Effects of Wind Power Intermittency on Generation and Emissions

Reid Dorsey-Palmateer

December 31, 2014

Abstract

The level of potential wind generation for a given set of turbines depends on wind conditions which vary over time and are imperfectly forecastable. Because grid operators must be prepared to compensate for expected or unexpected changes in wind generation, this intermittency affects the operation of the electric grid and the resulting emissions and fuel generation costs. Using ERCOT and EPA data for Texas, this paper finds that increased wind generation shifts the mix of the remaining fossil fuel generation toward natural gas generation, which has more flexible output levels than coal. Because natural gas generation is cleaner and more expensive than coal, this shift towards natural gas generation results in lowered emissions levels and increased fuel costs. The additional fuel generation costs have an average annual value of approximately $42 million from 2011 to 2013 while the reduction in CO$_2$ emissions has an average annual value of approximately $28$M over the same timespan. The intermittency effect shifting generation from coal to natural gas has shrunk substantially from 2011 to 2013 in Texas as short run wind generation forecasts have become more accurate and as market participants have obtained more experience with higher levels of wind generation. This effect is also smaller during periods where natural gas generation would otherwise comprise a relatively large portion of the fossil fuel generation mix. While wind intermittency does affect the operation of the grid and the resulting cost of electricity, its environmental benefits should also be accounted for when determining public policy as the estimated environmental benefits can non-trivially reduce its overall social cost.

*University of Michigan. Email: reiddp@umich.edu. Thanks to Ryan Kellogg, Shaun McRae, Daniel Ackerberg, Jeremy Fox, Tom Lyon, Catherine Hausman and seminar participants at the University of Michigan, Western Economics Association Annual Conference and Camp Resources for their feedback.
1 Introduction

Electricity generation is a major source of air pollution in the United States, responsible for 32% of greenhouse gas emissions in 2012. Because wind power does not generate any emissions, it has been promoted as a clean way to generate electricity, with a variety of government policies encouraging its use. However, wind power differs from fossil fuel generation in another way: its dependence on wind conditions which vary over time and are imperfectly forecastable. In the absence of storage technology, electricity generation must be continuously matched with consumption, so this wind power intermittency can affect the operation of the electricity grid.\footnote{Large scale storage of electricity is not currently feasible apart from hydropower. This paper examines the Texas market where hydropower is a very small part of the mix of generators.}

Wind generation reduces the required amount of generation from other sources so if wind generation capacity is relatively small compared to the overall electric load, any expected or unexpected variation in wind generation may not be substantial relative to the short-run variation in electricity load. However if wind generation capacity is relatively large and changes in wind generation are compensated for by changing fossil fuel generation levels, greater wind intermittency could increase the optimal desired flexibility of fossil fuel generation.\footnote{A 2008 report commissioned by ERCOT found that, for their model, when wind generation capacity in Texas was at 5000 MW, the wind generation would have “a limited impact on the system...[its] variability barely rising above the inherent variability caused by system loads”. But when wind generation capacity increased to 10,000 MW, “the impacts become more noticeable” and by 15,000 MW, “the operational issues posed by wind generation will become a significant focus of ERCOT operations” [GE Report, 2008].}

Thus because of its intermittency, wind power is imposing an externality on the rest of the electricity grid: other generators, and potentially the demand-side, must respond to changes in wind generation. Paying for reserve power and otherwise operating the grid in a less cost-minimizing manner imposes a financial cost. Beyond financial costs, wind power intermittency may have environmental externalities that should be accounted for as well.

Wind power intermittency could affect the emissions produced by electricity generation. Fossil fuel generators differ with respect to their marginal costs, their ability to quickly adjust output levels, as well as the pollution they produce. Compared to coal, natural gas generation
tends to be more expensive, less polluting and able to change output levels more rapidly. If wind power intermittency shifts the mix of fossil fuel generation toward cleaner and more flexible natural gas and away from coal, then this channel would reduce the pollution from fossil fuel generation. However, efficiency of individual generation units varies with output, generally with higher efficiency at higher output levels. If wind intermittency causes some fossil fuel generators to be operated at lower output levels than would otherwise be the case, this channel could increase their emissions rate (Bushnell and Wolfram [2005]). Furthermore, when generator units are changing output levels, as would be the case when compensating for wind power changes, they again lose efficiency and increase their emissions rate (Novan [forthcoming]).

Various government programs, such as the lapsed federal Production Tax Credit and state-level renewable energy credits, have sought to increase the amount of wind generation. California, for example, has a goal of generating 33% of its electricity from renewable sources by 2020. Historically, the value of these wind generation subsidies have at best only been linked to the quantity of power generated by turbines. If the purpose of subsidizing wind power is to reduce emissions, this subsidy policy would optimally instead connect the value of the externalities imposed by wind generation to the value of the subsidy. Varying subsidy levels across wind turbines based on their effect on emissions could lead to improved siting decisions (Novan [forthcoming]). If wind intermittency affects the operation of the grid, subsidization policy would ideally incorporate wind generation intermittency and the value of its corresponding externalities. This includes environmental externalities in addition to imposed financial costs.

Other papers have looked at the integration of large quantities of intermittent generation

---

3While wind generation does not pollute in the conventional sense, nearby residents can complain about noise and unsightly turbines.

4Hitaj (2013) and Carley (2009) examine the effectiveness of programs at encouraging wind generation.

5Alternative polices such as cap-and-trade or a carbon tax could also be preferable to a subsidy for wind generation, however this is beyond the scope of this paper.

6The creation of “green jobs” has also been suggested as a rationale for subsidizing wind power (Obama 2012).
resources such as wind and solar into the electric grid (van Kooten [2010], DeCarolis and Keith [2004], Gowrisankaran et al. [2014]).\(^7\) This set of papers uses 'engineering' approaches and models the dispatch of generation units. This approach is valuable for out-of-sample prediction but in practice the results from engineering models of electric grids can often deviate from what is ultimately observed (Callaway and Fowlie [2009]).\(^8\)

Instead of using a detailed dispatch model of the electricity grid, I use an instrumental variables regression approach to estimate the impact of wind generation intermittency on the operation of the electric grid and the resulting emissions. I use recent data from Texas, the state with the most installed capacity for wind generation in the United States, from approximately 2011 to 2013.

In Texas, wind was the source of approximately 10\% of electricity in 2013 and the share of total generation coming from wind power at a specific moment has reached as high as 36\%. I obtain hourly data regarding emissions, fossil fuel generation and and both potential and actual wind generation. I find that wind power does have an effect on electricity generation beyond reducing the necessary amount of generation from other sources. After flexibly controlling for the level of fossil fuel generation, increased wind generation is associated with shifting the fossil fuel generation mix away from coal and towards more flexible natural gas generation. There is a corresponding increase in fuel costs and a decrease in CO\(_2\) emissions, indicating that the environmental effect from shifting the generation mix towards cleaner natural gas dominates any increase in emissions due to increased ramping of fossil fuel generators or operating at less efficient output levels.

This intermittency effect of wind generation on emissions is greater when natural gas would otherwise comprise a smaller part of the generation mix, namely when total generation is at lower levels and baseload coal generation is a larger part of the fossil fuel mix. While the analysis in this paper only uses Texas data, this does suggest that wind power intermittency

\(^7\)Green and Vasilakos (2010) model how increased wind generation could affect market prices and output with profit maximizing bidding.

\(^8\)In a different context, Allcott and Greenstone (2012) discuss how engineering models of energy efficiency often understate costs of improved energy efficiency.
may have a larger impact on generation and emissions in regions where coal generation plays a larger role. This result is similar to Holland and Mansur (2008), who find that reducing daily electricity load variation has different effects on emissions depending on the generation mix in the region.

Examining the average impact of wind power intermittency effect does not distinguish between the different forms that wind power intermittency can take. Wind generation levels can vary in expected ways. Additionally, potential wind power could change in an unexpected manner if the forecasts are incorrect. These forecasts can have varying degrees of confidence. When examining the effect of more specific measures of wind intermittency, I find that variation in expected wind generation over a five-hour window (expected wind power variation) is associated with a shift in fossil fuel generation towards natural gas. I similarly find increased uncertainty in wind power forecasts also results in shifts from coal to natural gas.

The estimates in this paper are short-run effects that do not incorporate any long-run adjustments to the set of generators available in Texas as a response to increased wind generation capacity. Also, while total wind generation capacity did increase during the three year period examined, a clear majority of the capacity was already installed in Texas at the beginning of that three year period. Most of the observed variation in wind generation levels is a result of changing wind conditions. The impact of installing additional wind turbines on wind generation intermittency depends on how the new wind generation is correlated with the previously installed capacity.

Thus while wind intermittency increases financial costs of generation, it also results in reduced emissions by shifting fossil fuel generation towards cleaner natural gas generators. When measuring the social cost wind intermittency imposes, the value of these environmental benefits should be included. Using the estimates from Texas in this paper and the U.S. social cost of carbon estimates of $39/ton, the environmental benefit from increased wind intermittency from a 1 MWh increase in wind generation is associated with a reduction
in CO₂ emissions valued at $0.92. This value is smaller than the increase in fuel costs of $1.38, but nevertheless indicates a substantial fraction of those costs would be offset by environmental benefits.

2 Modeling Effects of Uncertain Wind Generation

To illustrate two channels of the effect of wind generation on the electrical grid and emissions, I use a simplified model of electricity generation. The planner must select a combination of generation sources to minimize costs with the constraint that the total generation must equal the load. The quantity of electricity that needs to be supplied is imperfectly forecast and the value of the load is distributed uniformly \( L \sim U \left[(1 - \alpha)\bar{L}, (1 + \alpha)\bar{L}\right] \). Wind power is also imperfectly forecast and its value is also distributed uniformly \( W \sim U \left[(1 - \nu)\bar{W}, (1 + \nu)\bar{W}\right] \). Uniform distributions are chosen for tractability. Wind generation has a per-MWh cost of zero.

Assume there are two other sources of power generation: coal and natural gas. Coal and natural gas generation have per-MWh costs of \( c_{\text{Coal}} \) and \( c_{\text{NG}} \) respectively. Assume \( c_{\text{NG}} > c_{\text{Coal}} \). Additionally, let coal power have an inflexible output level that must be chosen before the actual load and wind generation levels are determined. Natural gas generation is adjustable and its output level can be selected after the load and wind generation levels are known.

The lowest cost solution where \( W + q_{\text{Coal}} + q_{\text{NG}} = L \) is to set \( q_{\text{Coal}} \) equal to the minimum possible required generation, with the lowest realization of load and the highest realization of wind generation. This is

\[
q_{\text{Coal}} = (1 - \gamma)\bar{L} - (1 + \nu)\bar{W}
\]

---

9 This does not include the value of any emissions reductions besides CO₂.

10 Assume that \( \nu \) and \( \gamma \) are between zero and one.

11 I abstract away from wind curtailment, or using less wind power than could be generated. In the context of this model, however, wind curtailment would never be beneficial.
The amount of natural gas generation will be the quantity that is required to set total generation equal to total load, taking $q_{\text{Coal}}$ as given:

$$q_{\text{NG}} = L - W - (1 - \gamma)\bar{L} + (1 + \nu)\bar{W}$$

Increasing wind generation lowers the amount of natural gas generation.\textsuperscript{12} However, increased forecast uncertainty (higher $\nu$ or $\gamma$) will lead to increased levels of natural gas generation and lower amounts of coal. Because natural gas generation is more expensive and cleaner than coal generation, this increased uncertainty will also lead to increased costs and lower emissions levels. The relative value of these effects is unknown. This motivates the empirical work in this paper, which estimates the effect of wind generation intermittency on the use of coal and natural gas generation, along with the corresponding effect on emissions.

\section{Background}

The Electric Reliability Council of Texas (ERCOT) organizes the operation of the electricity grid for about 75\% of Texas, including 85\% of the state’s electric load. ERCOT’s boundaries are shown in Figure 1. Electricity generation can come from a variety of sources. Wind, coal, nuclear and natural gas power are the dominant sources for ERCOT, comprising 99.2\% of total generation in 2013.\textsuperscript{13} With wind power accounting for 9.9\% of generation in 2013, ERCOT has the highest wind generation capacity of any U.S. state.

Wind generation capacity in Texas has grown quickly from near-zero levels in 2000, though installation of additional wind generation capacity has slowed since 2009, as seen in Figure 2.\textsuperscript{14} The actual quantity of wind power generated in ERCOT, dependent on installed

\textsuperscript{12}In this simplified model, when wind generation reduces the total fossil fuel generation, only coal generation is lowered. In practice, this effect can reduce generation from both coal and natural gas power.

\textsuperscript{13}The remaining electricity is generated mainly by hydropower, solar and biomass.

\textsuperscript{14}Little wind generation capacity became active in 2013; this was likely due to the lapsing of the federal Production Tax Credit (PTC) at the end of 2012. In order to qualify for that subsidy, wind turbines needed to be operational by the end of that year. Later legislation extended the PTC so that any turbine that had begun construction by the end of 2013 would also qualify and additional turbines are expected to be completed throughout 2014 and 2015.
capacity, wind conditions and the ability of grid operators to dispatch the wind power, has also grown over time, though less so since 2011, as seen in Figure 3. Wind generation curtailment, where potential wind generation is not actually used, can occur and is mostly due to transmission constraints between the western region of Texas containing most of the wind generation capacity and the more populated regions. However, a long term project to increase transmission capacity between these areas (CREZ) has substantially reduced curtailment of wind power in recent years.

Additionally, while the electrical grid in the rest of the continental U.S. is more interconnected, ERCOT is relatively isolated with only a small number of connections to other regions, as seen in Figure 4. This isolation allows electricity dispatch operations within Texas to largely be conducted independently of the surrounding regions.

Under the current nodal system, instituted on November 1, 2010, ERCOT runs both day-ahead and real-time markets for electricity. Because electricity cannot be economically stored in large quantities, ERCOT identifies the most cost-effective way to generate electricity to match the expected load while respecting the system constraints, such as those imposed by the transmission lines. ERCOT also obtains reserve power so generation capacity is available to either increase or decrease generation quickly in response to unexpected changes.

Wind generation units participate with the other generator types in the wholesale ele-

---

15There are two DC connections to the Southwest Power Pool (SPP) with a combined capacity of 820 MW and three DC connections to Mexico with a combined capacity of 286 MW. The DC connections allow control over the flow of power. Additionally two power plants can generate electricity simultaneously for both ERCOT and an outside grid.

16For the day-ahead market, bids for both supply and demand of electricity for each hour of the next day at specific locations may be submitted to ERCOT by 10 AM. Unit characteristics such as minimum and maximum output levels must also be submitted. ERCOT releases the results of this auction by 1:30 PM. This stage of the market does not take ERCOT’s forecasted load into account and allows firms to reduce the price risk of transacting power in the real-time market. The next stage, day-ahead reliability unit commitment, occurs at 2:30 PM and does take forecasted load into account. ERCOT modifies expected generator output for all hours of the next day so that planned generation will meet expected load at least cost while respecting constraints placed by the transmission grid. This reliability unit commitment process is repeated hourly with updated ERCOT forecasts and operating plans on the part of the generation units. Under normal circumstances, the real-time market runs every five minutes. In the real-time market ERCOT adjusts the requested output from all generators based on changing conditions and does so to maintain system reliability while minimizing cost. As part of minimizing generation cost, ERCOT attempts to have the outcome of the real time market minimize the use of regulation service, where ERCOT can request changes in output within three to five seconds to maintain appropriate frequency.
tricity markets run by ERCOT. Because wind power does not consume any fuel and is very inexpensive to operate once built, these wind units generally, though not always, submit very low bids and are dispatched whenever possible, given constraints on the electric grid.\textsuperscript{17} There are differences in their treatment because of the intermittent nature of wind power. Penalties for deviating from the requested output are relaxed for wind generation units so that wind generation can “follow the wind”. Additionally, wind forecasts are critical in determining maximum potential generation in future periods. When operators of wind generation units report their maximum potential output level for each upcoming hour in the day-ahead and reliability unit commitment markets, this value cannot exceed ERCOT’s forecast of their potential wind generation. In the real-time market when dispatching wind turbines, ERCOT uses a telemetered value based on current conditions at that generation site for the maximum possible output for each wind generator instead of a value reported by the wind unit operator.

An extensive discussion of the ERCOT market arrangements with respect to wind generation can be found in Sioshansi and Hurlbut (2010)

4 Data

Data for this project comes from ERCOT, the EPA, Weather Underground and the U.S. Census. The analysis uses data from February 22, 2011 to December 31, 2013.\textsuperscript{18} Focusing on this period avoids ERCOT’s institutional shift from a zonal to a nodal market, which occurred on November 1, 2010 as well as large changes in the price of natural gas.\textsuperscript{19}

Generator output data comes from ERCOT. Generator output data from ERCOT’s real-time (SCED) market is available at 15 minute intervals and includes the quantity of electricity

\textsuperscript{17}Because of subsidies, wind generation units often submit bids with negative values.
\textsuperscript{18}I am missing data for some variables for a small number of days during this time period.
\textsuperscript{19}As seen in Figure 2, during the time period examined in this paper there is little growth in installed wind turbine capacity so observed changes in potential wind generation will be mainly due to changing weather conditions. Note that over longer time horizons, changes in wind generation could be due to the installation of additional wind turbines.
generated by and the maximum potential output of each generation unit.\textsuperscript{20} The maximum potential output levels for wind generation units at the time the generation units are dispatched depend on wind conditions and are telemetered data instead of being submitted by the wind unit operators. Quantity of electricity generated only includes power added to the grid and does not count any electricity consumed by the generator itself. This generation data is often aggregated to the ERCOT-level for analysis.

Forecasted levels of potential wind generation for upcoming hours are also available at hourly frequency from ERCOT. ERCOT’s forecasts of potential wind generation include a distribution of potential outcomes. The data includes values for potential wind generation that, according to the forecast, have a 80\% and 50\% chance of being exceeded.

Data on hourly CO\textsubscript{2} emissions from power generation units are obtained through the EPA’s Continuous Emissions Monitoring System (CEMS). CEMS allows the EPA to track compliance with emissions-related regulations.\textsuperscript{21} I use hourly emissions data for generation units within ERCOT and assume that all generation units that are affected by wind generation in ERCOT are included.

A small number of natural gas units are missing CO\textsubscript{2} data. I fill in these missing values using predicted values based on the heat rate, which is also available from CEMS.\textsuperscript{22} If valid readings are not available, EPA requires that high emissions levels be recorded as a penalty. The Sandy Creek coal facility recorded very high and unchanging emissions rates for an extended period of time that were clearly due to CEMS recording issues. The generation and emissions from this unit have been dropped from the analysis.

I create a single hourly temperature measure for Texas using a population-weighted average of the 10 largest cities in ERCOT. Historical temperature data for these cities was

\textsuperscript{20}This is called the High Sustainable Limit and assumes unlimited time to reach that speed. In practice the amount of power that can be generated on short notice can be less than this maximum level.

\textsuperscript{21}Generation units with a capacity less than 25 MW are not required to participate in CEMS and so this analysis omits emissions from those units.

\textsuperscript{22}The R\textsuperscript{2} for the regression used in the prediction is about 0.95. Novan (Forthcoming) also uses the heat rate to approximate CO\textsubscript{2} emissions for units with missing data.
obtained from the Weather Underground website.\textsuperscript{23,24} The city populations were taken from the 2000 Census.

Pricing data for coal is at the monthly level and is the average cost of coal delivered for electricity generation in Texas. Coal pricing data comes from the EIA’s Electric Power Monthly. Pricing data for natural gas at the daily level and is the spot price for delivery at the Henry Hub as reported by the EIA. Fuel costs are calculated using measures of the heat content of fuel consumed (from CEMS) and the cost of that fuel.\textsuperscript{25}

5 Wind Intermittency

Potential wind generation is dependent on actual wind conditions which changes over time. Intermittency can come from both expected and unexpected changes in wind generation. As an example, Figure 5 plots the hourly predicted and actual maximum wind generation for January 1, 2012, where the prediction for potential wind generation was made one hour earlier. The predicted maximum wind generation changes over the day, ranging from over 6000 MWh to less than 2000 MWh. Additionally, the actual maximum amount of wind generation was consistently different than the predicted value.

ERCOT’s forecast of future potential wind generation is used to help ensure the stability of the electric grid by anticipating future changes in fossil fuel generation requirements and to allow ERCOT to obtain those generation requirements in a low-cost manner. Furthermore, as noted by an ERCOT representative, “with the increased percentage of the system load served by wind, it becomes critical to have not only a good forecast of how wind will generate during the day, but also an assessment of the level of uncertainty in that forecast.” (ERCOT Press Release, 2010). The short run wind forecasts used by ERCOT have improved substantially \textsuperscript{23}The airport associated with the city was the location of the data. Some cities share an airport and in those cases the weight for that airport’s temperature was the sum of the population of both cities. \textsuperscript{24}Some cities did not have historical temperature data for some hours. In these cases, the statewide weighted temperature measure was calculated without those cities. \textsuperscript{25}These costs are approximations to the actual price paid by the generators, which will vary across generators. For example, natural gas prices vary geographically. Furthermore, coal prices can vary depending on the type of coal used by specific generators.
in recent years. Figure 6 shows the distribution of one-hour-ahead potential wind generation forecast errors. In all years from 2011-2013, the mean forecast error is near zero (-11.6 MWh in 2011, -8.5 MWh in 2012 and 4.9 MWh in 2013). However, the average magnitude of the forecast error has declined even as additional wind turbines have been installed and overall wind generation levels increased, falling from 471.97 MWh in 2011 to 305.06 MWh in 2012 and 312.80 MWh in 2013.\footnote{Six hour ahead potential wind forecasts have not noticeably improved in terms of average magnitude of forecast error over these three years.}

Because the generation must match total load, this wind intermittency will affect the operations of the electric grid. An decrease in wind generation must be balanced by either a decrease in electric load or an increase of electricity into the grid from another sources; either some form of storage or through increased generation from fossil fuel generators. Large scale battery storage is not financially feasible and Texas obtains a very small proportion of its electricity come from hydropower, another form of electricity storage that Texas lacks the necessary geography to effectively exploit.\footnote{In January 2013, a 36-MW battery project was completed, however this is not a substantial size given that the average wind generation in Texas is 3266 MWh.} Demand response to maintain grid stability is an alternative means of adjusting for changes in wind generation. While ERCOT has worked to incorporate some load to be capable of quickly reducing their power consumption in response to a signal, demand response has historically been used only several times per year.\footnote{There were 21 uses of demand response between April 2006 and October 2011.} Increased use of real-time pricing may also help, though having demand quickly adjust to unforeseen changes in wind generation may not be as straightforward as adjusting fossil fuel generation levels.

Adjusting the amount of fossil fuel generation in response to changes in wind generation is an alternative. However, fossil fuel generators have different abilities to adjust output levels; natural gas is much more flexible, with the ramping rate of combined cycle natural gas units generally about four times that of coal units (Tremath et al. [2013]). If it becomes more optimal from either a cost minimization or grid stability perspective to have a more
flexible mix of fossil fuel generation sources, then this could result in a shift towards using more natural gas to meet the same level of necessary fossil fuel generation.

Figure 7 shows the observed mix of hourly natural gas and coal generation at different levels of fossil fuel generation from Texas during the sample period. At any given level of fossil fuel generation, there is a range of observed mixes of coal and natural gas generation. Determining which mix to use in any given hour be based on a number of factors. Dynamic considerations are one; if a given fossil fuel generation level occurs in the middle of the night, that would likely result in a different generation mix than if it occurred in late afternoon because the latter would likely use more peaking generation. Plant maintenance is another, if a coal facility is being repaired then this will likely result in increased natural gas generation to compensate. If additional flexibility in fossil fuel output levels is preferred, this may also result in shifting generation mix towards natural gas, as suggested in the stylized model from Section 2.

While the wind power intermittency may result in a preference for more flexible fossil fuel output levels to better adjust to future changes in potential wind generation, wind power also directly offsets fossil fuel generation requirements, as also seem in the model from Section 2. Figure 8 illustrates these different effects: as the level of wind generation increases, the level of fossil fuel falls, decreasing natural gas generation. If the desire for fossil fuel output flexibility increases, however, the quantity of natural gas generation for a given level of total fossil fuel generation increases.

5.1 Electricity Generation and Emissions

Electricity generation was responsible for 32% of greenhouse gas emissions in the United States in 2012. While some generation sources such as wind, solar, geothermal or nuclear power do not produce emissions, burning coal or natural gas does. Any effect of wind power on emissions will depend on how it affects the operation of the grid. If the intermittent nature of wind power causes a shift in the fossil fuel mix towards more flexible natural
gas generation, then this could reduce emissions because natural gas generating units are generally cleaner than coal units. Additionally, when total fossil fuel generation is reduced in response to increased wind generation, the resulting reduction in emissions will depend on what type of generation unit was offset. Table 1 shows the average emissions rates for coal and natural gas generation units in the dataset. Electricity generated from coal, on average, emits over twice as much CO₂ pollution as electricity generated from natural gas. However, the cost of the fuel consumed in natural gas generation tends to be more expensive than coal generation.

If wind intermittency changes the fossil fuel generation mix, then this would likely impact emissions and fuel costs. For a given level of fossil fuel generation, emissions would be expected to be higher when coal makes up a larger share of the fossil fuel generation. Additionally, generators are less efficient when they are changing output levels. When fossil fuel generators must ramp their production levels up or down to compensate for changes in wind generation, this can reduce the efficiency of these generators and lead to increased emissions. The magnitude of this impact as compared to shifting fossil fuel generation mix is an empirical question.

In addition to impacting emissions through intermittency, wind generation affects emissions by reducing the total amount of fossil fuel generation. This effect results in a corresponding decrease in emissions. Kaffine et al. (2012) and Novan (forthcoming) find that the effect of additional wind generation on emissions is related to the type of generation units whose output is reduced by the wind power. Thus on average, if wind power reduces coal power instead of non-peaker natural gas power, the effect of that increase of wind power on emissions will on average differ substantially.

The marginal generator can in turn depend on what the overall load is. Figure 7 shows how on average the use of coal versus natural gas generation changes as the total fossil fuel }

\footnote{Novan (forthcoming) finds that increased wind generation results in larger emissions reductions when total generation levels are lower and coal is more likely to be the marginal unit.}

\footnote{Fell and Kaffine (2014) find that increased wind generation generally reduces coal generation capacity factors and this effect is stronger when natural gas prices are lower.}
fuel generation increases in Texas. Initially at low fossil fuel generation levels, additional
generation on average comes from both natural gas and coal generation. Once fossil fuel
generation is at about 30,000 MWh, further generation primarily comes from natural gas
plants, as can be seen by the essentially flat slope of the coal generation-net generation
relationship when net generation is high. Thus when total fossil fuel generation is high, the
effect of wind power on reducing total fossil fuel generation is likely to reduce natural gas
power.

6 Empirical Analysis

Using ERCOT-wide time series data, I examine how wind power intermittency affects the
fossil fuel generation mix, CO$_2$ emissions and fuel costs. I initially test if wind generation
has an effect on electricity generation and emissions apart from simply reducing the amount
of necessary fossil fuel generation and find this is the case. I then test if this additional effect
changes in different situations, across electric load levels and across years, before testing
the effect of explicit wind intermittency variables. I then test the impact of wind power
intermittency on CO$_2$ emissions and fuel costs.

6.1 Baseline Model

To observe the effect of wind intermittency, my baseline model estimates the average effect
of additional wind generation on the fossil fuel generation mix while controlling for the effect
of wind generation on reducing total fossil fuel generation using the following specification:

$$\text{NatGasGeneration}_t = \beta_1 W_t + f(\text{FossilFuel}_t) + \alpha_0 + \alpha_1 \text{Temp}_t + \alpha_2 \text{Temp}_t^2 + \gamma_{m} \text{HourMonth}_t + \epsilon_t \quad (1)$$
\( \text{NatGasGeneration}_t \) is the amount of natural gas generation in hour \( t \).\(^{31}\) The fossil fuel generation mix will be affected by the total amount of fossil fuel generation as seen in Figure 7. This is captured through the \( f(\text{FossilFuel}_t) \) term, a fifth-degree orthogonalized polynomial.\(^{32}\) The amount of required fossil fuel generation is total required electricity generation net of generation from other fuel sources. The amount of total electricity demand is assumed to be exogenous. Power must then be generated to meet this inflexible load. For the state of Texas, this mainly comes from nuclear, fossil fuel and wind power.\(^{33}\) Nuclear power reduces the amount of fossil fuel generation, but these generation levels do not substantially change in the short term and are also taken to be exogenous. Wind power also reduces the required amount of fossil fuel generation, as illustrated in Figure 8.\(^{34}\)

The amount of wind power generated in hour \( t \), \( W_t \), reduces the amount of fossil fuel generation, as illustrated in Figure 8 and this effect is captured in \( f(\text{FossilFuel}_t) \). Wind generation is allowed to have an additional effect, captured by \( \beta_1 \). Identifying these effects separately comes from variation in the total electric load as the wind power effect on total fossil fuel generation is set to have the opposite effect as total electric load. If \( \beta_1 \) is not equal to zero, then wind generation has an additional effect on the dependent variables apart from simply reducing the quantity of generation required from other sources. Considering that, unlike conventional generation sources, wind power is not perfectly dispatchable and depends on wind conditions, I will initially attribute this effect to wind intermittency. Later specifications will include specific intermittency related variables.\(^{35}\)

\(^{31}\)Note that because I control for the total level of fossil fuel generation, increasing the amount of natural gas generation is increasing the share of natural gas generation in the fossil fuel generation mix. These results are robust to directly using the share of natural gas in fossil fuel generation as the dependent variable, as shown in Appendix A.

\(^{32}\)Results are robust to using alternative degrees.

\(^{33}\)Other power sources such as biomass, solar and hydroelectric comprise less than 1\% of the generation.

\(^{34}\)I assume that wind conditions do not affect the total load. Novan (forthcoming) notes that most wind generation resources are located in a different area of Texas as most electricity demand. Novan further notes that the windspeed conditions on the ground are not highly correlated with windspeed conditions at the height of the wind turbine blades.

\(^{35}\)If \( \beta_1 \) does represent the effect of wind power intermittency, then nuclear power (which does not produce emissions and whose production is not dependent on weather conditions) should not have an additional effect on the dependent variables apart from its role in reducing fossil fuel generation. I separately run this test and, as expected, find no significant effect for nuclear power apart from reducing fossil fuel
Temperature affects the efficiency of generators, with high temperatures reducing efficiency. Heterogeneous effects of temperature on efficiency across generator types could affect the fossil fuel generation mix.

*HourMonth* is an hourly dummy variable that varies by year-month combination *m*, included to address dynamic issues. Figure 9 plots the average total generation and wind generation for each hour. The top panel shows that the average need for fossil fuel generation can change across the hours of the day.\(^3\)\(^6\) For the same level of total fossil fuel generation, baseload generators (those with lower marginal costs and less flexibility) should be a larger share of the fossil fuel generation when the total required fossil fuel generation is near a local minimum as compared to when it is near a local maximum; hourly controls are included to address this. Because both average total generation and average wind generation are related to the hour and this relationship can differ across months, as seen in the lower two panels of Figure 9, I also allow the hourly fixed effects to vary across months. This specification will also control for movement in relative fuel prices across months.

The amount of wind generation may not be exogenous. While wind speed likely is exogenous, actual wind generation can be less than the maximum level allowed if grid operators choose. This curtailment could happen for a number of reasons, most prominently transmission constraints. To address endogeneity issues with wind curtailment, I instrument for ERCOT-wide wind generation using the maximum possible generation (high sustainable limit) given current conditions for all wind generation units. This is the expected maximum potential output of wind power used by ERCOT when dispatching wind generation resources.\(^3\)\(^7\),\(^3\)\(^8\) Note that actual wind generation is on average quite close to the high sustain-

\(^3\)\(^6\)Total generation in Figure 9 includes nuclear power, however this does not vary substantially across hours.

\(^3\)\(^7\)The maximum possible wind generation values in the real-time market are set by ERCOT based on telemetered values, not on reported values from the operator of the wind generation resource. However, maintenance decisions for wind turbines could be endogenous.

\(^3\)\(^8\)This differs from Novan (forthcoming) who uses a measure of wind speed as an instrument.
able limit and wind curtailment drops substantially from 2011 to 2013. Appendix B tests the importance of using an instrument for the potentially endogenous wind generation variable and finds only minor differences.

To correct standard errors for heteroskedasticity and serial correlation, Newey-West standard errors with 69 lags are used. The lag order was determined through the automatic bandwidth selection procedure of Newey and West (1994).

Table 2 shows selected results for this specification. After accounting for its effect in reducing fossil fuel generation, a 1 MWh increase in wind generation is associated with a 0.034 MWh shift in the fossil fuel generation mix away from coal and toward natural gas.

### 6.2 Changes in Effect Across Load and Time

While additional wind power shifts the fossil fuel generation mix towards natural gas, this effect may be less prominent when natural gas is already a larger portion of the generation mix. To test if this intermittency effect falls as load gets larger, I use the following specification which allows for a different impact depending on if total generation net of nuclear power is relatively high or low:

\[
\text{NatGasGeneration}_t = \beta_1 W_t \times \mathbf{1}[\text{High Load}_t] + \beta_2 W_t \times \mathbf{1}[\text{Low Load}_t] + \beta_3 \mathbf{1}[\text{High Load}_t] + f(\text{FossilFuel}_t) + \alpha_0 + \alpha_1 \text{Temp}_t + \alpha_2 \text{Temp}_t^2 + \gamma_m \text{HourMonth}_t + \epsilon_t \tag{2}
\]

where the cutoff for the high or low load indicator function is having total generation net

\[39\] This is also close to the 3 days worth of lags used in Kaffine et al. (2012) when studying CO₂ emissions in ERCOT.
of nuclear power above or below 30,000 MWh, approximately its mean. When generation net of nuclear power is this high, generally there is already a larger share of natural gas generation, as seen in Figure 7. Table 3 shows the point estimate of the wind intermittency effect on shifting fossil fuel generation from coal to natural gas is weaker when total generation net of nuclear power is greater than 30,000 MWh, falling from 0.048 MWh to 0.028 MWh.

To test if the intermittency effect changes over time, potentially as experience is gained with relatively high levels of wind penetration and wind forecast precision increases, I allow it to differ across years as follows:

\[
\text{NatGasGeneration}_t = \beta_1 W_t \times 1[\text{year} = 2011]_t + \\
\beta_2 W_t \times 1[\text{year} = 2012]_t + \\
\beta_3 W_t \times 1[\text{year} = 2013]_t + \\
f(FossilFuel_t) + \\
\alpha_0 + \alpha_1 \text{Temp}_t + \alpha_2 \text{Temp}^2_t + \gamma_m \text{HourMonth}_t + \epsilon_t \quad (3)
\]

Coefficient estimates can be found in Table 4. The wind intermittency effect on shifting fossil fuel generation from coal to natural gas is strongest in 2011, as is its impact on CO₂ emissions. A 1 MWh increase in wind generation is associate of a shift in fossil fuel generation from coal to natural gas of 0.075 MWh. By 2013, the same 1 MWh increase in wind generation was responsible for a shift in fossil fuel generation from coal to natural gas of 0.021 MWh.\(^{41}\) To the extent that wind forecast precision has improved from 2011, as seen in Figure 6, any given level of wind generation may be associated with lower risk of unexpected change in wind generation in the later years, potentially contributing to the intermittency effect in

\(^{40}\)The difference in impact is statistically significant at the 10% level.

\(^{41}\)The difference in the effect on natural gas generation between 2011 and 2012 is significant at the 10% level while testing that the effect is the same in 2011 and 2013 has a p-value of 0.11.
2011, $\beta_1$, being substantially larger than the other $\beta$ parameters. Additional experience with higher levels of wind generation could also be a contributing factor.

### 6.3 Explicit Intermittency Variables

In previous specifications, the effect of additional wind beyond reducing fossil fuel generation has been interpreted as the effect of wind intermittency without indicating what feature or features of wind generation was causing such effects, such as forecasted or unforecasted change in wind generation. Identifying the specific features of wind intermittency responsible for effects on fossil fuel generation mix will be important if the value of wind intermittency is to be incorporated into policy decisions. I add a set of explicit wind intermittency variables to do so:

\[
NatGasGeneration_t = \beta_1 W_t + \psi[IntermittencyVars_t] + f(FossilFuel_t) + \alpha_0 + \alpha_1 Temp_t + \alpha_2 Temp^2_t + \gamma_m HourMonth_t + \epsilon_t \tag{4}
\]

where $IntermittencyVars$ are a vector of intermittency related variables that vary across specifications.

To capture the effect of expected changes in wind generation over time, I calculate the standard deviation of wind generation over a five hour window spanning two hours before and after hour $t$ (for the upcoming two hours I use forecasted potential wind generation for those hours in hour $t$ to distinguish between expected and unexpected change.) To capture the effect of uncertainty in wind power forecasts, I use the difference between the 20th and 50th percentiles of ERCOT’s potential wind generation forecast for the upcoming hour.

Four specifications are used with differing vectors of intermittency variables as follows:
1. No intermittency variables; reproduces results from equation 1 for ease of comparison

2. Standard deviation of expected wind generation (expected variation)

3. Uncertainty of wind forecast for upcoming hour (unexpected variation)

4. Standard deviation of expected wind generation (expected variation); uncertainty of wind forecast for upcoming hour (unexpected variation)

Table 5 shows the coefficient estimates for these specifications. Column 1 reproduces the results from Table 2. When the measure of expected variation, the standard deviation of expected wind generation over a five hour window, is included, it shifts fossil fuel generation from coal to natural gas, as seen in Column 2. Similarly, Column 3 shows additional uncertainty in potential wind power forecasts also shifts fossil fuel generation from coal to natural gas. Column 4 includes both types of intermittency (the standard deviation of expected wind generation over a five hour window and the measure of wind forecast uncertainty). The effects of both intermittency variables remain qualitatively the same, shifting natural gas generation from coal to natural gas, although the effect of each individual variable is not as strong as it was when the other was not included.

6.4 Effect of Intermittency on Emissions and Fuel Costs

Because natural gas generation is generally both more expensive and less polluting than coal generation, the effect of wind power intermittency on shifting fossil fuel generation from coal to natural gas should also affect total emissions and fuel costs. Any increase in fuel costs or decrease in emissions as a result of wind generation intermittency are costs and benefits imposed by wind generation but are the value of these impacts are not borne by the owners of wind generation units.

I directly test the effect of wind intermittency on measures of aggregate CO\textsubscript{2} emissions and fuel costs instead of using the fossil fuel generation mix results combined with measures
of average emissions and fuel costs across the generator types. This is because, as noted by Kaffine et al. (2012) and Novan (forthcoming), emissions for a given unit or type of unit is not always at its average level and directly estimating the effect of wind generation intermittency on emissions can account for these varying emissions levels. The same is true for the efficiency of generation units. See Kaffine et al. (2012) or Novan (forthcoming) for a more complete discussion.

To estimate the effect of wind generation intermittency on fuel costs, I use the same approach as in Equation 1, reproduced here:

\[
Dependent\ Var_t = \beta_1 W_t + f(Fossil\ Fuel_t) + \alpha_0 + \alpha_1 Temp_t + \alpha_2 Temp_t^2 + \gamma_m\ HourMonth_t + \epsilon_t \tag{5}
\]

\(Dependent\ Var_t\) is either CO\(_2\) emissions or fuel cost. Coefficient estimates for \(\beta_1\) for both specifications are found in Table 6. After controlling for the effect of wind generation on lowering total fossil fuel generation requirements, the additional effect of wind generation intermittency is associated with reduced overall CO\(_2\) emissions, assuming any additional effect of wind generation is due to intermittency, though the effect on the cost of consumed fuel is close to zero and not statistically significant.\(^{42}\) Considering that wind intermittency was found to shift fossil fuel generation from coal to natural gas, an increase in fuel generation cost may have been expected as the average fuel cost per MWh of every natural gas generator in the sample is higher than the average fuel cost per MWh of every coal generator.

The prior analysis only looks at the same-hour effects of wind generation intermittency on CO\(_2\) emissions and fuel costs. If wind intermittency has a dynamic impact, affecting

\(^{42}\)Measurement error in the dependent variable arises from assuming all coal generators are paying the statewide monthly average rate for coal and that natural gas generators are paying the daily closing price at Henry Hub. This does not incorporate individual long term contracts, individualized transportation costs or differences in coal price due to different coal types. This measurement error will result in less precise estimates of the effect of wind intermittency on fuel costs.
emissions and costs in neighboring periods, then the prior CO₂ and fuel cost estimates will be mismeasured. This could be especially true if wind generation affects the outcomes and timing of generator startup decisions as this process consumes fuel inefficiently. I incorporate effects across hours by allowing wind intermittency two hours before and after the current hour to affect the current hour fuel costs and emissions:

\[
\text{Dependent}Var_t = \sum_{i=-2}^{2} \left[ \beta_i \text{WindGen}_{t+i} + f(\text{FossilFuel}_{t+i}) \right] + \\
\alpha_0 + \alpha_1 \text{Temp}_t + \alpha_2 \text{Temp}_t^2 + \gamma_j \text{MonthHour}_t + \epsilon_t
\] (6)

The dynamic effect of wind intermittency is the sum of the \( \beta_i \) coefficients. The coefficient results are found in Table 7.\textsuperscript{43} Wind intermittency increases cost and decreases CO₂ emissions. The intermittency associated with a 1 MWh increase in wind generation is associated with a fall of CO₂ emissions of 0.0236 tons, with a value of $0.92 when using a social cost of carbon of $39/ton. The associated increase in fuel costs is $1.38. With average wind generation of 3467 MW per hour, the annual increase in fuel generation costs as a result of wind intermittency is about $42 million. However there is also an average hourly reduction of 81.82 tons of CO₂ with an annual value of about $28 million, which substantially offsets the increase in fuel generation costs.

The estimated effect of wind generation intermittency on CO₂ emissions and fuel costs should not be seen as a comprehensive measure of positive and negative externalities imposed by wind generation intermittency. The financial costs of electricity generation come from a number of sources beyond the cost of consumed fuel. Capital costs of constructing the generation units, including interest paid on any initial loan, are also costly. Usage patterns of generators also affect maintenance costs. Newly constructed generation facilities may also require investment in costly additional transmission capacity. Furthermore, natural gas

\textsuperscript{43}Appendix C adds variables measuring expected and unexpected changes in wind generation.
generation is cleaner than coal generation in more ways than just reduced CO$_2$ emissions. Natural gas generation also generally results in less NOx, SO$_2$ and particulate matter pollution. The estimated value of CO$_2$ emissions reduction and increased fuel costs are lower bounds of both costs and benefits of wind intermittency. For example, engineering estimates suggest that wind generation intermittency will have a financial cost of around $2 to $6 per MWh of wind generation (Albadi and El-Saadany [2010]).

7 Conclusion

Wind power intermittency imposes a financial cost on electricity generation. However this intermittency also provides an environmental benefit which should also be accounted for when determining the social impacts of wind generation. On average, wind generation intermittency is associated with increased natural gas generation and reduced coal power. Because natural gas generation is cleaner but more expensive than coal generation, this intermittency-induced shift reduces the emissions resulting from electricity generation but increases fuel costs. The fall in CO$_2$ emissions suggests this shifting effect dominates any generator-level increased inefficiency due to ramping production levels to accommodate wind intermittency.

Using the U.S. social cost of carbon of $39/ton, the average effect of wind intermittency from a 1 MWh increase in wind generation is associated with a reduction in CO$_2$ emissions valued at $0.92, not including the value of any emissions reductions apart from CO$_2$. This value is smaller than the estimated increase in fuel costs of $1.38 as well as engineering estimates of the overall financial costs of wind intermittency of around $2 to $6 per MWh of wind generation but nevertheless indicates a substantial fraction of those financial costs would be offset by environmental benefits. If the social cost of carbon is underestimated due to unmeasurable effects, as suggested by the IPCC (2007) report, then these environmental benefits from wind intermittency will be further understated as well.
The impact of intermittency on emissions reduction is relevant for subsidy policy. While subsidizing each MWh of wind power based on its associated emissions reduction would be ideal, this is not a practical solution. However, connecting the subsidy payments for each wind turbine in part to its expected or actual contribution to total wind power intermittency could be feasible; an additional wind turbine will contribute to the overall variation in wind generation based on how its output is correlated with other wind turbines. Incorporating this when setting subsidy levels would encourage any effect on variation in wind generation to be incorporated into siting decisions for new wind turbines and more accurately align the impact of additional wind turbines on emissions with the subsidy payment. Similarly, any subsidy payment related to wind intermittency could reflect the fossil fuel generation mix in the region. While it may be beneficial to lock in a methodology to calculate subsidy payments before turbine is built to simplify financing concerns (compared to other generation sources, the cost of wind generation is effectively all up-front when building the turbine), changes in the social cost of wind generation intermittency over time would ideally be incorporated as well. Most significantly, when determining the social costs of wind intermittency, the impact of intermittency on both generation costs and emissions reduction should be considered.
References


Figure 1

The ERCOT Region

Source: http://www.opuc.texas.gov/
Figure 2

Total utility-scale wind capacity in Texas (2000-2013)
megawatts (MW)

Source: EIA
Figure 3

Average Hourly Wind Generation By Month

Note: All other figures and analysis use 2011-2013 data
Figure 4

Source: http://www.opuc.texas.gov/
Figure 5
Figure 6

Potential wind generation forecast error is capped at 2000 MWh
Figure 7

Generation By Type vs Non-Nuclear, Non-Wind Generation
Figure 8

Natural Gas Generation

Required Fossil Fuel Generation

Wind Generation Increases

Total Fossil Fuel Generation

Natural Gas Generation with Higher Optimal Flexibility

Natural Gas Generation with Lower Optimal Flexibility
Figure 9

Generation By Hour in March

Generation By Hour in September

Total Generation (MWh) | Wind Generation (MWh)
Table 1

<table>
<thead>
<tr>
<th></th>
<th>Coal</th>
<th>Natural Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average CO2 Emissions (tons/MWh)</td>
<td>1.19</td>
<td>0.53</td>
</tr>
<tr>
<td>Average Fuel Cost ($/MWh)</td>
<td>21.42</td>
<td>30.75</td>
</tr>
<tr>
<td>Average Max Generation (MW)</td>
<td>632</td>
<td>201</td>
</tr>
</tbody>
</table>

Average maximum generation is the average of the highest observed output for each generation unit. Average fuel cost and CO2 emissions is the ratio of total CO2 and total fuel cost to total generation by fuel type.
Table 2

<table>
<thead>
<tr>
<th>VARIABLES</th>
<th>Nat Gas Generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Gen</td>
<td>0.0336*</td>
</tr>
<tr>
<td></td>
<td>(0.0176)</td>
</tr>
<tr>
<td>f(Fossil Fuel Gen)</td>
<td>X</td>
</tr>
</tbody>
</table>

Observations 23,665

Observations are hourly and aggregated to ERCOT-level. Data is from approximately 2011-2013. Newey-West standard errors with 69 lags used to correct for heteroskedasticity and serial correlation. Potential wind generation is used to instrument for actual wind generation. Coefficients for temperature, hour-month indicator variables and nonlinear controls for generation net of nuclear and wind power are omitted. *** p<0.01, ** p<0.05, * p<0.1
<table>
<thead>
<tr>
<th>VARIABLES</th>
<th>Nat Gas Generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Gen (High Load)</td>
<td>0.0282</td>
</tr>
<tr>
<td></td>
<td>(0.0178)</td>
</tr>
<tr>
<td>Wind Gen (Low Load)</td>
<td>0.0483**</td>
</tr>
<tr>
<td></td>
<td>(0.0189)</td>
</tr>
<tr>
<td>High Load Indicator</td>
<td>29.94</td>
</tr>
<tr>
<td></td>
<td>(58.67)</td>
</tr>
<tr>
<td>f(Fossil Fuel Gen)</td>
<td>X</td>
</tr>
<tr>
<td>Observations</td>
<td>23,665</td>
</tr>
</tbody>
</table>

Observations are hourly and aggregated to ERCOT-level. Data is from approximately 2011-2013. Newey-West standard errors with 69 lags used to correct for heteroskedasticity and serial correlation. Potential wind generation is used to instrument for actual wind generation. Coefficients for temperature, hour-month indicator variables and nonlinear controls for generation net of nuclear and wind power are omitted. *** p<0.01, ** p<0.05, * p<0.1
<table>
<thead>
<tr>
<th>VARIABLES</th>
<th>Nat Gas Generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Gen (2011)</td>
<td>0.0751***</td>
</tr>
<tr>
<td></td>
<td>(0.0235)</td>
</tr>
<tr>
<td>Wind Gen (2012)</td>
<td>0.0215</td>
</tr>
<tr>
<td></td>
<td>(0.0238)</td>
</tr>
<tr>
<td>Wind Gen (2013)</td>
<td>0.0209</td>
</tr>
<tr>
<td></td>
<td>(0.0286)</td>
</tr>
<tr>
<td>f(Fossil Fuel Gen)</td>
<td>X</td>
</tr>
</tbody>
</table>

Observations: 23,665

Observations are hourly and aggregated to ERCOT-level. Data is from approximately 2011-2013. Newey-West standard errors with 69 lags used to correct for heteroskedasticity and serial correlation. Potential wind generation is used to instrument for actual wind generation. Coefficients for temperature, hour-month indicator variables and nonlinear controls for generation net of nuclear and wind power are omitted. *** p<0.01, ** p<0.05, * p<0.1
<table>
<thead>
<tr>
<th>VARIABLES</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Gen</td>
<td>0.0336*</td>
<td>0.0300*</td>
<td>0.0200</td>
<td>0.0200</td>
</tr>
<tr>
<td></td>
<td>(0.0176)</td>
<td>(0.0177)</td>
<td>(0.0192)</td>
<td>(0.0191)</td>
</tr>
<tr>
<td>Forecast Uncertainty</td>
<td></td>
<td>0.355**</td>
<td>0.273*</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.160)</td>
<td>(0.161)</td>
<td></td>
</tr>
<tr>
<td>Std Dev of Expected Wind Gen (5 Hr Window)</td>
<td>0.155***</td>
<td></td>
<td>0.131**</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.053)</td>
<td></td>
<td>(0.053)</td>
</tr>
<tr>
<td>f(Fossil Fuel Gen)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Observations are hourly and aggregated to ERCOT-level. Data is from approximately 2011-2013. Newey-West standard errors with 69 lags used to correct for heteroskedasticity and serial correlation. Potential wind generation is used to instrument for actual wind generation. "Std Dev of Expected Wind Gen (5 Hr Window)" measures expected variance in wind generation. "Forecast Uncertainty" is the difference between the 20th and 50th percentile of predicted potential wind generation outcomes in the following hour. Coefficients for temperature, hour-month indicator variables and nonlinear controls for generation net of nuclear and wind power are omitted. *** p<0.01, ** p<0.05, * p<0.1
Table 6

<table>
<thead>
<tr>
<th>VARIABLES</th>
<th>CO₂</th>
<th>Generation Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Gen</td>
<td>-0.0551***</td>
<td>-0.00501</td>
</tr>
<tr>
<td></td>
<td>(0.0118)</td>
<td>(0.575)</td>
</tr>
<tr>
<td>f(Fossil Fuel Gen)</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Observations 23,665 23,665

Observations are hourly and aggregated to ERCOT-level. Data is from approximately 2011-2013. Newey-West standard errors with 69 lags used to correct for heteroskedasticity and serial correlation. Potential wind generation is used to instrument for actual wind generation. Coefficients for temperature, hour-month indicator variables and nonlinear controls for generation net of nuclear and wind power are omitted. NG and Coal results do not sum to "total" results due to a small number of other generation units. *** p<0.01, ** p<0.05, * p<0.1
Table 7

<table>
<thead>
<tr>
<th>VARIABLES</th>
<th>(1)</th>
<th>(2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CO₂</td>
<td>Generation Cost</td>
</tr>
<tr>
<td>Dynamic Wind Gen</td>
<td>-0.0236*</td>
<td>1.38**</td>
</tr>
<tr>
<td></td>
<td>[0.070]</td>
<td>[0.0301]</td>
</tr>
<tr>
<td>f(Fossil Fuel Gen)</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Observations</td>
<td>23,665</td>
<td>23,665</td>
</tr>
</tbody>
</table>

Observations are hourly and aggregated to ERCOT-level. Dynamic effects include impacts over a five hour window. Data is from approximately 2011-2013. Newey-West standard errors with 69 lags used to correct for heteroskedasticity and serial correlation. Potential wind generation is used to instrument for actual wind generation. Coefficients for temperature, hour-month indicator variables and nonlinear controls for generation net of nuclear and wind power are omitted. NG and Coal results do not sum to "total" results due to a small number of other generation units. P-value for F-test of summed effect in brackets. *** p<0.01, ** p<0.05, * p<0.1
Appendix A

The main text commonly uses the level of natural gas generation as a dependent variable. In those specifications, I control for the total level of fossil fuel generation, implying that any increase in natural gas generation increases the share of fossil fuel generation coming from natural gas. I rerun the specifications based on equation 4 using the ratio of natural gas generation to total fossil fuel generation as the dependent variable. Equation 4 is reproduced here:

\[
\left( \frac{\text{Natural Gas Generation}}{\text{Fossil Fuel Generation}} \right)_t = \beta_1 W_t + \psi [\text{IntermittencyVars}_t] + f(\text{FossilFuel}_t) + \alpha_0 + \alpha_1 \text{Temp}_t + \alpha_2 \text{Temp}^2_t + \gamma_m \text{HourMonth}_t + \epsilon_t
\]

I run five specifications, with different combinations of intermittency variables. These are the same as in Section 6.3:

1. No intermittency variables; reproduces results from equation 1 for ease of comparison
2. Standard deviation of expected wind generation (expected variation)
3. Uncertainty of wind forecast for upcoming hour (unexpected variation)
4. Standard deviation of expected wind generation (expected variation); Uncertainty of wind forecast for upcoming hour (unexpected variation)

The coefficient estimates can be found in Table A1. As compared to the earlier results from Table 5 where the dependent variable was natural gas generation levels, all variables except for forecast uncertainty that were statistically significant earlier remain so. No variable that
was not statistically significant in Table 5 is statistically significant in Table A1. Additionally, the signs on all coefficients are the same across Tables 5 and A1.
<table>
<thead>
<tr>
<th>VARIABLES</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NG-Coal Ratio</td>
<td>1.50e-06**</td>
<td>1.38e-06**</td>
<td>1.16e-06</td>
<td>1.16e-06</td>
</tr>
<tr>
<td></td>
<td>(6.77e-07)</td>
<td>(6.82e-07)</td>
<td>(7.58e-07)</td>
<td>(7.56e-07)</td>
</tr>
<tr>
<td>Forecast Uncertainty</td>
<td>8.95e-06</td>
<td>5.82e-06</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(5.83e-06)</td>
<td>(5.41e-06)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Std Dev of Expected Wind Gen (5 Hr Window)</td>
<td>5.50e-06***</td>
<td>4.98e-06**</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(2.05e-06)</td>
<td>(2.05e-06)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>f(Fossil Fuel Gen)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Observations are hourly and aggregated to ERCOT-level. Data is from approximately 2011-2013. Newey-West standard errors with 69 lags used to correct for heteroskedasticity and serial correlation. Potential wind generation is used to instrument for actual wind generation. "Std Dev of Expected Wind Gen (5 Hr Window)" measures expected variance in wind generation. "Forecast Uncertainty" is the difference between the 20th and 50th percentile of predicted potential wind generation outcomes in the following hour. Coefficients for temperature, hour-month indicator variables and nonlinear controls for generation net of nuclear and wind power are omitted. *** p<0.01, ** p<0.05, * p<0.1
Appendix B

While the weather conditions that determine the maximum potential wind generation are exogenously determined, the actual level of wind generation is determined by a combination of windspeed conditions, supply and demand in the wholesale electricity market and transmission constraints. Wind power can be curtailed by grid operators for a variety of reasons; mainly to address congestion issues on transmission lines. The main analysis uses the high sustainable limit of wind generation used by ERCOT in the dispatch process as an instrument for actual wind generation. The actual wind generation is on average close to the high sustainable limit, though this was less earlier in the period studied. Initially in 2011, approximately 8% of potential wind power was curtailed. By 2013, additional transmission capacity was introduced and average wind curtailment fell to under 2%.

To test the importance of using instrumental variables, I redo specifications 1 and 3, reproduced here, without instrumentation.

\[ \text{DependentVar}_t = \beta_1 W_t + f(\text{FossilFuel}_t) + \alpha_0 + \alpha_1 \text{Temp}_t + \alpha_2 \text{Temp}_t^2 + \gamma_m \text{HourMonth}_t + \epsilon_t \]

\[ \text{DependentVar}_t = \beta_1 W_t * 1[\text{year} = 2011]_t + \beta_2 W_t * 1[\text{year} = 2012]_t + \beta_3 W_t * 1[\text{year} = 2013]_t + f(\text{FossilFuel}_t) + \\
\quad \alpha_0 + \alpha_1 \text{Temp}_t + \alpha_2 \text{Temp}_t^2 + \gamma_m \text{HourMonth}_t + \epsilon_t \]

Comparing the parameter estimates from Table B1 to Tables 2 and 4, instrumenting for actual wind generation with potential wind generation does not result in substantial changes, even for the effect of wind intermittency in 2011.
Table B1

<table>
<thead>
<tr>
<th>VARIABLES</th>
<th>(1)</th>
<th>(2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nat Gas Generation</td>
<td>Nat Gas Generation</td>
</tr>
<tr>
<td>Wind Gen</td>
<td>0.0346*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.0178)</td>
<td></td>
</tr>
<tr>
<td>Wind Gen (2011)</td>
<td></td>
<td>0.0760***</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.0235)</td>
</tr>
<tr>
<td>Wind Gen (2012)</td>
<td></td>
<td>0.0294</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.0230)</td>
</tr>
<tr>
<td>Wind Gen (2013)</td>
<td></td>
<td>0.0181</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.0287)</td>
</tr>
<tr>
<td>f(Fossil Fuel Gen)</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Observations</td>
<td>23,665</td>
<td>23,665</td>
</tr>
</tbody>
</table>

Observations are hourly and aggregated to ERCOT-level. Data is from approximately 2011-2013. Newey-West standard errors with 69 lags used to correct for heteroskedasticity and serial correlation. Instrumental variables not used. Coefficients for temperature, hour-month indicator variables and nonlinear controls for generation net of nuclear and wind power are omitted. *** p<0.01, ** p<0.05, * p<0.1
Appendix C

In addition to testing the overall effect of wind intermittency on CO\textsubscript{2} emissions and fuel costs, I examine the effect of the explicit wind intermittency variables that measure expected and unexpected wind power variation. Following the approach from equation 6 (Section 6.4), I allow the intermittency variables from up to two hours before and after hour \( t \) to affect the current dependent variable in order to capture effects outside the current hour such as changing generator start-up decisions. The specification is as follows:

\[
DependentVar_t = \sum_{i=-2}^{2} \left[ \beta_i WindGen_{t+i} + f(FossilFuel_{t+i}) \right] + \\
\sum_{i=-2}^{2} \left[ \alpha_i StdDevOfExpectedWindGen_{t+i} \right] + \\
\sum_{i=-2}^{2} \left[ \gamma_i ForecastUncertainty_{t+i} \right] + \\
\alpha_0 + \alpha_1 Temp_t + \alpha_2 Temp_t^2 + \gamma_j MonthHour_t + \epsilon_t
\]

where \( DependentVar_t \) is either CO\textsubscript{2} emissions or fuel costs. Coefficient estimates for the sum of \( \beta_i, \alpha_i \) and \( \gamma_i \) can be found in Table C1. For fuel costs, the additional explicit intermittency variables are not statistically significant and the coefficient on the 'additional wind generation effect' after controlling for reduced fossil fuel requirements is largely unchanged from when the explicit intermittency variables were not included in Table 7. The CO\textsubscript{2} results, however, are different. The 'additional wind generation effect' is no longer statistically significant though the coefficient estimate is only slightly changed from Table 7. However the measure of expected wind generation variation (the standard deviation of expected wind generation over a five hour window) is statistically significant and reduces CO\textsubscript{2} emissions as would be expected from a shift from coal to natural gas generation. The measure of wind forecast uncertainty is also not statistically significant.
<table>
<thead>
<tr>
<th>VARIABLES</th>
<th>(1)</th>
<th>(2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic Wind Gen</td>
<td>1.44*</td>
<td>-0.021</td>
</tr>
<tr>
<td></td>
<td>[0.054]</td>
<td>[0.162]</td>
</tr>
<tr>
<td>Dynamic Std Dev of Expected Wind Gen (5 Hr Window)</td>
<td>0.179</td>
<td>-0.215***</td>
</tr>
<tr>
<td></td>
<td>[0.846]</td>
<td>[0.002]</td>
</tr>
<tr>
<td>Dynamic Forecast Uncertainty</td>
<td>-1.63</td>
<td>0.0685</td>
</tr>
<tr>
<td></td>
<td>[0.951]</td>
<td>[0.652]</td>
</tr>
<tr>
<td>f(Fossil Fuel Gen)</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Observations 23,665 23,665

Observations are hourly and aggregated to ERCOT-level. Dynamic effects include impacts over a five hour window. Data is from approximately 2011-2013. Newey-West standard errors with 69 lags used to correct for heteroskedasticity and serial correlation. "Std Dev of Expected Wind Gen (5 Hr Window)" measures expected variance in wind generation. "Forecast Uncertainty" is the difference between the 20th and 50th percentile of predicted potential wind generation outcomes in the following hour. Coefficients for temperature, hour-month indicator variables and nonlinear controls for generation net of nuclear and wind power are omitted. P-value for F-test of summed effect in brackets. *** p<0.01, ** p<0.05, * p<0.1