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Effects of wind power intermittency on generation and emissions

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ABSTRACT

Wind power depends on environmental conditions that vary and are imperfectly forecastable. This intermittency could increase the desired flexibility of fossil fuel generation, impacting emissions. This paper finds that various types of wind generation intermittency are associated with a shift towards natural gas generation and decreasing CO_2 emissions. The environmental effects of wind intermittency should be considered when determining the overall impact of intermittency-related activities such as expanded grid storage or turbine siting decisions.

1. Introduction

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 will affect the operation of the electricity grid.

Wind generation reduces the required amount of generation from other sources so if wind generation levels are relatively small compared to the overall electric load, any expected or unexpected variation in wind generation may not be substantial relative to the expected and unexpected variation in electricity load. However if wind generation levels are relatively large, the grid will need to be operated differently due to the intermittent nature of wind generation. In Texas, the region this paper studies, the share of total generation coming from wind power at a specific moment has reached as high as 54%. 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 (2010))

Beyond changes in financial costs of operating fossil fuel generation, wind power intermittency may impact the environmental impacts of the fossil fuel generation as well. 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 wind power intermittency shifts the mix of fossil fuel generation toward cleaner and more flexible natural gas and away from coal, then this would further reduce the pollution from fossil fuel generation, beyond from just the overall lower level of 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 average output levels, this 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 (2015)). The overall effect of this potential shift in the type of fossil fuel generation used and how it operated on emissions, based in increased wind intermittency, is not clear ex-ante.

In addition to impacting emissions through the effects of intermittency, wind generation also impacts emissions by simply reducing the total amount of fossil fuel generation, with a corresponding decrease in emissions. Kaffine et al. (2010) and Novan (2015) 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.[1] The marginal generator can in turn depend on what the overall load is. Fig. 1 shows how on average the use of coal versus natural gas generation changes as the total fossil 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 MW h, further generation primarily comes from natural gas plants. Thus when total fossil fuel generation is high, additional wind power reducing the need for fossil fuel generation, is more likely to result in a reduction in natural gas generation.

Other papers have looked at the integration of large quantities of intermittent generation resources such as wind and solar into the

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[1] Fell and Kaffine (2018) find that increased wind generation generally reduces coal generation capacity factors and this effect is stronger when natural gas prices are lower.

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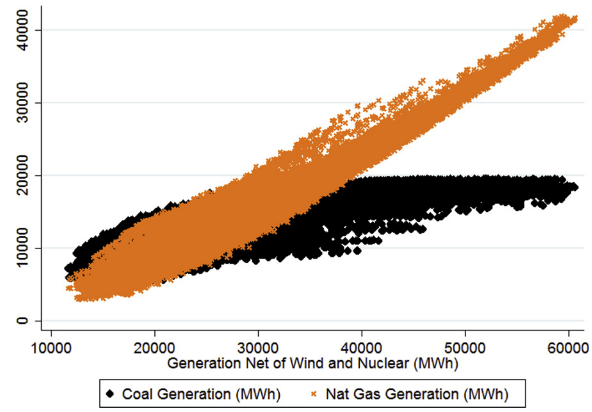

Fig. 1. Generation By Type vs. Non-Nuclear, Non-Wind Generation.

electric grid (Cornelis van Kooten (2010); DeCarolis and Keith (2004); Gowrisankaran et al. (2016)).[2] 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)).

Instead of using a detailed dispatch model of the electricity grid, I use a regression approach to estimate the impact of wind generation intermittency on the operation of the electric grid and the resulting emissions. I use data from Texas, the state with the most installed capacity for wind generation in the United States and the only one of the lower 48 states to have minimal imports and exports of electricity, from approximately 2011 to 2013. I obtain hourly data regarding emissions, fossil fuel generation and both potential and actual wind generation. I find that wind power intermittency does have an effect on the generation mix, increasing the amount of natural gas generation on average. Wind power intermittency is also associated with a decrease in CO_2 emissions.

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 $L \sim U[(1-\gamma)\bar{L},\ (1+\gamma)\bar{L}]$. Wind power is also imperfectly forecast and its value is also distributed uniformly $W \sim U[(1-\nu)\bar{W},\ (1+\nu)\bar{W}]$.[3],[4] 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_{Coal} and c_{NG} respectively. Assume $c_{NG} > c_{Coal}$. 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 $W + q_{Coal} + q_{NG} = L$ is to set q_{Coal} equal to the minimum possible required generation, with the lowest realization of load and the highest realization of wind generation. This is

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

The amount of natural gas generation will be the quantity that is required to set total generation equal to total load, taking q_{Coal} as given:

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

Increasing wind generation lowers the amount of natural gas generation.[5] However, increased forecast uncertainty (higher ν or γ) 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 chapter, which estimates the effect of wind generation intermittency on the use of coal and natural gas generation, along with the corresponding effect on emissions and generation costs.

3. Background

The Electric Reliability Council of Texas (ERCOT) organizes the operation of the electricity grid for about 75% of Texas, including 90% of the state's electric load. Wind, coal, nuclear and natural gas power are the dominant sources for ERCOT, comprising 99.2% of total generation in 2013.[6] With wind power accounting for 9.9% of generation in 2013, at the time ERCOT has the highest wind generation capacity of any U.S. state, and this remains true as of 2017.

ERCOT is relatively isolated with only a small number of connections to other regions.[7] 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 electricity 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. However, there are differences in their treatment because of the intermittent nature of wind power. An extensive discussion of the ERCOT market arrangements with respect to wind generation can be found in Sioshansi and Hurlbut (2010).

4. Data

The data used in the analysis comes from ERCOT, the EPA, Weather Underground and the U.S. Census. The analysis uses data from February 22, 2011 to December 31, 2013.[8] Generator output data comes from

[2] Green and Vasilakos (2010) model how increased wind generation could affect market prices and output with profit maximizing bidding.

[3] Assume that ν and γ are between zero and one.

[4] 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.

[5] 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.

[6] The remaining electricity was generated mainly by hydropower, solar and biomass.

[7] There 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.

[8] I am missing data for some variables for a small number of days during this time period.

ERCOT. Generator output data from ERCOT's real-time market is available at 15 min intervals and includes the quantity of electricity generated by and the maximum potential output of each generation unit given current weather conditions. This generation data is aggregated to the ERCOT-level for analysis.

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

Data on hourly CO_2 emissions from power generation units are obtained through the EPA's Continuous Emissions Monitoring System (CEMS).[9] 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_2 data. I fill in these missing values using predicted values based on their heat rate, which is also available from CEMS.[10] 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.[11] The emissions from this facility during that time period are also replaced with predicted values based on heat rate. I create a single hourly temperature measure for Texas using a 2010-Census population-weighted average of the five largest cities in ERCOT. Historical temperature data for these cities was obtained from the Weather Underground website.

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 (also obtained from CEMS) and the cost of that fuel.[12]

Summary statistics are found in Table 1.

Table 1
Summary Statistics.

Variable	Mean	Std Dev	Min	Max
Total Hourly Generation (MWh)	37,635.86	9,342.79	22,371.83	67,550.11
Hourly Wind Generation(MWh)	3,470.016	2,089.82	6.35	9,566.74
Hourly Natural Gas Generation (MWh)	15,916.63	7,526.25	2,934.97	42,021.29
Hourly Nuclear Generation (MWh)	4,389.814	817.73	1,349.44	5,203.19
Hourly CO2 Emissions (tons)	24,793.78	6,170.55	11,437.31	44,480.51
Hourly Fossil Fuel Generation Cost ($)	786,928.5	284,789	281,719.7	2,011,700
Forecast Uncertainty	735.48	144.46	87.1	906.70
Std Dev of Expected Wind Gen (5 Hr Window)	425.22	292.86	10.55	2,317.23

Observations are hourly and aggregated to ERCOT-level. Data is from approximately 2011-2013. "Std Dev of Expected Wind Gen (5 Hr Window)"measures expected variance in wind generation across a five hour window centered on the current hour. "Forecast Uncertainty" is the difference between the 20th and 50th percentile of predicted potential wind generation outcomes in the following hour.

5. Empirical analysis

Using ERCOT-wide time series data, I examine how wind power intermittency affects the fossil fuel generation mix, CO_2 emissions and generation fuel costs. These estimates are short-run effects that do not incorporate any long-run adjustments 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 2013 capacity was already installed in Texas at the beginning of that three year period. The impact of installing additional wind turbines on wind generation intermittency depends on how correlated the new wind generation is with the previously installed capacity.

5.1. Impact of wind power intermittency

To observe the effect of wind intermittency on the generation mix, CO_2 emissions and fuel cost for fossil fuel generation, I initially estimate the following model:

$$
\begin{aligned}
&NatGasGeneration_t \;\; OR\; CO_2Emissions_t \;\; OR\;\; FuelCost_t \\
&\quad = f\,(RequiredFossilFuel\;\; Generation_t) + \beta_1 Expected\; StdDev\; Wind_t \\
&\qquad + \beta_2 Forecast\; Uncertainty_t + \beta_3 Wind\; Generation_t + \alpha_1 Temperature_t \\
&\qquad + \alpha_2 Temperature_t^2 + \gamma_m Hour\; Month_t + \varepsilon_t
\end{aligned}
$$

$NatGasGeneration_t$ is the amount of natural gas generation in hour *t*. $CO_2Emissions_t$ is the amount of CO_2 emitted in hour *t*. *$FuelCost_t$* is the approximated cost of fuel consumed by fossil fuel generators in hour *t*[13]

Perhaps the most important control variable is *f (RequiredFossilFuelGeneration$_t$)*. This is modeled as a fifth-degree orthogonalized polynomial and is intended to capture the non-linear impact on the outcome variables of increasing the amount of fossil fuel generation that is required to have generation match electricity demand. Increased wind generation levels will lower this amount of required fossil fuel generation, which would be expected to lower natural gas generation, CO_2 emissions and the fuel costs of operating the fossil fuel generators. The impact of increased wind levels on offsetting aggregate required fossil fuel generation will be captured by this term.[14]

Beyond simply reducing the amount of fossil fuel generation needed, additional wind generation can further impact the outcome variables if increased intermittency concerns alter the operation of the grid. To capture the effect of expected changes in wind generation over time, I calculate *$ExpectedStdDevWind_t$*; the standard deviation of wind generation over a five hour window spanning two hours before and after hour *i*.[15] To capture the effect of uncertainty in wind power forecasts, I also test the impact of *$ForecastUncertainty_t$*, the difference between the 20th and 50th percentiles of ERCOT's potential wind

[9] 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.

[10] The R^2 for the regression used in the prediction is about 0.95. Novan (2015) also uses the heat rate to approximate CO_2 emissions for units with missing data.

[11] If valid readings are not available, EPA requires that high emissions levels be recorded as a penalty.

[12] 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.

[13] I directly test the effect of wind intermittency on measures of aggregate CO_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. (2013) and Novan (2015), 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. (2013) or Novan (2015) for a more complete discussion.

[14] I assume that wind conditions do not affect the total load. Novan (2015) notes that most wind generation resources are located in a different area of Texas as most electricity demand. Novan (2015) further notes that the wind-speed conditions on the ground are not highly correlated with windspeed conditions at the height of the wind turbine blades.

[15] For the upcoming two hours I use forecasted potential wind generation for those hours in hour *t* to distinguish between expected and unexpected change.

generation forecast for the upcoming hour.

*WindGeneration*t will capture any remaining impact of wind generation on the outcome variables not captured by the resulting reduction of required fossil fuel generation (as measured by the impact on the output variables via changes in $f(RequiredFossilFuelGeneration_t)$), the associated forecast uncertainty in the upcoming hour (as measured by $ForecastUncertainty_t$) and expected changes in wind generation over the surrounding hours (as measured by $ExpectedStdDevWind_t$). This is assumed to be intermittency-related, but not captured by the other two explicit measures of intermittency. For example, this could include the impact of even shorter run variation in expected wind generation, measures of wind forecast uncertainty not captured by the uncertainty measure calculated from the public data.

For each of the three outcome variables, four specifications are used, controlling in different ways for wind intermittency: only the unaccounted for intermittency impact ($WindGeneration_t$); the unaccounted for intermittency impact and $ExpectedStdDevWind_t$; the unaccounted for intermittency impact and $ForecastUncertainty_t$; and all three intermittency variables together.

Temperature is also controlled for non-linearly as high temperatures are associated with reduced generator efficiency and increased fuel costs and emissions. Furthermore, the mix of generators used will vary for the same amount of non-nuclear generation depending on the season and time of day. Controls for each hour-month-year combination are included to capture this effect.

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).[16] The identification of the impact of intermittency is through exogenous variation in the intermittency variables, which are assumed to be determined by wind conditions. A robustness check using instrumental variables follows in Section 5.2

Tables 2–4 contain the results for these specifications, for natural gas generation, CO_2 emissions and generation fuel costs as dependent variables, respectively. When looking at the first specification without either of the specific intermittency variables (column 1 in Tables 2–4), the impact of intermittency from additional wind generation does lead to a statistically significant increase in natural gas generation and reduction in CO_2 emissions.

When also controlling for a measure of expected wind intermittency, $ExpectedStdDevWind_t$, (column 2 in Tables 2–4), ExpectedStdDevWindt is associated with an increase in natural gas generation and a decrease in CO_2 emissions. The magnitude of the estimated "additional" impact of intermittency from wind generation as measured by $WindGeneration_t$ falls slightly in both cases and the estimated impact on natural gas generation is no longer statistically significant.

Similarly, when instead controlling for a measure of uncertainty in wind forecasts, $ForecastUncertainty_t$ (column 3 in Tables 2–4), increased wind forecast uncertainty leads to an increase in natural gas generation and a decrease in CO_2 emissions. Once again, when explicitly controlling for the impact of a specific type of wind intermittency, the magnitude of the estimated "additional" impact of intermittency from additional wind generation as measured by $WindGeneration_t$ falls for both outcome variables (to a greater extent in this case) and the estimated effect on natural gas generation is again no longer statistically significant.

When controlling for all three measures of wind intermittency at the same time (column 4 in Tables 2–4), only $ExpectedStdDevWind_t$ has a statistically significant effect on the amount of natural gas generation; $ForecastUncertainty_t$ and the remaining wind intermittency effect from wind generation are also estimated to increase natural gas generation but not in a statistically significant fashion. Both $ExpectedStdDevWind_t$ and the additional intermittency effect from wind have a statistically significant effect by reducing the amount of CO_2 emissions; $ForecastUncertainty_t$ is also estimated to reduce CO_2 emissions as well, but not in a statistically significant manner.

Lastly, none of the intermittency variables are found to have a statistically significant effect on generation fuel cost in any of these specifications. Note that measurement error in the dependent variable arises from assuming all coal generators are paying the statewide

Table 2
Effect of Wind Intermittency on Natural Gas Generation.

Variables	(1) NG Gen	(2) NG Gen	(3) NG Gen	(4) NG Gen
Wind Generation (Extra Intermittency Effect)	0.0287*	0.0252	0.0162	0.0160
	(0.0173)	(0.0174)	(0.0191)	(0.0191)
Std Dev of Expected Wind Gen (5 Hr Window)		0.139***		0.118**
		(0.0527)		(0.0523)
Forecast Uncertainty			0.319**	0.248
			(0.158)	(0.158)
f(Fossil Fuel Gen)	X	X	X	X
Temperature	7.691	7.723	7.565	7.620
	(26.57)	(26.55)	(26.58)	(26.56)
Temperature^2	−0.0962	−0.0969	−0.0990	−0.0989
	(0.209)	(0.208)	(0.209)	(0.209)
Observations	24,162	24,162	24,162	24,162
Adjusted R^2	0.986	0.986	0.986	0.986

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. "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 hour-month-year 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 3
Effect of Wind Intermittency on CO_2 Emissions.

Variables	(1) CO2 (tons)	(2) CO2 (tons)	(3) CO2 (tons)	(4) CO2 (tons)
Wind Generation (Extra Intermittency Effect)	−0.0386***	−0.0356***	−0.0295**	−0.0294**
	(0.0128)	(0.0128)	(0.0143)	(0.0143)
Std Dev of Expected Wind Gen (5 Hr Window)		−0.120***		−0.105**
		(0.0424)		(0.0427)
Forecast Uncertainty			−0.232*	−0.168
			(0.134)	(0.135)
f(Fossil Fuel Gen)	X	X	X	X
Temperature	−168.3***	−168.3***	−168.2***	−168.2***
	(21.74)	(21.73)	(21.75)	(21.74)
Temperature^2	1.383***	1.384***	1.385***	1.385***
	(0.174)	(0.173)	(0.174)	(0.173)
Observations	24,162	24,162	24,162	24,162
Adjusted R^2	0.985	0.985	0.985	0.985

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. "Std Dev of Expected Wind Gen (5 h 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 hour-month-year indicator variables and nonlinear controls for generation net of nuclear and wind power are omitted.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

[16] This is also close to the 3 days worth of lags used in Kaffine et al. (2013) when studying CO_2 emissions in ERCOT.

Table 4
Effect of Wind Intermittency on Generation Fuel Cost.

Variables	(1) Gen Cost	(2) Gen Cost	(3) Gen Cost	(4) Gen Cost
Wind Generation (Extra Intermittency Effect)	0.183	0.235	0.507	0.509
	(0.570)	(0.571)	(0.624)	(0.624)
Std Dev of Expected Wind Gen (5 Hr Window)		−2.068		−1.423
		(1.826)		(1.805)
Forecast Uncertainty			−8.297	−7.432
			(6.576)	(6.624)
f(Fossil Fuel Gen)	X	X	X	X
Temperature	−7,322***	−7,323***	−7,319***	−7,320***
	(1148)	(1148)	(1148)	(1147)
Temperature^2	58.40***	58.41***	58.47***	58.47***
	(9.281)	(9.278)	(9.269)	(9.267)
Observations	24,162	24,162	24,162	24,162
Adjusted R^2	0.986	0.986	0.986	0.986

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. "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 hour-month-year indicator variables and nonlinear controls for generation net of nuclear and wind power are omitted.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

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.

5.2. Robustness checks

For the results shown in Tables 2–4, a Newey-West standard error was used with 69 lags to address heteroskedasticity and serial correlation. As a robustness check, I rerun the final specification in each of the tables where all the intermittency variables were included with the standard error clustered at the weekly level. The results are found in Table 5. No parameter estimate switches from “statistically significant" to “statistically insignificant" or vice versa.

Additionally, for the results shown in Tables 2–4, all explanatory variables were assumed to be exogenous. While wind speed is surely 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 potential endogeneity issues with wind curtailment, I instrument for ERCOT-wide wind generation using the maximum possible generation 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.[17] Comparing the results from Tables 2–6, instrumenting for actual wind generation with potential wind generation does not result in substantial changes. Furthermore, as noted by Cullen (2013), if the wind curtailment is simply caused by transmission congestion that itself is caused by high levels of wind generation, this does not introduce endogeneity into the parameter estimates.

[17] This differs from Novan (2015) who uses a measure of wind speed as an instrument.

Table 5
Robustness Check: Clustering Standard Errors By Week.

Variables	(1) NG Gen	(2) CO2 (tons)	(3) Gen Cost
Wind Generation (Extra Intermittency Effect)	0.0160	−0.0294*	0.509
	(0.0212)	(0.0157)	(0.674)
Std Dev of Expected Wind Gen (5 Hr Window)	0.118**	−0.105**	−1.423
	(0.0498)	(0.0423)	(1.863)
Forecast Uncertainty	0.248	−0.168	−7.432
	(0.171)	(0.143)	(7.004)
f(Fossil Fuel Gen)	X	X	X
Temperature	7.620	−168.2***	−7,320***
	(27.45)	(24.10)	(1271)
Temperature^2	−0.0989	1.385***	58.47***
	(0.215)	(0.192)	(10.14)
Observations	24,162	24,162	24,162
Adjusted R^2	0.919	0.904	0.902

Observations are hourly and aggregated to ERCOT-level. Data is from approximately 2011-2013. Standard errors are clustered by week. "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 hour-month-year 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
Robustness Check: Instrumenting for Actual Wind Generation Using Potential Wind Generation.

Variables	(1) NG Gen	(2) CO2 (tons)	(3) Gen Cost
Wind Generation (Extra Intermittency Effect)	0.0168	−0.0300**	0.516
	(0.0190)	(0.0142)	(0.625)
Std Dev of Expected Wind Gen (5 Hr Window)	0.116**	−0.104**	−1.413
	(0.0522)	(0.0427)	(1.803)
Forecast Uncertainty	0.241	−0.163	−7.420
	(0.158)	(0.135)	(6.629)
f(Fossil Fuel Gen)	X	X	X
Temperature	8.054	−168.7***	−7,340***
	(26.58)	(21.74)	(1149)
Temperature^2	−0.102	1.388***	58.66***
	(0.209)	(0.173)	(9.280)
Observations	24,162	24,162	24,162
Adjusted R^2	0.986	0.985	0.986

Observations are hourly and aggregated to ERCOT-level. Data is from approximately 2011-2013. Instrumenting for actual wind generation using potential wind generation. 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 hour-month-year indicator variables and nonlinear controls for generation net of nuclear and wind power are omitted.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

6. Conclusion

This paper has shown that wind power intermittency can cause a shift towards more flexible generation sources and a reduction in CO_2 emissions. When those sources are cleaner, this intermittency provides an additional environmental benefit apart from simply offsetting fossil fuel generation, which should also be accounted for when determining the social impacts of additional wind generation or policies that would impact how wind intermittency affects the operation of the grid. For example, when determining the social value of different siting decisions where the output from additional wind turbines would be more or less correlated with existing wind turbines, a less correlated location would cause more intermittency concerns and thus potentially a shift to more flexible dispatchable generation sources.[18] To the extent that batteries could more fully address the intermittency problems of wind generation in the future by reducing the need of more flexible fossil fuel generators to compensate for expected and unexpected changes in wind generation, the marginal environmental value of additional wind generation may be lowered (assuming the more flexible generator types that are no longer needed as much were cleaner, as is the case when comparing natural gas and coal).

Furthermore, while this study looked estimated the impact of wind intermittency on key outputs in Texas, this impact will differ by region. Areas with a mix of natural gas and coal may find that this intermittency effect is larger as there would be more scope to shift between coal and natural gas generation. Similarly, while this study examined the impact of wind power, the same general issue of intermittency would apply to solar photovoltaic power as well.

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[18] This additional intermittency would also have additional financial costs which could come from a number of sources beyond the cost of consumed fuel, such as costs of constructing additional flexible generation units and increased maintenance costs from greater amounts of ramping output up and down. 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).