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 historical data for the Irish Single Electricity Market between 2008 and 2012. We find that wind generation decreases CO_2 emissions, but by less than average system emissions. When we disaggregate the results by fuel, we find that wind generation has the same cumulative effect on emissions from gas and coal plants. Evaluating the effect on electricity generation by coal and fuel plants, rather than emissions, determines that wind displaces more gas than coal generation on a MWh per MWh basis. The high number of gas plants in the system, their flexibility and position in the merit order explain the result on emissions. We also find that in the presence of an extended outage of the system's pumped storage plant, wind generation displaces 4% fewer emissions, suggesting that wind is less effective with less flexible systems.

1 Introduction

This paper evaluates how increasing wind generation affects CO_2 emissions of an electricity system with capacity payments. The analysis addresses the specification and econometric challenges that arise when estimating the effect of wind on power plant generation or emissions.

We use the Irish Single Electricity Market (SEM) as a test system. The SEM encompasses the electricity grids of both the Republic of Ireland and Northern Ireland, making it a cross-jurisdiction, cross-currency system.

Many jurisdictions strive to decrease emissions and increase 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).

The SEM 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]

Extensive data are available since the beginning of the SEM in November 2007. The data available for the SEM 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 in 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 (2005). This method allows to study the effect of changes in wind generation in a controlled setting, keeping all other variables constant. Its 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

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

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. Cullen (2013) finds that wind mostly offsets CCGT plants. Kaffine et al. (2013) use data from 2007 to 2009 for ERCOT. Both Cullen (2013) and Kaffine et al. (2013) find that the savings in CO_2, NO_x and So_2 emissions are not sufficient to cover the cost of subsidies to wind generation for the US areas they study. Kaffine et al. (2013) find that the largest savings in emissions are obtained in coal-dominated systems and the smallest in natural-gas 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 system emissions, as expected. Somewhat surprisingly, we find weak evidence of a non-linear effect of wind on emissions. Finally, emissions displaced by wind are lower than average system emissions.

To identify what drives the level of emissions displaced, we explore the relation between wind generation and CO_2 emissions by fuel and at the plant level. Wind has the same cumulative effect on gas and coal plants in terms of CO_2 reductions; however, it displaces generation from less emission-intensive gas plants more than from coal plants.

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. The SMP is based on a market schedule that does not account for transmission constraints. 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. 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.

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-hourly 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 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.

[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/`.

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). All information on prices is on a daily basis and in nominal terms. Fuels are traded Monday through Friday. We set weekend prices equal to those of the previous Friday.

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

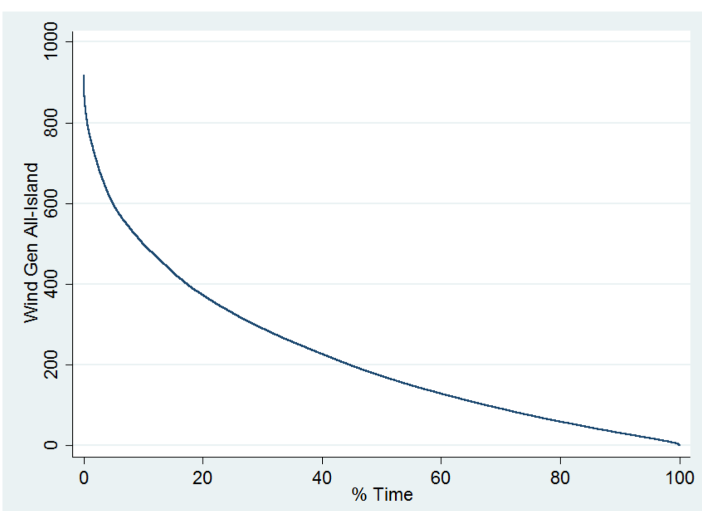
Variable	Obs	Mean	Std. Dev.	Min	Max
Wind (MWh)	81648	223.67	185.28	0.24	918.90
Load (MWh)	81648	2030.29	444.06	1073.50	3424.25
CO_2 Emissions (Tonnes)	81648	930.37	225.38	403.56	1923.16
Gas price$_{t-48}$ (€/MWh)	81648	19.87	5.88	4.62	32.14
Coal price$_{t-48}$ (€/MWh)	81648	4.36	1.18	2.48	8.11
Generation (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

Carbon dioxide emission permit prices are spot prices, taken from Point Carbon. Fuel and carbon dioxide permits are traded Monday through Friday. We set weekend prices equal to those of the previous Friday.

Table 1 reports summary statistics for our dataset for the period from 1 January 2008 to 28 August 2012 on a half-hourly basis. It shows that 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 shows the duration curve for wind generation during our period of analysis, or the share of time wind generation is above any given level.

Figure 1: Wind duration curve, 2008-2012



Average generation duration curve for onshore wind in 2008-2012, Data source: our calculations from EirGrid and SONI data

Wind generation in the SEM exceeded 200MWh for about 40% of the time and 100MWh for about 80% of the time.

We measure carbon dioxide emissions by following the methodology used in Wheatley (2013) and extending 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 with imports along the interconnector.

A few plants face 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 bidding) during a commissioning period. We eliminate these plants' generation and the associate emissions during the commissioning period during the econometric analsis. 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. 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 emissions. All the results presented in the aggregate econometric study are based on emissions excluding Edenderry.[5]

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.

[4] Peat plants were historically subsidised in Ireland as a labour-enhancing measure, to permit the employment of peat cutters. These subsidies are designed to be phased out over time.

[5] We verify the hypothesis that Edenderry's output is not affected by wind in the plant-level portion of our analysis.

4 Methods and results

System emissions are determined by the specific 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); the system operator decides which plants to dispatch, based on the bids received, expected load, expected renewables generation and expected outages; finally, realised load, wind, unplanned outages and transmission constraints determine the actual plant dispatch.

An important driver of CO_2 emissions is the level of electricity demanded. We therefore include final electricity demanded, or load, in our specification. We allow the coefficient for load to vary as load increases, by permitting up to 20 different slopes for different levels of demand.

We also include 20 different slopes for wind levels to examine if there are non-linear effects of wind generation. Both of these specifications are a bit more flexible than including a square term. Other determinants of the CO_2 are the fuel prices, the CO_2 prices and several dummies to take into account the seasonality. The ratio between gas and coal prices is built as follows. We take the coal and gas prices per MWh and add the implicit cost of carbon, which is 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 numbers we calculate 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, month and 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. Analysis of emissions in the Texas ERCOT system (Kaffine et al., 2013; Cullen, 2013) typically includes a separate temperature regressor, since generators are less efficient at high temperatures. In Ireland there are limited temperature changes over the year and this is therefore not a concern.

4.1 All System

We first check that system CO_2 emissions are stationary. We use the augmented Dickey-Fuller test and find that 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 periods flexibly. We estimate Equation 1 using an autoregressive specification.

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

where $\epsilon_t = \rho \epsilon_{t-1}$.[6]

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 percentile of load, where $i = 1$ ....20; wind generation W, where W is allowed to take different coefficients; the previous day's carbon dioxide permit price PC, the ratio of gas generation 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 (and therefore which plants are dispatched) is defined by day-ahead bids.

Table 3 presents the results of our regression. The level of electricity demanded has the expected positive effect on CO_2 emissions. Each ventile had a statistically significantly effect distinct from other ventiles. For ease of presentation, we aggregate load into four groups and present average coefficients (standard errors are 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 it increases emissions by less when CCGT plants start entering the merit order. Finally, at high load levels oil and distillate plants start producing, increasing total CO_2 emissions per MWh.

Once load is accounted for, wind generation has a weak non-linear effect on system emissions. The effect of the first 16 ventiles is statistically constant. It decreases slightly for ventiles 17 to 20, which in turn are non significantly different from each other. We present the results for wind as low (ventiles

[6] 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.

1-16) and high (17-20).

High wind has a smaller effect than low wind levels. System constraints and security of supply impose an upper limit to the role of the wind in the Irish system; after a certain level, wind reduces emissions less than proportionally. The average coefficient (calculated between low and high wind) is equal to -0.43, slightly lower than average emissions for the SEM, which was 0.48 tonnes of carbon dioxide per MWh of electricity during the period. [7] The actual effect of wind might reasonably depend on wind penetration, 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 the half-hourly data). Wind penetration therefore depends mostly on wind generation, varying from 0.06% for the lowest ventile to 33% for the highest ventile. We also rerun the regression for each year separately to see if the effect of wind has changed over time. The coefficient on wind by year varies from a minimum of -0.41 in 2011 to a maximum of -0.46 in 2012 . There is a clear decline in the effectiveness of wind generation in 2011. This can be ascribed to the fact that both the Moyle interconnector to Great Britain and the Turlough Hill pumped storage plant were offline due to unplanned outages.

[7] The (averaged) coefficient on wind is significantly higher than the one reported in Wheatley (2013) for 2011. The results differ for a few reasons. First, as mentioned below, in 2011 the system operated without the pumped storage plant and the interconnector. 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 is a better measure of demand, as explained in the data description section. 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)

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

The net effect of wind might be the combination of two opposing forces. On one hand wind might displace older, less efficient, plants. On the other, the need to maintain system reliability might push the system operator to keep some plants running at low capacity and therefore lower efficiency. We explore this explanation in the next section when we examine the effect of wind on each plant's output and carbon dioxide emissions.

CO_2 prices do not have a statistically significant effect on emissions, although they enter the estimation as a component of the gas-coal ratio variable as well. The ratio of gas to coal costs has a positive effect on emissions, as expected.

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 peak load for the SEM of about 6850MW 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 periods. 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 total 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. When the pumped storage plant is out of commission, balancing demand with supply has to rely more on thermal power plants, which are going to be kept on in order to be available to ramp up quickly if needed. We find that the effect of wind decreases by 0.02, or 4%.

Using the same methodology for the Moyle interconnector outage, we find that there was no statistically significant effect of interconnector outages on the ability of wind to cut emissions. This is not surprising considering that interconnector flows are not optimally used from a system perspective, as highlighted for example by McInerney and Bunn (2013).

To identify the types of plants that are displaced by wind, we focus on the effect of wind generation on each technology and, later, power plant.

4.2 Fuel-level regressions

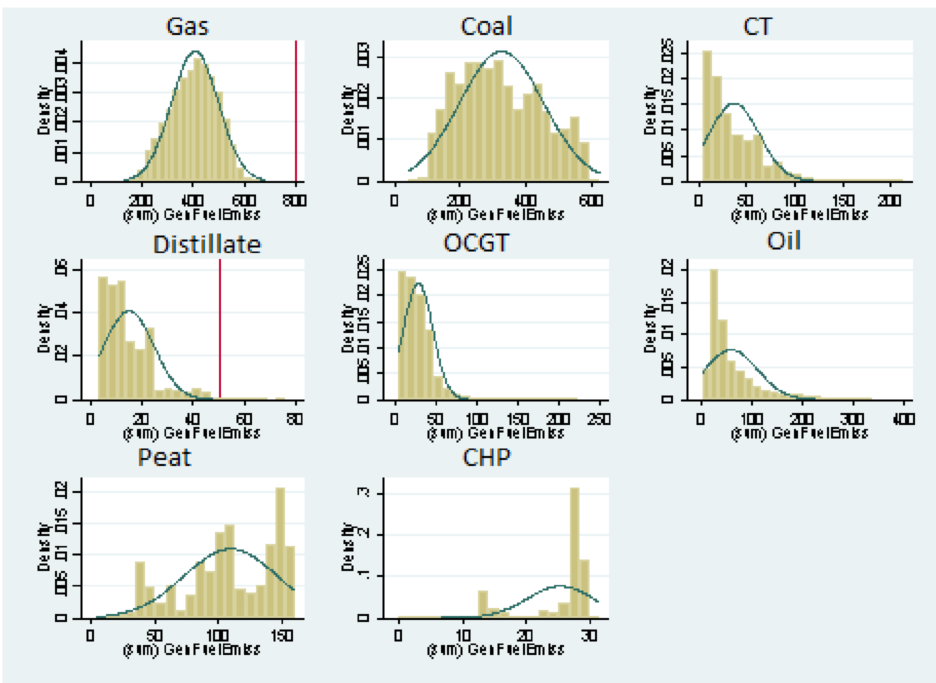
In this section we determine how wind generation affects emissions of plants when the are grouped by fuel and, for natural gas, technology. CCGTs are typically baseload natural gas plants that are fairly efficient. Open-cycle gas turbines (OCGT) tend to be used for mid-merit operations. They are cheaper to build, but less efficient to operate. Finally Combustion Turbine (CT) plants are also mid merit. We group older natural gas plants in this category. Combined Heat and Power plants (CHP) are typically associated with industry that uses the heat for internal processes. We consider them separately as electricity generation is often a secondary output and is therefore not directly affected by the drivers of electricity generation. All other plants are grouped by the primary fuel they use.

Emissions by fuel type may be zero a number of times. Power plants could be generating no output (and therefore contributing 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 generate because they do not fit in the merit order, given the level of demand at the specific time (this will be especially frequent when demand is low); 3. they do not generate given the level and demand, and the fact that wind has displaced them from the merit order in the specific period.

Of all of the cases listed above, wind generation is only responsible for the third one. At plant level, difference arises between plants in Northern Ireland and the Republic as in NI power plants are kept into the system in order to guarantee the security of supply.

If the number of zeroes is sufficiently high, emissions by fuel are characterized by a positive mass at zero (no emissions) followed by a right-skewed discrete distribution for positive emission values. When dealing with zero-modified count and discrete data, parametric mixture distributions known as two-part models are used to address both the abundance of zeroes and the often highly skewed distribution of non-zero values. Figure 2 shows the distribution of the fuel types with positive emissions. Gas and coal distributions are fitted against a normal distribution. All the other fuels have been compared to a negative binomial distribution.

Figure 2: Fuel distributions



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

Gas and coal don't have zeros in their distribution, as at least one coal and one gas plant are always dispatched for to maintain system reliability. All the other fuels show a skewed distribution and a significant amount of zeroes. The distributions of CHP and peat plant emissions are not rightly skewed, as their generation is almost constant during the different hours of the day.

The different characteristics of the series suggest different estimation strategies.

4.2.1 Gas and coal: CO_2 emissions

We estimate gas and coal controlling for heterogeneity and autocorrelation as described by Eq.(2). This is similar to Eq.(1, except that it adds the effect of generation margin to take into account the state of other plants on the system. Other plants availability ($OthAvail$) is defined as total availability in the system in each period minus the availability of the plants of the considered fuel type. Including the availability of the other plants lead us to take the relation between the different fuels into account.

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

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

Table 4 reports the results for gas and coal emissions in column 1 and 2 respectively. As in the analysis of system-wide emissions, we allow both the loads and the wind coefficients to vary. For both fuels, all the load ventiles are statistically different from each other.[8]

The effect of wind on coal is linear, i.e. it affects emissions from coal equally, independent of the level of wind. For CCGT, wind in the 5th to 20th ventile has a larger effect than lower levels of wind. As wind increases, it displaces a larger share of CCGT plants. We therefore allow wind to have a separate coefficient for the larger ventiles. The average between these two coefficients gives the average gas coefficient, equal to -0.162. The result is very close to the coefficient on coal, which is -0.164.

Changes in system flexibility, proxied for by the outages at Turlough Hill and Moyle, have no effect on coal emissions. This is reasonable since coal plants are fairly inflexible baseload plants. The outage of the pumped storage plant however has an effect on CCGT emissions. When Turlough Hill is on outage, the effect of wind on CCGT plants is even stronger. This suggests that CCGT plants may become the balancing plants in this situation.

As expected, the other plants availability has a negative sign: if other fuels are able to generate, the emissions of the considered fuels decrease.

[8] In the table above, loads coefficients are grouped together to make the table more readable. The joint SEs were calculating using the variance-covariance matrix of the standard errors.

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

	Gas	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

Coal plants emit more CO_2 per MWh generated than CCGT plants, as they are less efficient and coal has a higher carbon content, but there are fewer of them in the system. Coal plants are also less flexible than gas plants. They take longer to turn on and off and have higher minimum down and up times. If their output is needed at times of peak demand they will have to be turned on for a few hours before or after. Coal plants usually bid lower prices in the market, as coal prices have been below natural gas prices at least until the second half of 2011. As a result, coal plants may be kept in the system because they are cheaper (the merit order effect) and at times for system reliability. We do not have enough information to disentangle these two effects. We can however determine why wind has a similar effect on coal and CCGT plants. We can verify if the results on emissions are due to the higher emissions of coal versus CCGT by examining the effect of wind on coal and CCGT generation (rather than emissions). We can determine if the effect is due to the number of gas relative to coal plants by estimating the impact of wind on each plant separately. We discuss the first point in the next paragraph. Regressions by plant are presented in the next section.

4.2.2 Gas and coal: generation

We use the model given by Eq. 2 to estimate the effect of the wind on generation by fuel for coal and gas, except that the dependent variable is now total electricity generation (Gen) by fuel rather than level of CO_2 emissions:

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

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

Table 5 shows that wind has a non-linear effect on generation of CCGT, just as for emissions. However, in this case the average effect of wind on CCGT is equal to -0.320 which is almost double the effect wind has on coal plants (-0.168).

Wind displaces gas power plants more than coal, and this may be due essentially to the technical characteristics of these plants and their flexibility, and to the merit order effect.

Moreover, results included in Table 5 show that high levels of wind displace gas much more than low wind levels. In particular, high wind levels reduce the generation of gas plants by 0.4, where low level of wind displaces generation just by 0.2.

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

	Gas	Coal
$Load_{1-4}$	0.549***	0.198***
	(0.03)	(0.016)
$Load_{5-8}$	0.431***	0.174***
	(0.01)	(0.01)
$Load_{9-12}$	0.333***	0.171***
	(0.01)	(0.01)
$Load_{12-16}$	0.286***	0.177***
	(0.02)	(0.01)
$Load_{17-20}$	0.249***	0.133***
	(0.004)	(0.01)
$Wind_{LOW}$	-0.221***	-0.168***
	(0.007)	(0.004)
$Wind_{HIGH}$	-0.407***	-
	(0.010)	
$Cost_{Gas}/Cost_{Coal}$	-4.895	5.340*
	(4.063)	(2.563)
OtherAvail	-0.0635***	-0.013***
	(0.002)	(0.001)
Moyle Outage dummy	-1.299	13.56
	(18.14)	(13.16)
*Moyle Out * Wind gen.*	-0.002	-0.0159*
	(0.015)	(0.008)
Tur.Hill Outage dummy	49.84***	4.707*
	(2.197)	(2.239)
*Tur.Hill Out * Wind gen.*	-0.190***	-0.0118**
	(0.005)	(0.004)
Month-Year dummies	Yes***	Yes***
Constant	208.6***	-82.98***
	(34.332)	(23.38)
AR(1)	0.966***	0.977***
	(0.001)	(0.001)
N.Obs.	81648	81648

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

4.2.3 Other fuels

For all the other fuels, we estimate the effects of the wind with the following two-part hurdle model, where the first part estimates the probability of having a positive output, and the second part estimates the model conditional on there being a positive output:

$$g[Pr(Y > 0)] = g(\pi_i) = \mathbf{x_i'}\beta_\mathbf{1}$$
$$\mu_i = \mathbf{x_i'}\beta_\mathbf{2}, i = 1...N \tag{4}$$

The probability of generating and therefore emitting CO_2 (π) is specified by a probit, and the second part is modelled with a negative binomial, to account for the skewness of the fuel distributions.

We focus on the marginal effects, which have been calculated using the STATA13 `mfx` command.

The impact of wind on other fuels (mainly oil and distillate) is not particularly strong, as shown by Table 6. Some plants, like peat, are must run in the system, so wind does not have any effect on their emissions and does not displace their generation significantly.

Table 6: Effects on emissions and generation, other fuels (2008-2012)

	Emissions (tonnes CO_2)	Generation (MWh)
CT	-0.008	-0.031
CHP	NS	NS
Distillate	-0.0003	-0.0001
Hydro	-	0.004
OCGT	-0.011	-0.023
Oil	-0.020	-0.020
Peat	NS	NS
Pump.Storage	-	NS
Waste	-	NS

NS=not significant

Most of the effect of wind on the system as a whole depends on the effect on coal and CCGT. Only high wind generation has an effect on both emissions and generation of all other fuels. Some of the plants have very few positive observations, or times with positive generation. Table 6 reports the average effects of high wind on these fuels.[9]

It is interesting to note that wind generation has a positive effect on hydro generation. One explanation is that hydro is used at times of high wind to better balance the system, due to its high flexibility.

4.3 Plant-level regressions

In this section we repeat the analysis of wind's impact, but do it on a plant-by-plant basis. There are a total of 74 thermal units in the SEM database. We separate coal, gas and oil power plants to check if differences arise in the response to wind generation. Table **??** show the average results by type of plant.

[9] For CT wind is significant after the 18th ventile; for OCGT and oil after the 17th ventile.

Table 7: Emissions by plant, tonnes of CO_2

Hunts	-0.0204***
Hunts2	-0.0192***
Dublin Bay	-0.0022***
Poolbeg	-0.0104***
Whitegate	-0.0206***
Tynagh	-0.0102***
Ballylumford 32	-0.0117***
Ballylumford 10	-0.00999***
Coolkeragh	-0.02***
Ballylumford 31	-0.0118***

(a) Gas

Moneypoint 1	-0.052***
Moneypoint2	-0.028***
Moneypoint3	-0.034***
Kilroot1	NS
Kilroot2	-0.021**

(b) Coal

Northwall4	-0.002**
Rhode1	-0.001**
Rhode2	NS
Aghada1	NS

(c) EmissionPlant

For both coal and gas plants wind affects the CO_2 produced by each power plant linearly. The Wald test cannot reject the null hypothesis of equality between all coefficients for the wind ventiles.

Interestingly, coal plants in NI (Kilroot1 and Kilroot2) are less displaced by wind than plants in the Republic. Coal plants in NI are often kept in the system in order to guarantee the security of supply in NI. Despite these plants being older and less efficient that plants in the Republic of Ireland, limitations on the North-South tie line, connecting Northern Ireland with the Republic, mean that NI cannot obtain all the electricity it would import efficiently.

Wind affects gas plants in the Republic less than plants in the north for the same reason. Power plants in NI (Ballylumford) have a slightly lower coefficient than other plants with the exception of Poolbeg which is in the Republic but is constrained on for most of the analyzed period. The sum of both gas and coal coefficients are close to the results found in the previous section: the sum of the wind coefficients for coal plants is -0.143, where for gas the sum of plants coefficient is equal to -0.136.

5 Conclusions

In this paper we analysed the effects of wind generation on CO_2 emissions in the SEM. At the whole system level, we estimate the model by OLS, correcting for the presence of serial correlation and heteroskedasticity. We find a significantly negative effect of wind on emissions. 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.

In order to understand which type of fuel is the most affected by wind generation we run the analysis at the fuel level. Coal and CCGT emissions are well-behaved since at least one gas and coal plants are kept into the system for security of supply. We can therefore estimate the effect of wind on fuels by a corrected OLS model.

For other fuels we use a hurdle two-part model to estimate the effect of the wind on 6 different fuel types, in order to control for the significant amount of zeroes in their distribution.

We find that wind has a non linear effect on the gas and oil fired peakers plant, and that wind affects coal plants linearly. Moreover, our results show that wind generation impacts on gas and coal emissions by almost the same amount. In order to understand this result we use the same model to investigate the impact of the wind on generation and we analyse the effects of the wind generation at the plant level. Our results show that each gas plant is displaced by wind more than the coal plants. Gas plants are more flexible and expensive to dispatch than coal plants. It is plausible that, when the wind blows, gas plants are turned down more frequently than coal plants. As gas plants are more efficient than coal plants (i.e. on average, they emit less CO_2) the cumulative effect of wind in terms of emissions is not statistically different between these two plants.

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6 Appendix

6.1 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.