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The Effect of Wind on Electricity CO_2 Emissions: The Case of Ireland

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Abstract: This paper evaluates the effect of wind generation on CO_2 emissions using 2008-2012 historical data for the Irish Single Electricity Market. Wind generation decreases CO_2 emissions, but by less than the average system emissions. When we evaluate the results by technology, we find that wind generation has the same cumulative effect on emissions from both CCGT and coal plants, but displaces more generation from CCGTs than from coal for every MWh of wind. This result is driven by the high number of CCGT plants on the system, their flexibility and position in the merit order. Moreover, as wind displaces CCGTs, it also pushes them to generate less efficiently, displacing somewhat fewer CO_2 emissions. Finally wind displaces about 5% fewer emissions when the pumped storage plants are on outage, suggesting that wind is more effective in more flexible systems.

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1 Introduction

This paper measures the CO_2 emissions displaced by increasing wind generation in an electricity system with capacity payments. We use the Irish Single Electricity Market (SEM) as a case study.

The SEM encompasses the electricity grids of both the Republic of Ireland and Northern Ireland, making it a cross-jurisdiction, cross-currency system. It is a compulsory pool system, where plants bid their short-run marginal costs and are called to generate on the basis of the merit order: plants that provide lower bids are dispatched before more expensive plants.[1]

Many jurisdictions are interested in decreasing emissions and increasing the share of renewable energy to meet environmental targets and mitigate climate change. In 2012 renewable energy amounted to 6% of total energy consumed and 11% of electricity in the Republic of Ireland (SEAI, 2014) and generated 12% of electricity in Northern Ireland (NISRA, 2013). To achieve the targets set by the European Directive (2009/28/EC), both governments have set a goal of 40% penetration of renewables in electricity generation by 2020, with most of it coming from wind (DCENR, 2012; DETI, 2010).

Extensive data are available from the beginning of the SEM in November 2007. The SEM data are particularly well suited to our analysis for several reasons: first, the island has limited interconnection with other systems allowing us to identify the effect of wind more easily. Second, it has experienced a large increase in installed wind capacity, more than doubling from about 900MW at the end of 2007 to almost 2100MW by August 2012 and reaching levels of instantaneous wind penetration equal to 50% of demand. Third, it is a compulsory pool system and therefore the published data refer to almost all of the electricity traded in the SEM. All generators with a capacity greater than 10MW have to sell their generation into the centralised pool. Similarly, all buyers have to buy from the pool.

The standard approach when evaluating the effect of wind on emissions is to use bottom-up simulation models, as in Traber and Kemfert (2011) or Denny and O'Malley (2006). This method allows the study of the effect of wind generation in a controlled setting, keeping all other variables constant. The main drawback is that such studies assume that demand and wind generation are perfectly forecast and thereby tend to underestimate the uncertainty caused by the variability of wind.

This paper differs from the studies above by undertaking an econometric analysis of the effect of wind using historical data. Historical information on electricity markets is becoming more common. Cullen (2013) uses an econometric approach to examine the effects of wind on the ERCOT market in Texas between 2005 and 2007. Because firms are allowed to bid freely in that market, he concentrates on the effects of wind on firms' bidding and generating decisions and finds that wind mostly offsets Combined-Cycle Gas Turbine (CCGT) plants in a system where natural

[1] As of the summer of 2014, there are ongoing discussions on how to change the SEM to comply with the EU Target model by the end of 2016 (SEM, 2014).

gas accounted for 43% of generation. Kaffine et al. (2013) use data from 2007 to 2009 for ERCOT. Kaffine et al. (2013) suggest that larger savings in emissions are likely in coal-dominated systems.

We start by measuring the effects of wind on system-wide CO_2 emissions and find that an additional MWh of wind decreases emissions, as expected, although by less than the average system emissions. As noted by Cullen (2013) and Campbell (2009), wind is likely to displace generation from flexible sources. In a merit-order system it is also more likely to displace more expensive generation.

To identify what drives the emissions displaced, we extend the analysis to study the relation between wind generation and CO_2 emissions by plant type (coal, baseload gas, etc.). We find that wind tends to displace generation from baseload gas plants more than from coal plants, a finding that is consistent with both the hypotheses that more flexible plants are displaced first and that there is a merit-order effect. When estimating the results by plant type we deal with numerous periods when plants do not generate, especially for plant types that generate less frequently (e.g. oil or distillate-fuelled plants). We address the challenges introduced by "zero-inflated" data when discussing an appropriate estimation strategy.

The rest of the paper is organised as follows. Section 2 introduces the SEM in more detail. Section 3 describes the data. Section 4 explains the methodology and the results. Section 5 concludes.

2 The SEM

The SEM is a gross mandatory pool with a single System Marginal Price (SMP) in each period. Plants bid in the day-ahead market and are stacked according to their bids, from cheapest to most expensive. They are called to generate in that order until they produce enough to service existing demand, after accounting for each plant's technical constraints. The SMP is based on a market schedule that does not account for transmission constraints. If transmission constraints arise in the real time market, plants that are constrained off still collect the SMP for that period but have to return the equivalent of the costs they did not incur, based on their bids. Plants that are called to generate even if they were not included in the unconstrained market schedule will be compensated for their generation costs, but do not receive that period's SMP.

In addition to the SMP, plants receive capacity payments. The payments are based on a capacity payment pot determined every year by the regulators (Commission for Energy Regulation -CER- in the Republic or Ireland and Northern Ireland Authority for Utility Regulation -NIAUR- in the North) and allocated depending on how tight the market is in every period. Higher payments are given at times when demand is large relative to available generation capacity.

The SEM operates within the EU and is therefore subject to the EU Emissions Trading System (ETS).

The regulatory authorities monitor the market through the Market Monitoring Unit. Power plants are required to bid their short run marginal cost in line with the bidding code of practice (available from the regulator's website: www.allislandproject.org), based on day-ahead spot prices.

The SEM has limited interconnection to other electricity systems. During the period of our study there was only one interconnector between Northern Ireland and Scotland, the Moyle interconnector, with an import capacity of about 400MW. Since then a second 500MW interconnector has been commissioned between Wales and the Republic of Ireland (the East-West Interconnector).

Wind generators in the SEM obtain the system marginal price (SMP) for each MWh they generate. They are guaranteed a minimum price for 15 years under the REFIT scheme in addition to a small fixed payment. If the SMP falls below the marginal price they receive an additional payment to cover the difference (Devitt and Malaguzzi Valeri, 2011).

3 Data description

We use half-hourly information on electricity generation and demand and daily fuel and carbon costs for the period that goes from 1 January 2008 to 28 August 2012.

The market operator SEMO publishes data on the shadow price, the amount generated by each plant and the availability of each plant (among other variables) on a half-hourly basis. Generation by plant is downloaded from the system operator's website (www.sem-o.com). We use the Transmission System Operators' (TSO) data for demand and wind generation.[2] For the Republic of Ireland, the TSO data on demand is calculated by measuring not only generation that is registered with the SEM, but all installed wind capacity on the island, some of which is estimated, and imports and exports along the interconnectors. It does not include the output of some small CHPs.[3]

Quarter-hour wind generation for the Republic of Ireland comes from EirGrid, and half-hour wind generation for Northern Ireland comes from SONI, the system operator of Northern Ireland. We average the Republic of Ireland data to build a half-hourly series and add it to the SONI wind information to obtain an all-island (RoI+NI) wind series. This wind generation series accounts not only for wind directly registered with SEMO, but also for wind generation that is smaller than 10MW capacity and does not bid into the market directly. Total wind is about 20% to 25% higher than the wind generation registered with SEMO, depending on the year.

Information on fuel prices comes from Datastream. Specifically, coal prices are the API2 prices traded on the London market, converted in euro using daily exchange rates from Datastream. Natural gas prices are from the UK hub (UKNBP). Carbon dioxide emission permit prices are spot prices, taken from Point Carbon. Fuel and carbon dioxide permits are traded Monday through

[2]The SEMO variable 'load' is not a good proxy for demand. For example it excludes imports and exports, includes pumped storage demand and excludes demand that is met by plants that do not bid directly in the SEM.

[3]Details at `http://www.eirgrid.com/operations/systemperformancedata/systemdemand/`.

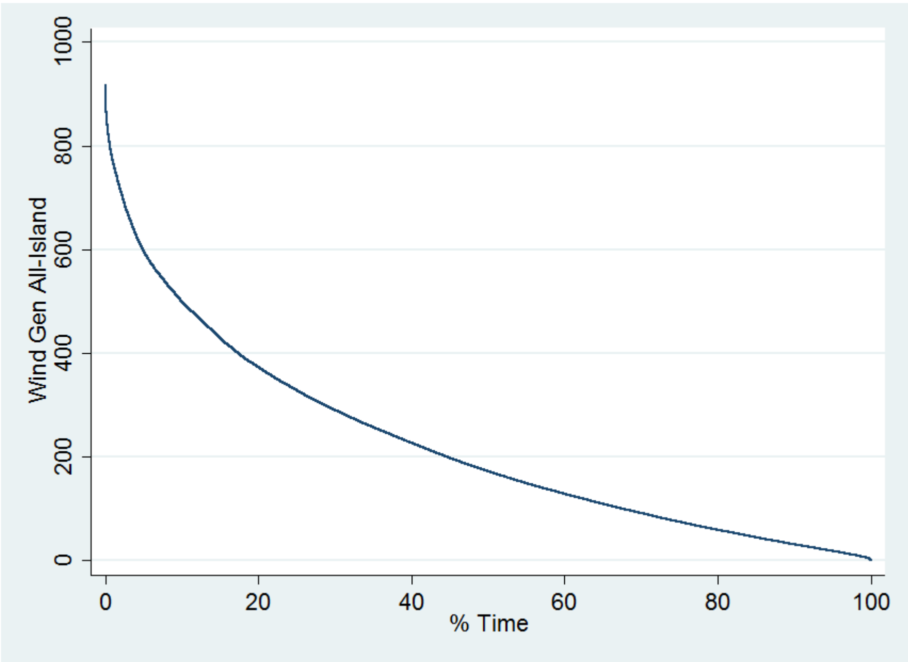
Friday. We set weekend prices equal to those of the previous Friday. All information on prices is on a daily basis and in nominal terms.

Table 1: Summary statistics, half-hour data 1 January2008 - 28 August 2012

Variable	Obs	Mean	Std. Dev.	Min	Max
Wind (MWh)	81648	223.67	185.28	0.24	918.90
Load (MWh)	81648	2030.29	444.06	1073.50	3424.25
CO_2 Emissions (Tonnes)	81648	930.37	225.38	403.56	1923.16
Gas price_{t-48} (€/MWh)	81648	19.87	5.88	4.62	32.14
Coal price_{t-48} (€/MWh)	81648	4.36	1.18	2.48	8.11
Generation (MWh)	81648	1687.50	443.17	587.81	3208.33
CO_2 price_{t-48} (€/tonne)	81648	12.59	6.39	0.01	24.95

Table 1 reports summary statistics for our dataset for the period from 1 January 2008 to 28 August 2012 on a half-hourly basis. The system is relatively small, with a peak demand of about 6850 MWh (note that since the demand and generation variables are per half hour, they need to be multiplied by two to obtain the hourly value.)

Figure 1: Wind duration curve, 2008-2012



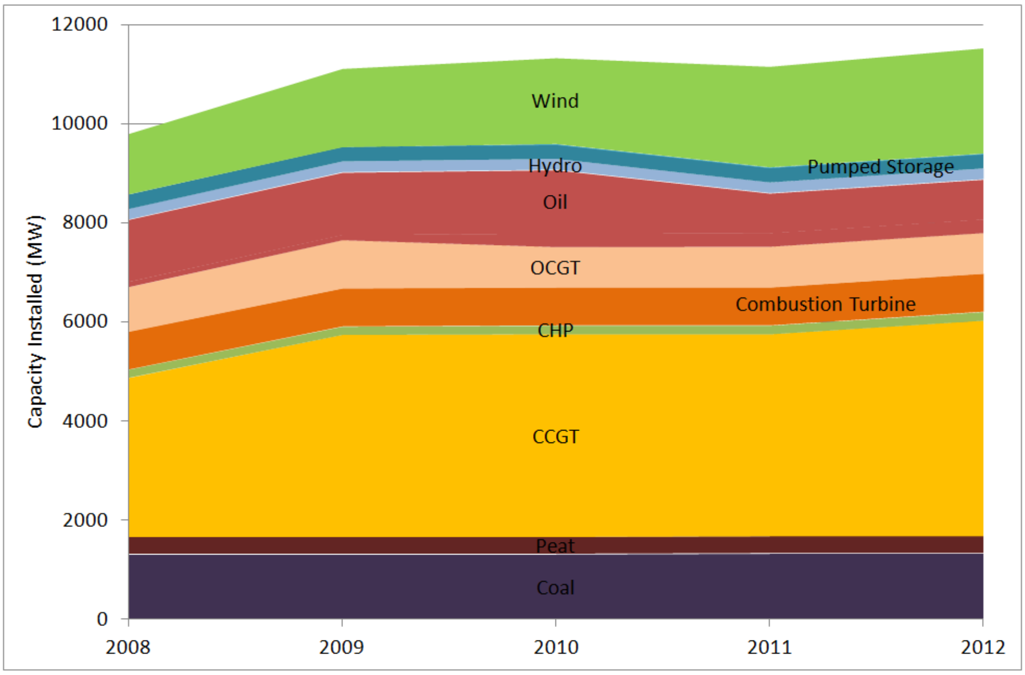
Duration curve for onshore wind in 2008-Aug.2012; source: our calculations from EirGrid and SONI data

Figure 1 shows the duration curve for wind generation during our period of analysis, or the share of time wind generation is above any given level. Hourly wind generation in the SEM exceeded 200MW about 40% of the time and 100MW about 80% of the time.

During the period of analysis there have been some changes in the SEM plant portfolio. Installed wind capacity increased from about 12.5% in 2008 to 18.5 % of total generation capacity (interconnection is excluded). Capacity of flexible fossil sources was 60.9 % of the total (including combined-cycle, open-cycle gas turbines, natural gas combustion turbines, distillate and oil). Finally, coal and peat were 14.5% of the total capacity installed in 2012, down from 16.9% in 2008.

Figure 2 shows the changes in installed capacity on the Island of Ireland from 2008 to 2012.

Figure 2: Installed generation capacity, All Ireland (MW), 2008-2012



Source: our elaboration of validated files from the All Island Project and data from EirGrid and SONI.

We calculate carbon dioxide emissions by following the methodology used in Wheatley (2013) and extend it to encompass Northern Ireland and multiple years. We use the amount of electricity generated by plant, from SEMO, and the plant-level heat rates available from the regulators' yearly review of the market model (at www.allislandproject.org) to calculate fuel consumed in each period by each plant. From here, using the appropriate fuel carbon content factors published in Howley et al. (2012), we calculate carbon dioxide emissions associated with each plant in each period and sum them over all plants to obtain system-wide emissions for each period. Note that we do not associate any emissions to imports along the interconnector.

To verify that our calculations are correct, we compare cumulative emissions for the Republic of Ireland plants to the emissions associated with Irish power plants in the EU Emissions Trading System (EU ETS) per year. Table 2 shows that our estimated emissions fall within 2% of reported emissions.

Table 2: Our calculation versus EU CO_2 inventories for ROI, 2008-2011, thousand tonnes

Year	EU Gas Inventories (ktonnes CO_2)	Our calculations (ktonnes CO_2)	Difference(%)
2008	13704	14005	2%
2009	12382	12466	1%
2010	12687	12745	0%
2011	11254	11420	1%

Source: own calculations and European Environment Agency (2013), Annex 1.5.

A few plants faced special circumstances during the study period. Aghada and Whitegate, two Combined-Cycle Gas Turbine generators (CCGTs), were commissioned in 2010 and 2011. To facilitate their integration in the system the TSO imposed specific generation times (independent of their bids) during a commissioning period. We eliminate these plants' generation and the associated emissions during the commissioning period for the system-wide econometric analysis. The Edenderry peat-powered plant switched to biomass co-firing during the study period, starting by co-firing about 1% of fuel and ending with about 15%. We do not have day-specific shares of peat versus biomass inputs. We also know that peat plants have preferential dispatch and therefore are not affected by wind generation.[4] We therefore exclude the Edenderry plant from the system CO_2 emission analysis. All the results presented in the aggregate econometric study are based on emissions excluding Edenderry.

4 Methods and results

System emissions are the sum of the emissions of the plants that generate in each period. How plants are dispatched depends on the decisions of several agents, in addition to a series of exogenous variables: plant managers decide when to perform maintenance on the plants and what price and quantity to bid in the day ahead market (in accordance with the bidding code of practice); plants are dispatched based on the bids received, the expected load, expected renewables generation and expected outages; finally, realised load, wind, unplanned outages, transmission constraints and the need to maintain appropriate voltage and frequency determine the actual plant dispatch.

In this study we do not analyse the generation decisions of each plant manager or the constraints that need to be met to maintain reliability of the system directly. Rather, we evaluate how all the joint decisions and constraints affect wind's effectiveness at displacing emissions. In essence, we are trying to identify the marginal unit of generation that is displaced by an increase in wind generation and its associated emissions, net of any changes needed to maintain reliability. The marginal unit is not constant over time: the generating mix varies as the quantity of electricity demanded changes over the course of the day and the year and plant closure and commissioning occurs.

4.1 All System

We first check that system CO_2 emissions are stationary using the augmented Dickey-Fuller test. The null hypothesis of unit root is rejected at the 1% level with a value of the Dickey-Fuller statistic equal to -26.85 and a critical value equal to -3.430

Emissions of carbon dioxide tend to be correlated over time, since it takes a few hours for thermal plants to turn on or off. Consequently it is important to specify correlations between time

[4]Peat plants were historically subsidised in Ireland to maintain the employment of peat cutters. These subsidies are designed to be phased out over time.

periods flexibly. We estimate Equation 1 using an autoregressive specification.

$$\begin{aligned} CO_t = \alpha + \beta L_t^i + \gamma W_t^i + \mu PC_{t-48} + \theta gascoalratio_{t-48} + \nu THOut_t + \zeta THOut_t.W_t \\ + \lambda MoyleOut_t + \phi MoyleOut_t.W_t + \sum \kappa^s D_t^s + \epsilon_t \end{aligned} \quad (1)$$

where $\epsilon_t = \rho \epsilon_{t-1}$.[5]

System CO_2 emissions in hour t depend on: the load L, where L is allowed to take on different coefficients depending on the ith ventile of load, where $i = 1$ ....20; wind generation W, where W is also allowed to take different coefficients according to the ith ventile; the previous day's carbon dioxide permit price PC, the ratio of gas to coal generation costs $gascoalratio$, using prior day prices and representative plant efficiencies; a dummy for the periods of outage of the pumped storage plant Turlough Hill and its interaction with wind generation; a dummy for the period of outage of the Moyle interconnector and its interaction with wind generation; and finally a set of dummies D to account for days of the week and month-year combinations. We expect emissions to increase when loads are very high, as peaking plants emit more than CCGT baseload plants, to decrease as the cost of carbon dioxide permits increases, and to decrease as more electricity is generated by wind. We use fuel and CO_2 prices at time $t - 48$ since the merit order is based on the day-ahead bids.

To calculate the ratio between gas and coal prices we take the coal and gas prices per MWh and add the implicit cost of carbon, equal to the carbon content of each fuel times the EU ETS price in each period. We then divide this fuel and carbon cost by the efficiency of a newer Combined Cycle Gas Turbine (CCGT) plant (0.56) and the existing Moneypoint coal plant (0.34) respectively. The resulting measures can be thought of as 'base costs' of generating a MWh of electricity. They are not full marginal costs as they do not include operation and maintenance costs not related to fuel or CO_2. Finally, we take the ratio of the gas to the coal costs. As the ratio increases, CCGT plants become less competitive with respect to coal plants and we therefore expect CO_2 emissions to (weakly) increase. The opposite is true as the ratio decreases.

We include day of week and month-year dummies to account for any other systematic effect that we might not capture with our other explanatory variables. For example, the level of capacity payments changes based on the capacity pot, which is set each year. This might slightly change the incentives plants have to be available at any given time.

When analysing emissions in the Texas ERCOT system, Kaffine et al. (2013) and Cullen (2013) also include a separate temperature regressor to capture the fact that generators are less efficient at high temperatures. In Ireland there are limited temperature changes over the year and this is therefore not a concern.

Table 3 presents the results of our regression. The level of electricity demanded has the expected

[5] We select an AR(1) after observing that the partial autocorrelation graph drops off sharply after the first period, whereas the autocorrelation graph decreases gradually.

positive effect on CO_2 emissions. Each ventile has a statistically significantly and distinct effect. For ease of presentation, we aggregate load into four groups and present average coefficients, with standard errors calculated using the variance-covariance matrix.

Low loads are associated with generation from baseload coal and peat plants, explaining the larger effect on emissions. As load increases CCGT plants start generating leading to lower emissions per MWh. At high load levels oil and distillate plants start producing, increasing CO_2 emissions per MWh.

Once the non-linear effect of load is accounted for, the effect of wind generation on emissions is only weakly non-linear. The coefficient of the first 16 wind ventiles is statistically constant. It decreases slightly for ventiles 17 to 20, which in turn are not significantly different from each other. We present the results for wind as low (ventiles 1-16) and high (17-20). Note that we measure the effect of wind based on actual wind generation. During this period some wind was dispatched down for both system-wide reasons and local grid congestion. For 2012, EirGrid and SONI (2013) reports that 2.1%, or 110GWh, were curtailed, similar to the 2.2% and 119GWh curtailed in 2011 (EirGrid and SONI, 2012).

The net effect of wind might be the combination of two opposing forces. On one hand wind displaces older, less efficient, plants (the merit-order effect). On the other, the need to maintain system reliability might force the system operator to keep some thermal plants on, but running at low capacity and therefore lower efficiency. We keep these opposing effects in mind during the discussion of the results. We are unable to disentangle the two effects with the current data.

The average wind coefficient (an average of low and high wind) is equal to -0.43, slightly lower than average emissions per MWh for the SEM, which were 0.48 tonnes of carbon dioxide per MWh of electricity during the period.[6] One could argue that the effect of wind should be a function not of how much wind there is on the system, but of wind penetration, defined as the share of wind generation with respect to quantity demanded. For the SEM, the data suggest that wind and load are uncorrelated (0.08 correlation using half-hourly data, although the correlation increases with more aggregated data, as both wind and demand are on average higher in the winter in the SEM). Wind penetration therefore depends mostly on wind generation, varying from an average of 0.06% for the lowest wind generation ventile to 33% for the highest ventile.

[6]The (averaged) coefficient on wind is higher than the one reported in Wheatley (2013) for 2011. The results differ for a few reasons. First, in 2011 the system operated without the pumped storage plant and the interconnector (the latter for part of the year). However, our results remain larger even when we limit the analysis to 2011. The main driver of the different results is that Wheatley (2013) uses the load information from SEMO, whereas we use the information from EirGrid and SONI, which we argue is a better measure of demand. We also analyse the whole SEM instead of focusing on the Republic of Ireland and use a different econometric specification.

Table 3: Effect of wind on CO_2, half-hourly data, 2008-2012

$Load_{1-4}$	0.465***
	(0.022)
$Load_{5-8}$	0.39***
	(0.012)
$Load_{9-12}$	0.378***
	(0.016)
$Load_{13-16}$	0.398***
	(0.023)
$Load_{17-20}$	0.455***
	(0.024)
$Wind_{LOW}$	-0.458***
	(0.01)
$Wind_{HIGH}$	-0.399***
	(0.01)
$Cost_{Gas}/Cost_{Coal}$	15.994***
	(4.8)
CO_2Price	0.717
	(0.41)
Moyle Outage dummy	65.963***
	(13.45)
*Moyle Out * Wind gen.*	-0.046***
	(0.01)
Tur.Hill Outage dummy	-3.974
	(4.07)
*Tur.Hill Out * Wind gen.*	0.021**
	(0.01)
Month-Year dummies	Yes***
Constant	139.412***
	(25.17)
AR(1)	0.901***
	(0.002)
N. Obs	81648

Standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$
$Wind_{LOW}$ = ventiles 1-16; $Wind_{HIGH}$ = ventiles 17-20

CO_2 prices do not have a statistically significant effect on emissions. This can be explained by the fact that the CO_2 prices were quite low during the period, averaging €12.6 per tonne (see Table 1). Low emission prices probably didn't affect the system merit order, and then, they didn't impact on the final emissions. During the study period the pumped storage plant, Turlough Hill, and the interconnector between Northern Ireland and Scotland (Moyle) were off line for extended periods, especially in 2011. Pumped storage is a very flexible generation technology that is often used to balance the system and might be used to compensate for wind fluctuations. Turlough Hill is almost 300MW, fairly large when compared to 6850MW of SEM peak load during this period.

The direct effect of the outage at Turlough Hill is to decrease emissions since pumping water to the upper reservoir consumes more electricity than the amount produced by the plant during generation. We are more interested in the interaction between wind generation and pumped storage outages, which measures how the effect of wind changes when pumped storage is off line. We find that CO_2 emissions displaced by wind decrease when pumped storage is not available: wind is more effective when the rest of the system is more flexible, consistent with the discussion in Benitez et al. (2008). When the pumped storage plant is out of commission, balancing demand with supply relies more on thermal power plants, which are kept on in order to be available to ramp up quickly if needed. The emissions displaced by wind decrease by 0.02 tonnes of CO_2 per MWh, or about 5% of the average displacement.

The interconnector to the SEM imports electricity much more often than it exports electricity. When the Moyle interconnector is on outage this automatically causes an increase in SEM emissions since we do not measure the carbon content of imports. Moreover, wind displaces more CO_2 emissions when the interconnector is not available. When electricity cannot be imported, the marginal plant generating on the system tends to be further up in the merit order and above certain levels of demand this implies that the marginal plant (which will be displaced by wind) is also more carbon intensive. This makes the marginal MWh of wind displace more emissions. Kaffine et al. (2013) suggest another channel by which the interconnector could affect emission displacement: the interconnector could export wind. If this is the case, an interconnector outage implies that more wind is available for the internal market. Combined with our finding that the effect of wind is linear up to the 17th ventile and decreases slightly thereafter, this suggests that restricting exports is likely to cause wind to be slightly less effective at displacing emissions, somewhat offsetting the merit order effect. There are reasons to think that the second effect is small: in the SEM interconnector flows have not responded to contemporaneous conditions and prices, as highlighted for example by McInerney and Bunn (2013), implying that the interconnector does not necessarily export at times of high wind.

We rerun the regression for each year separately to see if the effect of wind changes over time, but do not find any qualitative differences. The coefficient on wind by year varies from a minimum of -0.41 in 2011 to a maximum of -0.46 in 2012 . The decline in the effectiveness of wind generation in 2011 is consistent with the findings in Table 3, since the Turlough Hill pumped storage plant was offline all of 2011.

To identify the types of plants that are displaced by wind, we focus on the effect of wind generation on each technology.[7] Moreover, we explore if the results on emissions are driven by the carbon content of the various fuels, or the amount generated by plants with different technologies by also examining how wind displaces generation (rather than emissions).

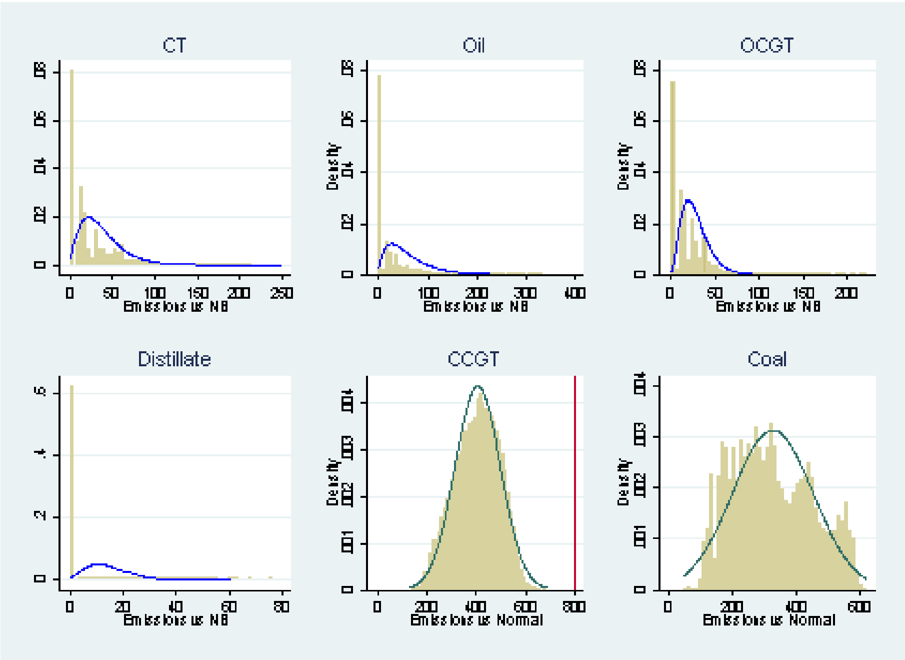
4.2 Technology-level results

In this section we determine how wind generation affects emissions of plants when they are grouped by technology. CCGTs are fairly new and efficient baseload natural gas plants. Open-cycle gas turbines (OCGT) tend to be used for mid-merit operations. They are cheaper to build, but operate

[7] We also analyse the effect of the wind on a plant-by-plant basis (results available from the authors). The results confirm the findings by technology type.

at higher cost per unit of output. Combustion Turbine (CT) natural gas plants are also mid merit. We group older natural gas plants in this category. All other plants are grouped by the primary fuel they use.

Figure 3: Distributions of emissions by technology



CCGT: Combined-Cycle Gas Turbine; CT: Combustion turbine; OCGT: Open-Cycle Gas Turbine
Sum of area in bars is equal to 1.

Figure 3 shows the distribution of the technologies associated with positive emissions that can potentially be displaced by wind.[8]. CCGT and coal don't have zeroes in their distribution, as a minimum of one coal and one gas plant are dispatched at all times to maintain system reliability. We compare them to a normal distribution. The emissions of all other technologies display a right-skewed distribution. We compare them to a negative binomial distribution when emissions are positive. Oil, distillate, OCGT and CT plants also display a large number of periods when they do not generate any electricity, an issue we address in Section 4.2.3. Distillate plants, for example, generate only in 2274 periods, or less than 3% of the cases.

Power plants generate no output (and therefore contribute no emissions) for at least three separate reasons: 1. they are not available during the period, due to scheduled maintenance or an unexpected outage; 2. they do not fit in the merit order at the current level of demand (this will be especially frequent when demand is low); 3. they do not generate given the level of demand and the fact that wind has displaced them from the merit order in the specific period.

Wind generation is only responsible for the third case listed above. Our specification will therefore try to control for the first two cases.

[8]The distributions of CHP (Combined Heat and Power) and peat plant emissions, while not displaying many zeroes, are not reported. These fuels are unlikely to be displaced by wind generation: peat is predominantly must run in the SEM; CHP is driven by the demand of the industrial or commercial processes it serves rather than the electricity market. This is consistent with their unusual distribution (available from authors) and we therefore exclude them from the technology-level analysis

Emissions by technology depend on the specific characteristics of the technology studied, but also on the state of all other plants. If other plants are out of commission, the plants examined are more likely to generate and therefore emit CO_2. We account for this by including the availability of all other plants in the specification.

4.2.1 CCGT and coal: CO_2

Given the shape of the distribution of coal and CCGT plants' emissions, we estimate the effect of wind in a way that is similar to the estimate of total emissions. We control for heterogeneity and autocorrelation as described by Eq.(2). The difference from Eq.(1 is that it includes the availability of other plants ($OthAvail$) defined as total availability of all plants in the system in each period minus the availability of the plants of the considered type.

$$CO_t = \alpha + \beta L_t^i + \gamma W_t^i + \mu PC_{t-48} + \theta gascoalratio_{t-48} + \tau OthAvail_t + \nu THOut_t + \zeta THOut_t.W_t + \lambda MoyleOut_t + \phi MoyleOut_t.W_t + \sum \kappa^s D_t^s + \epsilon_t \quad (2)$$

where $\epsilon_t = \rho\epsilon_{t-1}$.

Table 4: Effect of wind on CO_2 emissions, CCGT and coal plants (2008-2012)

	CCGT	Coal
$Load_{1-4}$	0.195***	0.18***
	(0.03)	(0.03)
$Load_{5-8}$	0.143***	0.155***
	(0.01)	(0.01)
$Load_{9-12}$	0.108***	0.149***
	(0.01)	(0.01)
$Load_{12-16}$	0.087***	0.148***
	(0.01)	(0.01)
$Load_{17-20}$	0.085***	0.099***
	(0.01)	(0.01)
$Wind_{LOW}$	-0.133***	-0.154***
	(0.022)	(0.006)
$Wind_{HIGH}$	-0.164***	-
	(0.004)	
$Cost_{Gas}/Cost_{Coal}$	-5.007**	8.968*
	(1.826)	(3.668)
OtherAvail	-0.0243***	-0.0115***
	(0.001)	(0.001)
Moyle Outage dummy	4.991	13.27
	(6.88)	(16.139)
*Moyle Out * Wind gen.*	0.00294	-0.0114
	(0.01)	(0.012)
Tur.Hill Outage dummy	6.548***	3.53
	(1.497)	(3.308)
*Tur.Hill Out * Wind gen.*	-0.0239***	-0.0084
	(0.005)	(0.006)
Month-Year dummies	Yes***	Yes***
Constant	126.2***	26.77
	(22.29)	(28.54)
AR(1)	0.903***	0.964***
	(0.001)	(0.001)
N.Obs	81648	81648

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1
$Wind_{LOW}$ = ventiles 1-5; $Wind_{HIGH}$ = ventiles 6-20

Table 4 reports the results for CCGT and coal emissions in column 1 and 2 respectively. As in the analysis of system-wide emissions, we allow both load and wind coefficients to vary. For both technologies, all load ventiles are statistically different from each other.[9]

The effect of wind on coal is linear, i.e. we find no change in the effect of wind as wind increases. For CCGTs, wind in the 6th to 20th ventile has a larger effect than when wind output is lower. As wind increases, it displaces CCGT emissions slightly more. The average between these two coefficients gives the average CCGT coefficient, equal to -0.162. The result is very close to the coefficient on coal, which is -0.154.

Change in system flexibility, proxied for by the outages at Turlough Hill, have no effect on coal emissions. This is reasonable since coal plants are fairly inflexible baseload plants. The same

[9]In the table above, loads coefficients are grouped together to ease presentation. The joint SEs were calculated using the variance-covariance matrix of the standard errors.

is not true for CCGT plants. When Turlough Hill is on outage CCGT plant emissions increase, suggesting that CCGT plants play a (stronger) role in balancing the market in this situation.

As expected, other plants' availability has a negative sign: if plants with alternative technologies are able to generate, the emissions of plants with the considered technology decrease.

We explore the determinants of the magnitude of wind's coefficient on coal and CCGT plants. Coal plants emit more CO_2 per MWh generated than CCGT plants. They are less efficient and coal has a higher carbon content, but there are fewer of them in the system.

To verify whether the results on emissions are due to the higher emissions of coal versus CCGT plants, we examine the effect of wind on coal and CCGT generation (rather than emissions).

4.2.2 CCGT and coal: generation

We use Eq. 3 below to estimate the effect of the wind on generation by fuel for coal and CCGT plants. The dependent variable is now total electricity generation (Gen) by technology, although we exclude the technology subscript for readability:

$$Gen_t = \alpha + \beta L_t^i + \gamma W_t^i + \mu PC_{t-48} + \theta gascoalratio_{t-48} + \tau OthAvail_t + \nu THOut_t + \zeta THOut_t.W_t \\ + \lambda MoyleOut_t + \phi MoyleOut_t.W_t + \sum \kappa^s D_t^s + \epsilon_t \tag{3}$$

where $\epsilon_t = \rho\epsilon_{t-1}$.

Table 5 shows that wind has a non-linear effect on CCGT generation, just as for emissions, although the non linearity arises at a different level of wind generation (in this case ventiles 17 and above have a statistically different effect on CCGT generation instead of ventiles 6 and above for emissions). The average effect of wind on CCGT is equal to -0.502. Each MWh of wind generation displaces 0.502MWh of CCGT generation, which is more than the double of the effect the wind has on coal plants (-0.168). When there is more wind on the system, an additional MWh of wind displaces about 0.52MWh of CCGT generation. When wind is lower, a MWh of wind displaces 0.48MWh of CCGT generation.

The relatively large displacement of CCGT plants as a group is due to a variety of factors: 1. there are a large number of CCGT plants on the system (10) with respect to coal plants (5); 2. they are typically more expensive to run than coal and therefore are displaced earlier; 3. they are more flexible than coal and therefore may be called upon to follow wind and demand changes more closely.

Table 5: Effect of wind on generation (MWh), CCGT and coal plants (2008-2012)

	CCGT	Coal
$Load_{1-4}$	0.554***	0.198***
	(0.03)	(0.016)
$Load_{5-8}$	0.431***	0.174***
	(0.01)	(0.01)
$Load_{9-12}$	0.335***	0.171***
	(0.01)	(0.01)
$Load_{12-16}$	0.291***	0.177***
	(0.02)	(0.01)
$Load_{17-20}$	0.25***	0.133***
	(0.003)	(0.01)
$Wind_{LOW}$	-0.482***	-0.168***
	(0.007)	(0.004)
$Wind_{HIGH}$	-0.516***	-
	(0.01)	
$Cost_{Gas}/Cost_{Coal}$	-6.369	5.340*
	(3.958)	(2.563)
OtherAvail	-0.00688	-0.0130***
	(0)	(0.001)
Moyle Outage dummy	-6.369	13.56
	(3.958)	(13.16)
*Moyle Out * Wind gen.*	0.0248	-0.0159*
	(0.016)	(0.008)
Tur.Hill Outage dummy	5.377	4.707*
	(3.307)	(2.24)
*Tur.Hill Out * Wind gen.*	-0.0273***	-0.0118**
	(0.007)	(0.004)
Month-Year dummies	Yes***	Yes***
constant	225.2***	-82.98***
	(35.31)	(23.39)
AR(1)	0.960***	0.977***
	(0.001)	(0.001)
N. Obs	81648	81648

Standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$
$Wind_{LOW}$ = ventiles 1-16; $Wind_{HIGH}$ = ventiles 17-20

To determine if wind displaces CCGT plants more than proportionally, we compare the displacement to the relative share of CCGT versus coal generation. During our sample period, CCGTs jointly generated an average of 2047MW per hour, or 50% of demand, whereas coal plants generated 660MW per hour or 16% of demand. As shown in Table 5 1MWh of wind displaces 0.17MWh of coal and 0.50MWh of CCGTs, suggesting that wind displaces coal and gas proportionally.

We conclude that the similar effect of wind on the displacement of emissions from coal and CCGT plants is driven by the higher CO_2 emissions of each MWh of coal and the lower efficiency of coal power plants.

We can also check if the emissions displacements that correspond to the generation displaced by wind in Table 5 are equivalent to the emissions estimated in Table4. Displacing 0.168MWh of coal is equivalent to 0.162 tons of CO_2, using the the maximum (and constant) efficiency of the most efficient coal plant on the system (calculated using heat rates from allislandproject.org) and the Irish-specific content of CO_2 per unit of coal from Howley et al. (2012). This is about 5% higher than the estimate of 0.154 from Table 4. Similarly, if wind displaces 0.502MWh of CCGT generation, we can calculate how many emissions this corresponds to, if the marginal plant's efficiency does not decrease. We take the maximum efficiency of a relatively new CCGT, Huntstown 2, and the Irish-specific content of CO_2 per MWh of natural gas from Howley et al. (2012). We calculate that eliminating 0.502MWh of generation from Huntstown 2 should displace 0.185 tons of CO_2. This is about 14% higher than the displacement of emissions from CCGTs, estimated at 0.162 tons of CO_2 per MWh of wind generation in the previous section.

Let's define the difference between imputed emission changes (emissions corresponding to displaced generation) and estimated emission changes (from Table 4) as the 'emissions error'. An emissions error is to be expected, in part from approximations that are inherent in the regression approach and in part because the system will adjust to wind generation in complex ways. The interest of this exercise is that it highlights the higher emissions error for CCGT plants, which is consistent with the hypothesis that wind pushes CCGT plants to generate at lower efficiency levels much more frequently than coal plants.

4.2.3 Other generation technologies

Figure 3 shows that when there are many zeroes, emissions by technology are characterized by a positive mass at zero (no emissions) followed by a right-skewed distribution for positive emission values.

For technologies that often do not generate -CT, OCGT, oil and distillate- we estimate the effect of wind with a two-part hurdle model. This specification allows us to address both the abundance of zeroes and the highly skewed distribution of non-zero values. The first part estimates the probability of each technology generating a positive amount of electricity and the second estimates the model conditional on there being positive generation. If d is an indicator equal to 1 when emissions are positive, and zero otherwise, the two-part hurdle model can be represented as:

$$\begin{cases} Probability(d = 0|\mathbf{X}) = F(\mathbf{X}) & \text{if} \quad Emissions = 0 \\ Emissions_t = G(\beta\mathbf{X}') + \epsilon & \text{if} \quad Emissions > 0 \end{cases} \tag{4}$$

where $\mathbf{X}$ is the matrix of explanatory variables and ϵ is the error vector.

In the first part, the probability of generating and therefore emitting CO_2 is captured by a probit. The second part is modelled with a poisson with overdispersion, to account for the right skewness showed by the distribution of oil, distillate, CT and OCGT plants.[10] The poisson distribution is non linear, which, together with the lower number of observations, drives our decision to insert wind and load in the equation without a spline function specification. All other control

[10] The poisson distribution can be used for continuous dependent variables, even with overdispersed distributions. In the latter case the standard errors of the coefficients must be corrected: in Stata the correct procedure is to use the vce(robust) command. See for example Wooldridge (2010); Cameron and Trivedi (2010).

variables are the same as in Equation 2. The poisson specification used for the second part of eq.4 is non-linear, implying a non-linear effect of wind. We show how the effect of wind on emissions changes depending on the point at which the partial effect of wind is calculated. We calculate the partial marginal effects measured at the quartiles of the wind distribution. We follow Cameron and Trivedi (2010) and implement the method using the STATA13 `margins` command.

Wind affects the probability of generating electricity fairly weakly. Table 6 reports the coefficient on wind by technology and shows that the probability that emissions are positive decreases slightly for distillate and oil plants. The effect of wind on CT and OCGT is statistically different from zero and positive, although the effect is small, suggesting that CT and OCGT plants are not used to balance wind. The effects on generation are similar to those on emissions.

Table 6: Probit: effect of wind on probability of positive emissions and generation

	Emissions	Generation
CT	0.000	0.000
Distillate	-0.002	-0.003
Hydro	-	-0.001
OCGT	0.000	0.000
Oil	-0.002	-0.002
Pump.Storage	NS	NS
Waste	-	-0.001

NS: not significantly different from zero at the 5% level
Regression includes all control variables reported in Eqs 2 and 3, but both load and wind are in levels (not ventiles).

For the second stage, estimated with a Poisson, the average marginal effect of wind on the different technologies is reported in Table 7. As expected, the effect on emissions is stronger than the effect on generations for fuels that have relatively high carbon content (distillate, oil).

Table 7: Average Marginal Effects of wind on emissions and generation, other technologies (2008-2012)

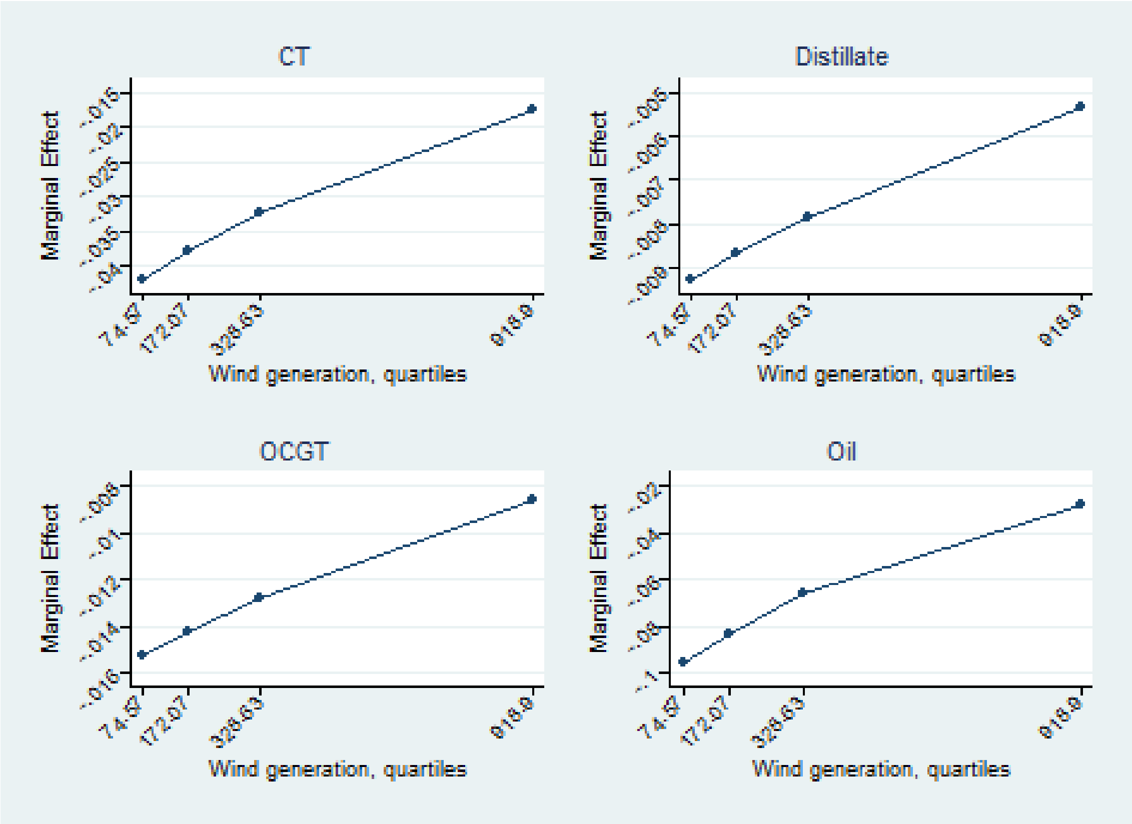
	Emissions	Generation	N. Obs
CT	-0.037	-0.037	52,838
Distillate	-0.009	-0.001	2,274
Hydro	-	-0.002	26,448
OCGT	-0.014	-0.018	53,501
Oil	-0.084	-0.047	37,586
Pump.Storage	-	NS	62,688
Waste	-	-0.001	11,568

NS: not significantly different from 0 at the 5% level.
All other reported coefficients are significant at the 1% level
Regression includes all control variables reported in Eqs 2 and 3, but both load and wind are in levels (not ventiles).

The largest effect of wind is on CT and oil plant generation and emissions. Wind generation has a negative albeit small effect on hydro generation, suggesting that some hydro is used to balance the system and compensate for wind. As shown earlier, in the absence of pumped storage, wind is less effective at reducing emissions. However the coefficient of wind on pumped storage generation is not significantly different from 0 at the 5% level, suggesting that pumped storage does not operate primarily to compensate for changes in wind generation.

The results reported in Figure 4 show fairly constant wind coefficients across quartiles, denoted by the almost straight line. Oil plants are the ones that denote a stronger non-linear effect: as wind increases, they tend to be displaced less.

Figure 4: Predictive margins of wind on CO_2 emissions by technology evaluated at wind quartiles



CT: Combustion turbine; OCGT: Open-Cycle Gas Turbine

Although wind has a negative and significant effect on emissions and generation of oil, OCGT, distillate and CT plants, the magnitude of these effects is much lower than for CCGT and coal plants. In part this is driven by the lower generation share of these plants.

5 Conclusions

In this paper we analysed the effects of wind generation on CO_2 emissions in the SEM, the electricity market of the island of Ireland. The SEM is a small market with a large share of baseload natural gas plants, an increasing penetration of wind and is fairly isolated from the rest of the European power markets.

We find that wind decreases emissions of the system as a whole, as expected, although it displaces fewer than the average system-wide emissions per MWh. We also determine that when the pumped storage plant is on extended outage, each MWh of wind displaces fewer emissions, suggesting that wind is most effective with flexible systems.

To understand why wind displaces less than the average system emissions we analyse the effect of wind on generation and emissions by technology. Coal and CCGT emissions have the largest share of total SEM generation. Since generation and emissions of these plant types are well behaved, we can use a simple corrected OLS model. The results show that wind generation displaces similar total emissions from CCGT and coal-fired plants, despite coal-fired plants having a lower share of total generation. This result is driven by the higher carbon content of coal and the lower efficiency of coal-generation plants. In fact, when we examine the effect of wind on generation we find that it displaces more CCGT than coal per MWh of wind. The generation displacement is proportional to the share of generation by these two technologies. When we compare generation to total emissions displaced for CCGT plants, we find that the estimated displaced emissions are slightly lower than those consistent with the level of generation displaced, assuming no change in CCGT generation efficiency. This is consistent with the hypothesis that wind generation pushes CCGTs to operate at lower output and lower efficiency.

For technologies other than CCGT and coal we use a hurdle two-part model to estimate the effect of the wind; this allows us to account for the frequent instances when there is no generation by plants of these technologies. We find that on average effects of wind are small on these technologies, in part due to their limited share of generation in the SEM.

Finally, looking at the empirical estimation of system-wide electricity generation emissions we find that it is important to allow the effect of load to vary as it increases. Electricity system emissions tend to be non-linear over generation since each generator embodies different technological characteristics. By allowing the coefficient on load to reflect these changes, it will be easier to identify the effect of other variables of interest, in our case wind generation. Our analysis also shows that once load is properly accounted for, wind has a significant non-linear effect on CCGT emissions and generation, but we find no evidence that the effect of wind varies for other technologies.

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Appendix

Data

We use data on plant-level availability from SEMO. We clean the data so that plant availability is:

1. Never larger than maximum capacity (allowing for 10% tolerance);
2. Never 0 when the plant is actually generating;
3. Interpolated from non-missing data when it is missing.

Some of the data is missing and some is registered as 0 even when a plant is generating, which can occur for a couple of reasons: a. availability is registered as 0 for system operation reasons. For example a thermal plant that is associated with a windfarm location is defined as unavailable according to the SEM. Some of the data might also be registered as 0 when data providers (plant operators) enter 0 instead of missing.

EirGrid publishes monthly availability for Republic of Ireland (ROI) plants (`http://www.eirgrid.com/operations/systemperformancedata/availabilityreports/#d.en.797`). We make sure that where information on availability is missing, the interpolated version is compatible with the EirGrid availability reports.

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