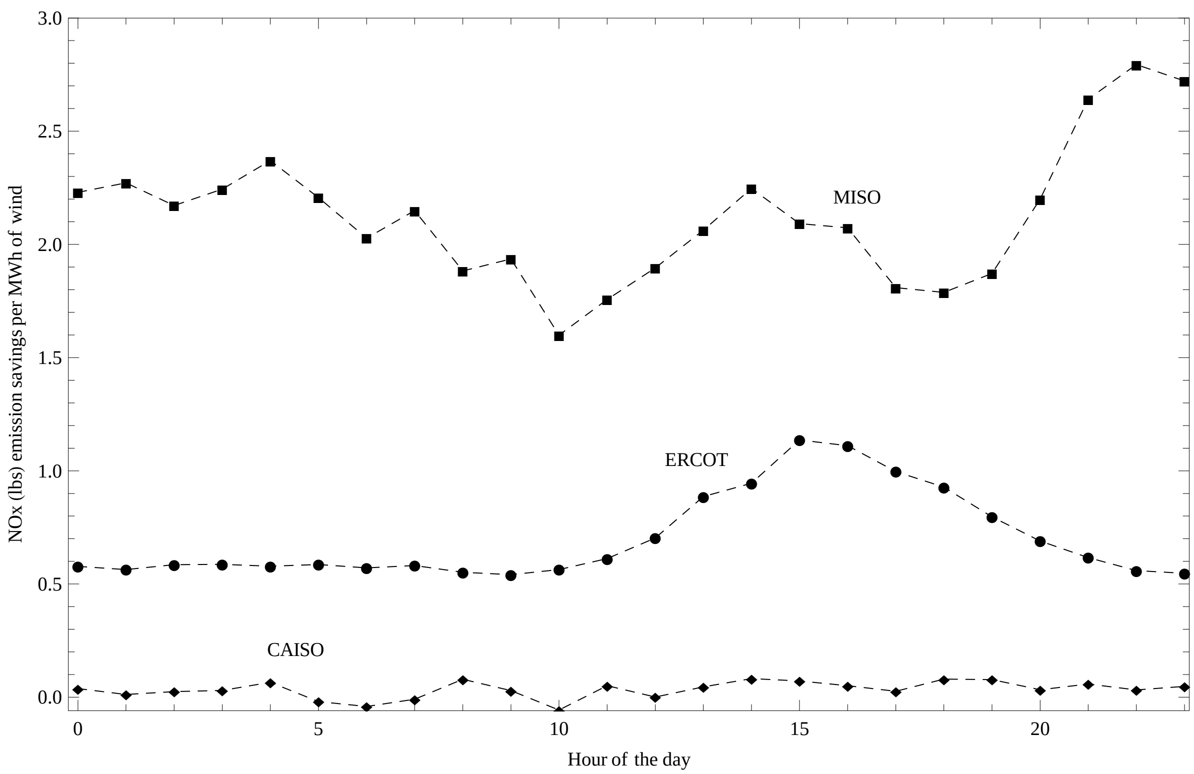

Figure 4: Hour-by-hour NO_x emission savings per MWh of wind power by territory

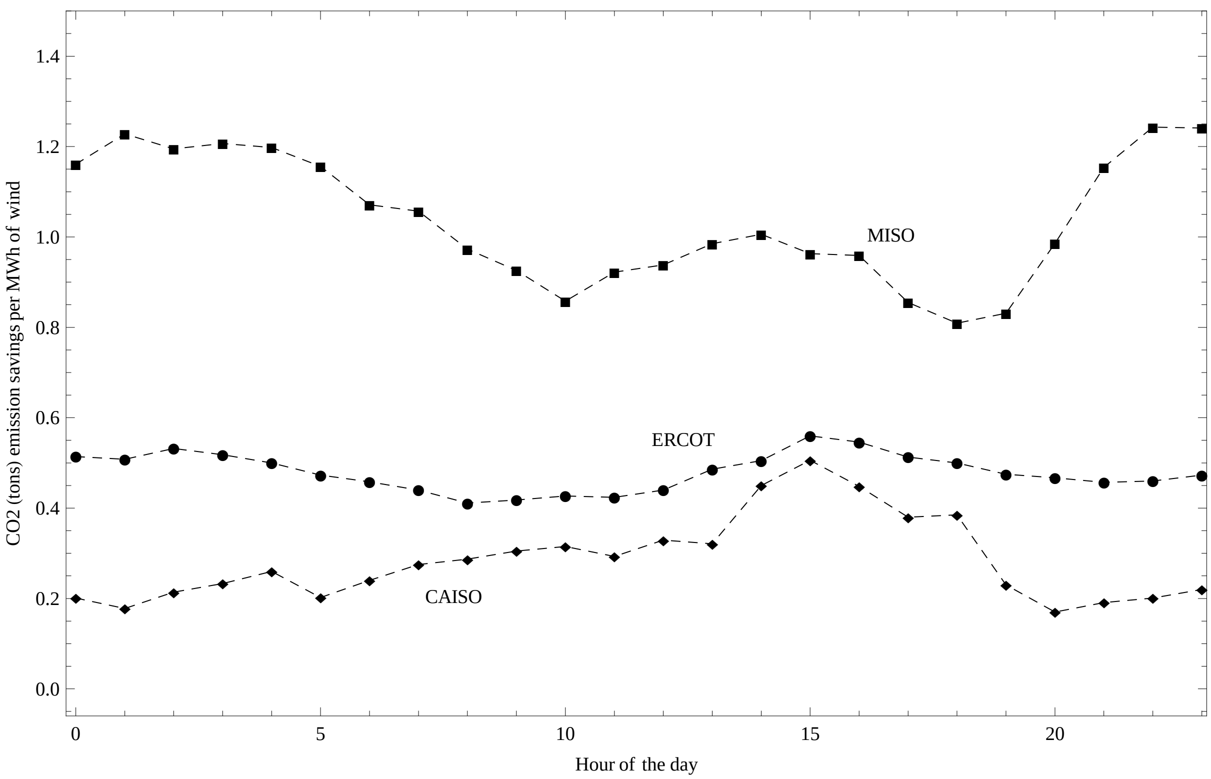

Figure 5: Hour-by-hour CO_2 emission savings per MWh of wind power by territory

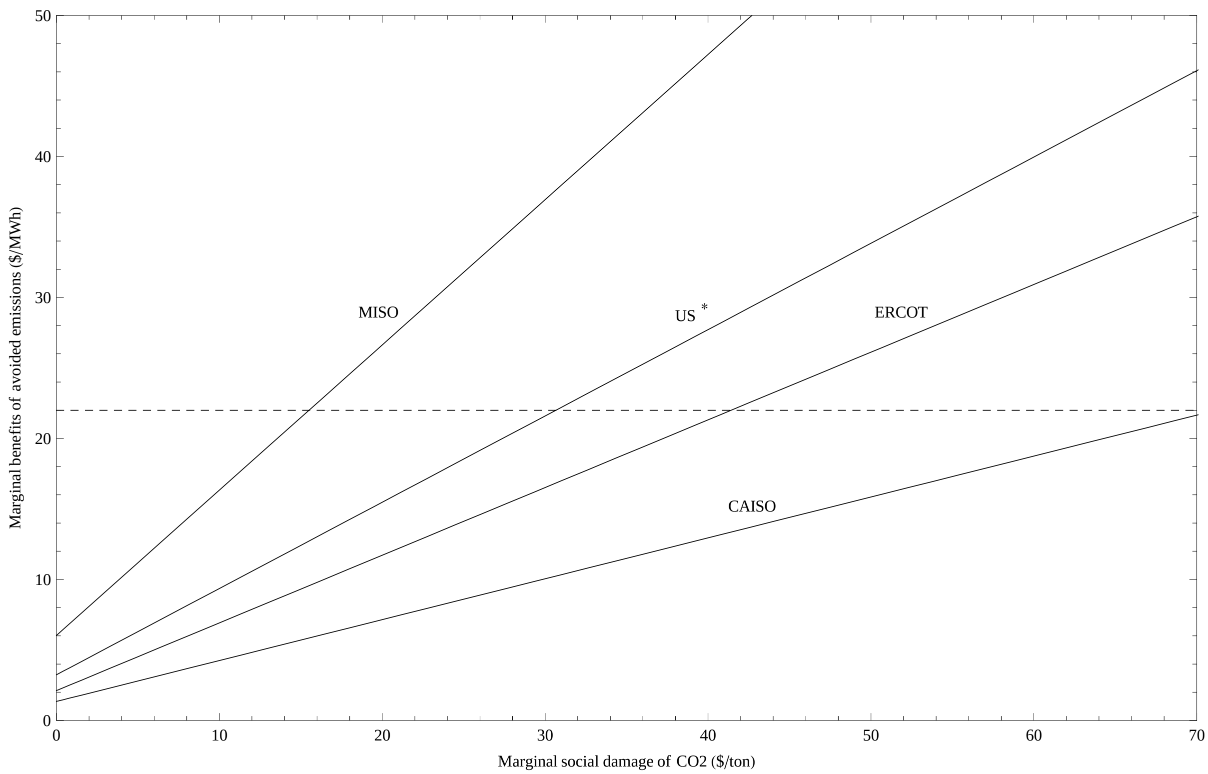

Figure 6: Marginal benefits of avoided emissions per MWh of wind power by territory for various marginal social damages of CO_2 emissions. Dashed line indicates government production subsidy for wind power. The vertical intercept represents the benefits of avoided emissions of the regulated pollutants SO_2 and NO_x.