Intermittency and the Effect of Wind Generation on Emissions

Reid Dorsey-Palmateer

Camp Resources Presentation

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How Does Wind Power Affect Emissions?

- Electricity generation was responsible for 32% of all GHG emissions in the U.S. in 2012
- Increased wind generation can reduce emissions
  - Burning fossil fuels creates emissions
  - Wind generation replaces fossil fuel generation
- Potential wind generation depends on wind conditions
  - Wind conditions change over time
  - Wind conditions are not perfectly forecastable

Research Question

- Earlier research has estimated average impact of wind generation on emissions
  - Novan (2011), Cullen (2013), Kaffine et al. (2013)
- Earlier research finds intermittency in generation increases generation costs
  - Gowrisankaran et al. (2013)
  - Backup energy sources are costly

How important is wind intermittency to the overall effect of wind generation on emissions?

How Could Wind Generation Intermittency Affect Emissions?

- Natural gas generators...
  - Produce fewer emissions than coal
  - Have more flexible output levels than coal
- Changing wind conditions cause potential wind generation to vary over time
  - Increases variance of fossil fuel generation
  - Shifts fossil fuel generation towards natural gas?
  - Inferior emissions rates due to increased ramping?
- Day-ahead wind generation forecasts could influence generator startup decisions

Data

- Texas data
  - More wind generation capacity than any other state
  - Isolated electric grid
  - Natural gas represents a relatively large share of generation (40% of production)
- Feb 2011- Dec 2013
- Hourly data on CO2, SO2, and NOx emissions from generators in Texas (EPA)
- Data on individual generation unit output (ERCOT)
  - Includes actual output and maximum potential output
  - Data is aggregated to hourly average, TX-wide level
- Hourly temperature data for 10 largest cities in ERCOT (Weather Underground)

What is the Average Effect of Wind Power on Emissions?

$$Emissions_h^{TYPE} = \beta_1 WindGen_h + f(Load_h - NukeGen_h) + \alpha_0 + \alpha_1 Temp_h + \alpha_2 Temp_h^2 + \theta_i Week_h + \gamma_j HourMonth_h + \varepsilon_h$$

- Dependent variable is CO2/NOx/SO2 emissions from fossil fuel generators
- $f(Load_h - NukeGen_h)$ is fifth-degree orthogonalized polynomial
  - Higher levels of total generation should be associated with higher levels of emissions
- Maximum wind generation is used as instrument for observed wind generation
- Standard errors are clustered at weekly level

Does Wind Generation Have An Additional Effect Beyond Reducing Total Fossil Fuel Generation?

$$Emissions_h^{TYPE} = \beta_1 WindGen_h + f(Load_h - NukeGen_h - \mathbf{WindGen_h}) + \alpha_0 + \alpha_1 Temp_h + \alpha_2 Temp_h^2 + \theta_i Week_h + \gamma_j HourMonth_h + \varepsilon_h$$

- β_1 is average effect of wind generation on emissions controlling for the effect of wind power reducing total fossil fuel generation

Including Explicit Intermittency-Related Variables

$$\begin{aligned} Emissions_h^{TYPE} = & \beta_1 WindGen_h + f(Load_h - NukeGen_h - WindGen_h) + \\ & \beta_2 \mathbf{WindStdDevWithinHr_h} + \\ & \beta_3 \mathbf{ShortfallVsForecastedWind_h} + \\ & \alpha_0 + \alpha_1 Temp_h + \alpha_2 Temp_h^2 + \theta_i Week_h + \gamma_j HourMonth_h + \varepsilon_h \end{aligned}$$

- $WindStdDevWithinHr_h$ measures short term variation in wind generation
- $ShortfallVsForecastedWind_h$ measures how much higher day-ahead forecasted maximum wind generation was compared to actual maximum wind generation

Effect Of Wind Generation on CO2 Emissions

VARIABLES	(1) CO2	(2) CO2	(3) CO2
Wind Generation	-0.615***	-0.0677***	-0.0532***
	(0.00910)	(0.0106)	(0.0128)
Wind Std Dev Within Hour			-0.167***
			(0.0608)
Shortfall Vs. Forecasted Wind			0.0359***
			(0.0133)
f(Gen. Net Nuclear)	X		
f(Gen. Net Nuclear and Wind)		X	X
Observations	24,279	24,279	23,965
R^2	0.990	0.991	0.991

Robust standard errors in parentheses. Control variables omitted.

*** p<0.01, ** p<0.05, * p<0.1

Effect of Wind Intermittency on CO2 Emissions

- Mean reduction in CO2 from 'within hour wind standard deviation': 22.3 tons/hour
- Mean reduction in CO2 from 'shortfall vs day ahead forecast': 34.4 tons/hour
  - 49.4% of observations have forecasted potential wind above actual potential wind
  - Failed to reject symmetric overforecast/overforecast effect
- Remaining effect of wind generation on CO2 may in part be due to short run forecast error?
- For comparison, average hourly reduction in CO2 for overall wind power is 2134 tons

Source of Effect of Wind Generation on CO2 Emissions

VARIABLES	(1) NG Generation	(2) CO2 Rate (Coal)	(3) CO2 Rate (NG)
Wind Generation	0.0159	-1.41e-06***	-1.67e-06***
	(0.0171)	(5.27e-07)	(3.80e-07)
Wind Std Dev Within Hour	0.205***	3.48e-06	-1.37e-06
	(0.0731)	(3.22e-06)	(2.13e-06)
Shortfall Vs. Forecasted Wind	-0.118***	-4.13e-06***	1.03e-06**
	(0.0177)	(7.27e-07)	(4.51e-07)
f(Gen. Net Nuclear)			
f(Gen. Net Nuclear and Wind)	X	X	X
Observations	23,965	23,965	23,965
R^2	0.992	0.767	0.910

Robust standard errors in parentheses. Control variables omitted.

*** p<0.01, ** p<0.05, * p<0.1

SO2 and NOx Results Are Similar

VARIABLES	(1) SO2	(2) SO2	(3) NOx	(4) NOx
Wind Generation	-1.371***	-0.0432	-0.733***	-0.162***
	(0.0975)	(0.159)	(0.0203)	(0.0293)
Wind Std Dev Within Hour		-1.261**		-0.313**
		(0.540)		(0.136)
Shortfall Vs. Forecasted Wind		0.430***		0.123***
		(0.151)		(0.0292)
f(Gen. Net Nuclear)				
f(Gen. Net Nuclear and Wind)	X	X	X	X
Observations	24,279	23,965	24,279	23,965
R^2	0.893	0.897	0.967	0.969

Robust standard errors in parentheses. Control variables omitted.

*** p<0.01, ** p<0.05, * p<0.1

Conclusion

- Reducing total fossil fuel generation is responsible for the majority of emissions reductions from wind generation
- Approximately 10% of the CO2 reduction, 30% of the NOx reduction and 20% of the SO2 reduction comes from other channels
  - Increased variation of wind generation within an hour lowers emissions
  - Shortfalls in wind generation (compared to day-ahead forecast) increase emissions
- For more cost-effective results, subsidy policy could compensate wind turbines differently depending on how intermittent their output is
  - When determining value of intermittency, include effect on operational costs as well as value of environmental impact