Responses to EU Carbon Pricing:
The Effect of Carbon Emissions Allowances on Renewable Energy Development in Advanced and Transitional EU Members

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Abstract

Using electricity price, generation, installed capacity, and carbon price data from the European Union from January 2015 to December 2018, this study finds that the carbon pricing in the European Union Emissions Trading Scheme (EU ETS) incentivizes electricity sector carbon emission reductions through renewable energy deployment only for economically advanced EU members. Transitional economies show a weak to modest carbon emission increase despite a common carbon price. This study estimates an electricity supply curve, or merit order, for 24 EU ETS members using a Tobit regression model and analyzes changes in this curve using a linear b-spline. These shifts provide insight into how carbon pricing affected energy generation, price, and CO_2 emissions for two distinct categories of EU member states. The advanced category as a whole saw a strong electricity sector decrease in carbon emissions, both over time and from carbon pricing, while the transitional category as a whole saw a weak increase. This indicates that advanced EU members in Northern, Western, and Central Europe likely sold permits to transitional ones in Southern and Eastern Europe. While these findings may initially reflect the gains from trade of carbon emissions permits inherent in the European Union Emissions Trading Scheme's design, the implications of how these two distinct groups have changed electricity generation present challenges to the ultimate long-term goal of EU-wide carbon neutrality by 2050, particularly in transitional economies' electricity sectors.

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I. Introduction

Several advanced nations and regions have instituted variations of a carbon cap-and-trade permit system to reduce emissions without the severe cost impacts or distortionary taxation common to other carbon-reduction policies. Although parts of the United States (17 Cal. Code Regs. § 95801), Canada (Climate Change Mitigation and Low-carbon Economy Act 2016), and Australia (IPART - Greenhouse Gas Reduction Scheme 2003) have formed similar markets, the European Union Emissions Trading Scheme (EU ETS) is by far the largest, most established, and most imitated carbon permit market (Ellerman & Buchner 2007). Unlike similar markets, however, the EU ETS covers both transitional economies like Bulgaria and advanced ones like Germany. Broadly, this variation provides an opportunity to study whether the gains from carbon permit trading have disproportionate effects between nations of different economic development. Furthermore, as environmental policies often shift emissions from advanced to transitional economies as companies shift production to avoid emissions costs (Babiker 2005), electricity's unique stationary generation provides a secondary incentive to study whether production must physically relocate to shift carbon emissions elsewhere. Several international and supranational policies like the Kyoto Protocol have addressed global carbon transfer (UNFCCC 1997), aiming to minimize this shift that can offset carbon emission declines in advanced nations, potentially undermining the policy's net success. However, while extensive research on carbon leakage out of the EU ETS altogether has been extensively conducted since 2005, addressed in Section II, little to none has looked at different carbon emissions trends between nations in the market itself. This study aims to fill that gap in relation to the electricity generation industry, marked by significant differences in production and transportation compared to other carbon-intensive industries.

Unlike most other industries, electricity generation has a highly unique production and transportation mechanism that significantly differentiates it from other heavily carbon-intensive industries like manufacturing and metal processing. First, despite a common, identical output, electricity generation technologies are highly diverse, including fossil fuel combustion, nuclear fission, solar radiation, and hydropower, among others. Furthermore, as different generation techniques emit varying levels of carbon dioxide, ranging from carbon-free renewable and nuclear technology to carbon-intensive fossil fuel generation, carbon price effects should similarly vary between production methods, resulting in different marginal costs of electricity generation despite an identical output. Moreover, unlike any other carbon-intensive industry, the electricity sector relies on cables and wires for distribution. Assuming companies wish to remain in a particular electricity market, this transmission method prevents electricity generators from physically shifting production to regions with lower-cost environmental regulation, instead reducing carbon emissions by other means. These unique factors, however, do not prevent differences in carbon emissions trends between EU member states as electricity generators may profit from the sale of unused carbon permits.

For differential carbon price responses to exist in the electricity sector, generators in wealthier nations must reduce domestic carbon output and sell the resulting unused emissions permits abroad. Increasing the domestic share of renewable electricity sources like wind, solar, hydroelectric, or geothermal power with marginal costs lower than carbon-intensive sources would present the most direct method to reduce permit use. However, as such stations are expensive due to direct capital costs and sunk costs of early fossil fuel plant retirement, companies with the best access to capital and investment, those in wealthier nations, would have a better ability to finance a shift towards renewable electricity generation, resulting in a rightwards supply curve shift. Furthermore, transitional economies, particularly those in the EU with extensive, existing electricity infrastructure, would still face the high sunk cost of early fossil fuel plant retirement but may instead purchase additional permits (particularly if inexpensive) for the electricity sector as a short-run alternative. If the EU ETS induces differential carbon price responses between advanced and transitional economies, then permits and the emissions they represent should be sold to transitional economies, particularly those with relatively high marginal emissions reduction costs. These higher costs and abatement strategies should reflect the generally higher carbon intensity of electricity generation, or the carbon dioxide emissions per MWh generated, seen in relatively poor EU countries.

While not exclusive to the electric power sector, carbon allowances in the ETS nonetheless play an important factor in electricity generation in each EU member state. Like coal, natural gas, or petroleum prices, carbon allowances increase fossil fuel electricity generation costs, as explained further in Section II. Furthermore, the EU ETS influences the electricity supply curve, or merit order, of individual EU member states by affecting the marginal cost of each generation type differently. This change should be evident in the available data, as renewables alone have expanded significantly in the measured period. For example, according to the data used in this study, combined British wind and solar electricity generation increased from 33.5% to 40% of peak electricity generation while coal electricity generation decreased from 37% to 22% from 2015 to 2017. If costs change due to carbon allowance price, an upwards merit order shift should be noticeable, as should a rightwards merit order shift from increased low-cost renewable generation in the long run.

As explained by the European Commission EU ETS Handbook (European Commission 2015), the current cap-and-trade system began as a series of phases designed to ease European economies into the new environmental policy with minimal economic disruption. Phase I (2005-2007) limited the introduction to large, carbon-intensive industries like electricity generation, oil refining, and metal processing. However, that phase did not reduce carbon emissions successfully, increasing EU-wide emissions by 1.9% over its duration. In Phase II (2008-2012), the EU expanded the mechanism to include more carbon-intensive industries. While this phase did succeed in reducing carbon emissions by 3%, such reductions may be attributable to the global recession that itself reduced carbon emissions from reduced economic output. The current phase, Phase III (2013-2020), represents the most significant shift in the EU ETS's structure, with an auctioned permit system gradually replacing a freely-allocated permit system. It has also been marked by a notably stable but generally low carbon permit price, barring a recent price increase since early 2017.

Phase III (2013-2020) data is both more prevalent and more informative of electricity generation in EU member states. While separate from its carbon trading scheme initiative, the EU has also begun a process of consolidating electricity generation across borders under the European Network of Transmission System Operators for Electricity (ENTSO-E). Since 2015, the ENTSO-E has published hourly day-ahead price and generation data by energy type and yearly generation capacity for individual generators in each member country. This data can be used to estimate an electricity supply curve, otherwise called a merit order, for each country, with cross-border trade currently a relatively minimal source of electricity supply. This study will use a two-step system, first estimating a monthly merit curve for each country through a Tobit censored regression model, then interacting changes in the merit order with the carbon permit price. This uniform analysis of carbon pricing effects on electricity generation will provide a metric to analyze differences in merit order changes between advanced and transitional EU members. This merit order is central to this study, as its shifts over the four-year period will indicate how the advanced and transitional categories responded to carbon pricing by increasing the share of renewable generation or by buying carbon permits to cover carbon output.

Highlighted by the presence of wealth transfers from advanced to transitional or underdeveloped nations in other multinational agreements like the Clean Development Mechanism (UNFCCC 1997), the cost of renewable energy development is often prohibitively high for transitional economies. Analyzing the entire EU thus provides a useful metric to determine how the uniform carbon price shifts electricity supply in different ways between the two economic categories, potentially undermining or slowing the policy's long-term goal of carbon neutrality. This study shows that advanced economies have responded to carbon pricing by increasing domestic renewable electricity generation, strongly reducing electricity sector emissions, while the incentive to reduce carbon emissions in transitional economies is nonexistent, weakly increasing electricity sector emissions. Transitional electricity sectors without the capital to invest in renewable generation would be instead expected to buy permits on the carbon market. In the absence of direct permit flow data, this study will focus instead on the effects of carbon pricing on electricity generation indicating that while the EU ETS incentivizes carbon emission reductions in the advanced bloc from renewable energy development, it may undermine its long-term effectiveness by failing to incentivize comparable renewable growth in the transitional bloc. Furthermore, this study will expand on previous works by focusing on all members of the EU simultaneously. If significant differences do exist between the EU's advanced and transitional economies, this trend would have significant policy implications for the EU, particularly if differential carbon price effects in electricity generation threatens the EU ETS's long-term success.

This paper begins with a brief literature review in section II outlining past studies on carbon pricing and carbon emissions in the EU. It will then include a brief theoretical background in section III explaining carbon price effects on electricity supply curves, a central aspect of this study. It will then be followed by a description of the ENTSO-E and EU data in section IV and the empirical strategy of the model used to derive the merit order curves in section V. Finally, the study will conclude with an analysis of the results in section VI and a discussion of their implications on the EU ETS regarding its upcoming structural reforms in section VII.

II. Literature Review

While extensive research on electricity markets in several advanced EU member states since the EU ETS began in 2005, relatively few have analyzed similar effects on electricity markets in transitional EU economies. Furthermore, few studies have incorporated all or most EU members. As this paper will draw data exclusively from Phase III (2013-2020), it will rely heavily on more recent literature discussing the effects of carbon pricing, while drawing insight from earlier papers. The substantial shift in the EU ETS after 2013, marked by a significant change from freely-allocated to auctioned permits during Phase III, justifies this greater reliance on more recent studies than those focused solely on its first two phases.

Ellerman & Buchner (2007) provide one of the most cited studies on the effects of carbon allowances on electricity prices, finding that, despite free allocation, electricity producers incorporate the opportunity cost of selling or retaining a carbon permit in electricity prices. Studying Belgium, France, Germany, and the Netherlands, Sijm et al., (2006) find that these pass-through effects vary drastically and depend on the fuel mix differences between countries, ranging from €1-5/MWh (2-9% of the average electricity cost) in France to €13-19/MWh (14-22% of the average electricity cost) in Germany. Furthermore, this study finds that the carbon intensity of the marginal generator, the last operator at equilibrium, most directly affects the equilibrium electricity price. Other studies have upheld these results in each EU ETS phase. Freitas & Silva (2015) find that in Phase II and III, a 1% increase in the carbon allowance price was associated with a 0.24% short-run increase in the Spanish electricity price. Kirat & Ahamada (2011) find that the long-run merit order carbon price response depends on the share of fossil fuel generation in total electricity production. Finally, Hirth (2018), finds that the carbon allowance price reduced the electricity price by 19% in Germany and by about 8% in Sweden between 2010 and 2015, reflecting the stronger incentive for more carbon-intensive Germany to shift production methods towards carbon-reducing or carbon-free alternatives. This paper will expand upon these studies by including lesser-studied EU members and by analyzing effects distinct to the EU's advanced and transitional blocs.

Notably, very few studies take an EU-wide approach to investigate the effects of carbon allowance prices despite the market's broad geographic range. While excluding Balkan and Baltic nations and Ireland, Lise et al. (2010) conducts the broadest analysis of the European electricity market, incorporating twenty EU members into their model. This model essentially expands the same analysis of pass-through costs used in the Sijm et al. (2006) study to a larger set of EU nations. However, this model establishes only a single supply curve for the 20-nation sample, treating the EU as a fully-integrated market and ignoring the generally fragmented system currently in place. Furthermore, it does not incorporate wind or solar energy into its analysis even through several nations in its study have had extensive renewable energy production since the early 2000s. This paper will build upon the Lise et al. (2010) study by instead establishing merit orders for individual EU members and including renewable generation, the combined output of which surpassed that of both nuclear and solid fuels throughout the EU in 2013.

Other studies that broadly analyze the EU focus on macroeconomic factors like energy intensity (energy consumption per unit of GDP) or carbon intensity (carbon emissions per unit of GDP), which are still relevant to this study's focus. Momete (2017) finds that despite their relatively lower economic development, nearly every nation in the eastern EU has increased its renewable generation and decreased energy and carbon intensity from 2005 to 2015, with Balkan member states showing the greatest overall improvement. Verbič, Filipović, & Radovanović (2017) find a notable negative correlation in energy intensity and energy prices within the EU, with high energy intensity associated with lower electricity prices and vice-versa. Furthermore, this study also finds that the high energy intensity in emerging economies decreased due to the ETS compared to comparable non-member neighbors in 2005. These studies' conclusions will aid in highlighting the magnitude of changes between the advanced and emerging blocs within the EU, aiding in distinguishing between EU members of this study.

As the EU ETS ultimately aims to reduce carbon emissions efficiently, analysis of its success or failure is also necessary. Studies that estimate hourly emissions rates by electricity generators do find long-run effects of carbon and electricity prices on carbon emissions reductions, while short-run effects are minimal to nonexistent. Stoll, Brandt, & Nordström (2014) find that while hourly electricity market price and time of day do not reliably predict hourly emissions from electricity production, there is a correlation between electricity market price and carbon intensity of electricity generation over time. Similarly, Hawkes (2010) finds that the marginal emissions factor (MEF), the emissions rate of the marginal generating unit, has a clear relationship with electricity system merit order. Furthermore, Hawkes (2010) notes that a merit order based on generation cost could be used to explore time-of-day emissions, while Lise et al. (2010) find that emissions trading reduces carbon emissions by affecting long-term consumer and producer behavior. This paper will expand upon these studies by estimating reductions in emissions attributable to the carbon price's effect on electricity generation in EU electricity markets.

Several broad and specific studies analyze the EU ETS's effects on electricity prices, renewable generation, carbon emissions reductions, and macroeconomic trends. Macroeconomic trends, particularly carbon intensity and energy intensity of the economy, will be used to determine which countries fall into one of two economic development categories. Data on electricity generation, prices, and cross-border flows will be taken from the ENTSO-E. Merit curve shifts should mirror trends in sustainable development costs acknowledged by multilateral climate frameworks of both the EU and UN. Similarly, this study will expand on past papers to include electricity price effects for sparsely-studied Balkan and Baltic nations while allowing for an EU-wide comparison of the carbon market's overall effect.

III. Theoretical Framework

Carbon cap-and-trade markets primarily rely on the gains from trade and changes to input prices from carbon pricing to incentivize efficient emissions reductions. Theoretically, nations who can abate carbon emissions more cheaply will sell their additional permits to those with higher reduction costs. This concept indicates that net permit buyers are expected to rely on carbon-intensive generation and have a higher marginal abatement curve. Conversely, net sellers are expected to rely less on carbon-intensive generation and have lower marginal abatement curves. This uniform input price would notably change the country-specific electricity generation supply curve, known as the merit order, by changing input prices. This paper will use the terms "merit order," "merit supply", and "electricity supply" interchangeably. The curve orders generators in an electricity system by marginal cost to determine which to operate at a given equilibrium price. As carbon allowance prices constitute additional input cost similar to fuel or operating costs, then the change in carbon price should affect merit order by varying input costs along the different generators in the electricity system.

Largely simplified, this example of gains from trade highlights that differences between countries should be evident by analyzing the carbon price's different effects between transitional and advanced economies. As the carbon intensity of electricity tends to be higher in transitional economies, reflected by their greater relative share of fossil fuel generation in total electricity generation, then carbon abatement costs should be relatively higher in these economies. High capital costs for renewable development and high sunk costs from the early retirement of existing fossil fuel generators would result in a higher abatement cost for transitional economies than for advanced ones, which have relatively lower carbon intensities and likely have greater capital available for renewable investment. This disparate effect in responses to carbon pricing should be most evident in changes to the merit order over time, altering the marginal cost of fossil fuel generators and shifting the merit order from renewable development.

Despite the different electricity market structures by country, the merit order has the same fundamental structure, with cheap, base-load plants listed first and expensive, peak-load generators listed last. “Base load” generation operates nearly continuously and typically consists of nuclear and renewables with little to no marginal cost, while “peak load” generation operates only when demand requires and typically consists of fossil fuels with relatively high marginal costs. All other generation falls in between to ensure that supply simultaneously meets demand, preventing dangerous overcapacity or grid blackouts if not met. Figure A, below, shows some potential effects of merit order changes to the curve of a generic electricity system. Represented by upward-facing arrows for coal, natural gas, and oil, carbon pricing would raise portions of the curve, depending on the emissions level of each plant affected. If near the marginal unit, as is the case with peak demand in Figure A, this carbon price would also increase the equilibrium electricity price due to its effect on the input cost of the marginal unit. Conversely, the increase in renewables would shift the merit order rightwards, resulting in a reduction in electricity price if the marginal generator changes, as is seen for base demand in Figure A. These set of changes to the merit order constitute a “merit order effect,” inducing long-run electricity generation and equilibrium price changes that will be a primary focus of this study.

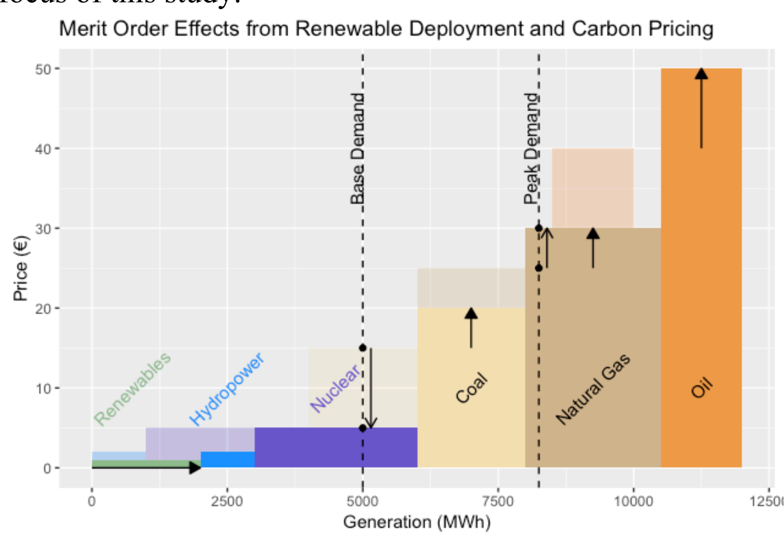

Figure B: Representation of electricity merit order effects

Changing the input price from carbon permit pricing directly alters the merit order, as would happen for the supply curve of any market if input prices increased. However, by analyzing the merit order effects on individual EU nations, this study hypothesizes that these effects will vary between advanced and transitional economies due to different carbon price responses.

Specifically, advanced countries would be expected to invest in capital-intensive renewable generation, thereby showing an overall rightwards shift in the merit order, with some potential but relatively lesser effects from efficiency improvements or carbon abatement technology. On the other hand, transitional economies would be expected to purchase unused carbon permits, with a lesser focus on increasing renewable energy generation, showing an overall upwards merit order effect from carbon pricing.

Establishing a merit order for multiple periods will provide insight into changes in its overall structure due to the carbon permit price, evident in individually estimated merit curves over several periods in the EU ETS. In practice, transmission system operators do not strictly follow an established merit order, as congestion, transmission constraints, and renewable electricity intermittency often require that more expensive units be used in place of their cheaper counterparts in real-time. Nevertheless, merit order effects from carbon pricing should be evident through changes in fossil fuel generation prices and renewable generation over time.

IV. Data

Data in this study primarily come from the European Union, with the European Commission providing macroeconomic data for individual member states and the ENTSO-E providing data for electricity generation by country. European Commission data range from 1990 to 2016 for all current members and cover 400+ yearly variables and sub-variables, including carbon intensity of the economy (carbon output per unit of GDP), energy intensity of the economy (energy output per unit of GDP), and GDP per capita. While these data range from 1990 to 2016, this study will only use data from 2015 to 2018 due to ENTSO-E data limitations. Although this limits the timespan of the study, this range allows consistent, high-quality data for each member state unavailable to older studies. Furthermore, as the permit allocation system changed from a grandfathering mechanism to a partially auctioned mechanism in Phase III (2013-2020), limiting the study to only the third phase maintains a constant permit allocation method and eliminates any permit banking, allowed for up to one year, from the second period to the third. The ENTSO-E provides hourly day-ahead prices in local currency, hourly generation by type of generator unit, and installed generation capacity for individual generators. These data range will range from January 2015 to December 2018. Data on currency conversion to euro and carbon allowance prices are available online through Bloomberg on a daily basis.

European Commission macroeconomic data will be used to separate EU countries into transitional and advanced categories through a k-means cluster based on carbon intensity of GDP, energy intensity of GDP, and GDP per capita. These variables will compare like-countries based on the relative dependence on carbon emissions, energy intensity, and GDP per capita, reflective of economic development. This k-means clustering model uses data from 2016, the most recent year in the European Commission data, and indicates an optimum of 3 groups within the EU; however, as the third group consists of only Luxembourg, for practical purposes, it will be aggregated into the second cluster, consisting primarily of its western and northern EU neighbors. Croatia, Cyprus, Iceland, and Malta will be excluded from this study due to a lack of electricity data even though they are full EU ETS members. Figure B and Table A, below, respectively provide a map of countries included in this study colored by category and the average value by category for each indicator variable used in the k-means cluster output. This study will compare trends between the two categories, not between individual members of the carbon market.

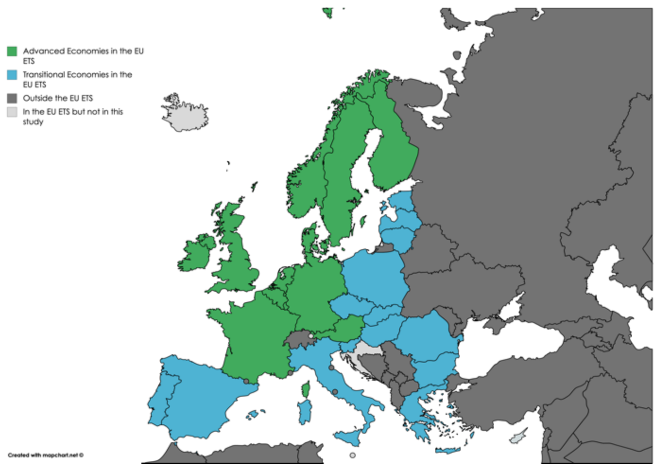

Figure C: Classification of EU ETS countries

Category	*GDP per Capita*	*Carbon Intensity (tons CO_2 per GDP)*	*Energy Intensity (tons oil eq. per GDP)*
Advanced	€46,649	211.6	109.3
Transitional	€15,524	506.8	210.8

Table A: Average indicator values by category

The ENTSO-E is the EU's body of electricity transmission system operators that, while currently only coordinating generation and transmission between regions, eventually plans to consolidate transmission and deregulate EU-wide generation. For each hour from January 1, 2015 to the present, the ENTSO-E publishes day-ahead prices in the local currency of each transmission system operator. Similarly, the network publishes hourly generation for 20 distinct generation types. Table B, below, provides a sample of the UK zone on September 15, 2018, from 7am to

5pm, while Appendix B provides a broader overview of the full data.

Hour	*Price (£)*	*Biomass*	*Natural Gas*	*Coal*	*Nuclear*	*Solar*	*Offshore Wind*	*Onshore Wind*
7	68.00	2829	12677	2494	14572	16	2427	3910
8	61.92	2796	16269	3256	14574	977	2180	3951
9	69.10	2962	20156	4583	14581	3410	1891	3428
10	80.00	3008	21419	5317	14576	6180	1721	3323
11	78.99	3047	21060	5289	14558	8600	1782	3273
12	70.00	3213	20814	4447	14567	9700	1564	3593
13	68.00	3232	20671	4014	14561	10310	1695	3813
14	55.07	3209	19948	4026	14572	9510	1744	3892
15	54.92	3237	18976	3675	14556	7905	1898	3988
16	56.52	3247	19135	3270	14554	6420	1977	4111
17	60.00	3237	20506	3892	14531	4480	1929	4462

Table B: UK price and generation, from 7am to 5pm on September 15, 2018

These data will be used to estimate individual monthly merit orders by nation for the four-year period by determining each marginal cost of generators in an electricity system. Although the generation data are denoted in megawatts (MW), as they are hourly, these values also reflect megawatt-hours (MWh)[2] of generation. As cross-border flows represent a small proportion of total electricity consumption in most countries, these data are omitted from this study. Furthermore, as the ENTSO-E publishes data on individual generators for each country and their installed generation capacity for each year, the estimated merit orders will include individual generators and their estimated marginal costs. While the ENTSO-E also provides data on installed capacity for large facilities like nuclear generators or wind farms, it does not provide similar data on capacity for small-scale generators, such as residential solar panels. As such information does still appear aggregated into the hourly generation data, this study will treat the total installed small-scale capacity as a single representative generator.

This study will also look at changes in carbon output by fuel generation types, particularly of fossil fuels, as the EU ETS primarily aims to reduce total EU carbon output. While data on carbon output by individual generators are not available, the Intergovernmental Panel on Climate Change (IPCC) in 2006 published benchmark figures on emissions factors[3] by generation type. Furthermore, the European Covenant of Mayors, a branch of the European Union, uses these values to estimate its members' own electricity sector carbon output. These values are denoted in

[2] A megawatt (MW) is a measurement of the rate of production while a megawatt-hour (MWh) is a measurement of the amount produced. Electricity generated at one MW over the period of one hour equals one MWh produced.
[3] An emissions factor is the carbon output or equivalent per unit of energy.

metric tons of CO_2 per MWh, allowing a direct estimate of carbon output from the generation data. Values for these emissions factors are provided in Appendix C.

As the euro is the most widely used currency in the EU – adopted by 19 of the 28 member states – it serves as a reasonable common benchmark to compare electricity prices across borders. Only four countries in the ENTSO-E data report values denominated by other currencies – Poland, Romania, Bulgaria, and the United Kingdom, so monthly exchange rates from Bloomberg will be used to convert these values to the euro. No systemically odd results appear in merit order estimates for these four countries, so this euro conversion should not significantly alter any analysis. Furthermore, annual European Commission economic and financial data are also noted in euros for every country, eliminating any further conversion needs. Because carbon permit spot, futures, and auction prices are highly correlated, the carbon index Carbix (CBX) in euros per ton of CO_2, also taken from Bloomberg, will be used as a proxy. A producer price index for the electricity sector on a monthly basis was taken from the European Central Bank to control for inflation.

V. Empirical Strategy

As the k-means cluster method previously determined the two country categories, establishing a method to estimate merit orders and their changes will be the central focus of the rest of this study, relying heavily on the ENTSO-E data to estimate marginal costs from day-ahead prices and generation. While the data are collected at an hourly, daily, monthly, and yearly interval, estimating a monthly merit order will provide the best time-varying model while reducing the effects of daily electricity market anomalies like blackouts or extreme weather. The marginal cost of generating 1 MWh for each type of generation can be estimated with a vectorized general linear Tobit model from the R package censReg, which models trends bounded by a minimum and/or maximum possible value that can obscure a normal linear model. In this model, the minimum and maximum values are the minimum and maximum electricity produced by a type of generator within a given month. The linear model specification is provided, in equation (1), below:

$$Generation = \beta_0 + \beta_1 Price + \beta_2 Hour + \beta_3 Price * Hour + \varepsilon \tag{1}$$

In this model, $Generation$ is the generation by a specific type of electric plant, i.e. nuclear, solar, natural gas, coal, etc., in MWh; $Price$ is the day-ahead price for electricity by hour in each country; $Hour$ is the time of day, ranging from 0 to 23; and $Price * Hour$ is the interaction between price and time of day accounting for time-of-day effects like the sunlight availability for solar generators. This effect is incorporated into the estimated marginal cost only if found to be statistically significant. This trend is reflected in the above regression by allowing β_2 and β_3 to represent the effects of time of day and the interaction between time of day and price, respectively.

As the marginal cost of generation also depends on the interaction of price and hour, an estimate for the effect of $Hour$ will be found using an average weighted by total generation at each hour throughout the given month. Thus, an estimate for intermittent marginal cost of generation is equal to $1/_{(\beta_1 + \beta_3 * Hour)}$, with the $Hour$ variable being this weighted average. If a value for either equation is found to be below zero, indicating a negative marginal cost, it will be changed to zero for the purposes of constructing a merit order curve. Furthermore, if this value, the marginal cost $1/_{\beta_1}$, or both are not found to be statistically significant at the 95% or greater level, their marginal cost estimate will also be changed to zero, as this trend implies that such plants do not change output with price, thereby operating nearly continuously in base-load generation. Similarly, for small-scale solar plants not present in ENTSO-E plant-specific data, the marginal cost will also be changed to zero, as such plants operate only due to available sunlight and not from changes in price. This approach is consistent with the Hirth (2018) study that constructed a merit curve analyzing only carbon-emitting plants at marginal generation, arranging all else below the estimated marginal costs.

While not encompassing data from household and small-scale generation, the ENTSO-E data containing installed capacity per year can be used in conjunction with the estimated marginal costs to construct a merit order for each month analyzed. Differences in installed capacity and realized capacity for residential and small-scale generation can be incorporated as an aggregation into one representative unit. This would not be present in sources that require large generators, such as nuclear, coal, hydroelectric, and natural gas facilities. Furthermore, the capacity of each type of plant is multiplied by an estimated capacity factor, or the ratio of mean generation for one month to the total installed capacity for that type of plant. For example, if natural gas generation holds a total installed capacity of 10,000 MW but only generates an average of 7,000 MW, the capacity of each natural gas generator would be multiplied by 70%. By multiplying the estimated marginal cost, the estimated capacity factor, and the maximum capacity for each generator, a price for average generation at each plant can be established. While this assumes equal marginal costs and equal capacity factors for each generation type, not fully representative of real-world generators, it nonetheless provides a reasonable estimate for the overall production from each generation type. Individual generators within a certain group should not be expected to differ systematically from the estimated marginal cost or capacity factor.

The results of this merit order approximation reflect real-world electricity generation trends. Large-scale hydroelectricity from reservoirs and rivers falls in the base-load area, although its ability to increase or decrease production more quickly often puts it slightly higher. Nuclear, wind, solar, and other renewable generation also generally fall in base-load generation. Fossil fuels generators reside at or near peak generation due to their higher marginal costs from fuel, maintenance, and emissions controls. Many of these plants do not operate at full capacity for much of the year. Finally, although they do not have the same emissions or fuel costs as fossil fuel plants, many countries also operate hydroelectric pumped storage stations, where water is sent uphill to a small storage facility during off-peak hours to be converted back to electric energy during on-peak hours, giving them a high price despite the lack of fuel and emissions costs. Figure C, below, estimates Spain's merit order for July 2018 using this method. A sample for each country for July 2018 is provided in Appendix A. Data was sufficient to estimate 1,068 monthly merit orders from 24 EU ETS member nations from January 2015 to December 2018.

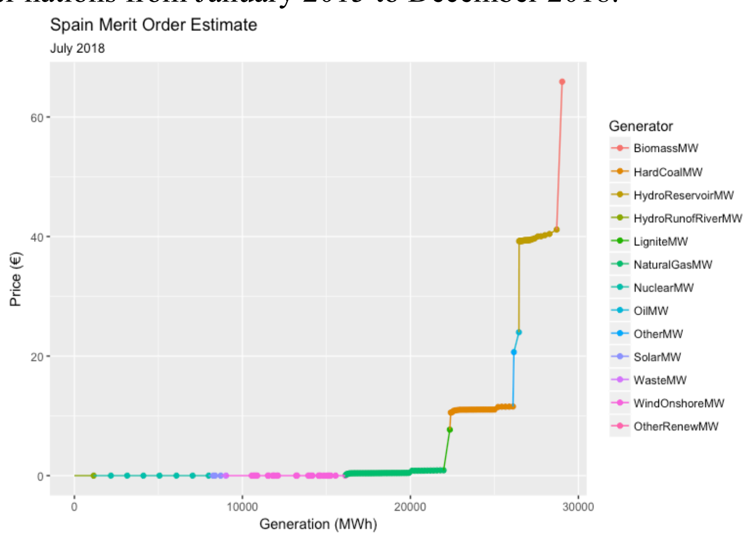

Figure D: Spanish merit order estimate, July 2018

As carbon prices are expected to induce changes in the merit order, analyzing shifts in the overall merit order over time while controlling for time-of-year and geographic region will allow an understanding of how carbon permit pricing over time has affected the merit order structure. In Figure C, an increase in the carbon price would be expected to raise the marginal cost of coal and natural gas generation, respectively, the orange and lime green sections. Conversely, a rightwards merit order shift over time would reflect increasing low-cost, renewable generation in the electricity market. These trends will be captured by a non-uniform linear b-spline with one knot at the point with the lowest sum of squared residuals. In the later analyses, the optimal knot position, measured from its generation and price values, will be used to detect merit order changes over time. This model ran monthly for each country from January 2015 to December 2018 except for Poland and Bulgaria, whose data began in January 2016, instead. Figure D, below, provides an illustration of this linear b-spline approximation for the February 2018 United Kingdom merit order estimate.

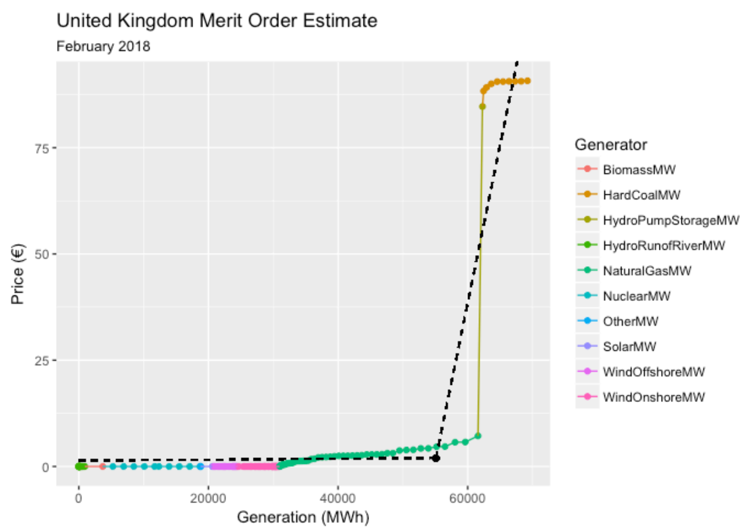

Figure E: British merit order estimate, February 2018, with linear b-spline

While this method provides a useful mechanism to compare merit order differences, its main drawback is that the optimal point calculated incorporates some non-renewable generation that exists near base-load renewable, nuclear, and hydroelectric generation. Furthermore, for countries with an already high level of renewable generation, the optimal generation point would be calculated at or near the very end of the estimated merit order, providing little or no opportunity for the hypothesized increase in low-carbon generation, particularly if such countries are also in the process of reducing electricity consumption. To alleviate this concern, the carbon output from total generation in a given month will be calculated using the emissions factors from the IPCC and European Convention of Mayors previously mentioned. The share of nonrenewable electricity generation by type will be first summed for each month, multiplied by its respective carbon emissions factor, then summed again to determine the total emissions from electricity generation. If carbon output decreases over time, this trend should indicate either an increase in the share of zero-carbon generation or a reduction in the carbon output of carbon-intensive generation by fossil fuels within the merit order.

Finally, the country classification, carbon allowance price, optimal linear spline location, and carbon output will be incorporated in three linear regressions analyzing the effects of carbon pricing, time, and country category on generation, price, and carbon output. For the generation point, advanced countries are expected to shift rightwards while transitional countries are expected not to change or to shift backwards due to the carbon price effects. While analyses including historical average prices for Carbix could be helpful to study the effects of permit banking, they highly correlate with the Carbix variable itself as well as with other averages available in the Bloomberg data, so they will be omitted to prevent issues with multicollinearity. A correlation matrix in Table C, below, shows the strong relation between each of five otherwise potentially helpful variables provided in the Bloomberg data.

Correlations of Monthly Carbix Averages

	Carbix	50-day average	100-day average	200-day average
Carbix	1	0.977	0.951	0.876
50-day average	0.977	1	0.986	0.931
100-day average	0.951	0.986	1	0.974
200-day average	0.876	0.931	0.974	1

Table C: Correlations between Carbix and rolling averages

The three regressions follow a similar overall format. Generation will be analyzed using equation (2), below, which measures the effect of carbon price (CBX), measured in euros; time ($Time$), measured as the number of months since January 2015; and country category ($Category$), defined as "advanced" or "transitional," on the natural log of the optimal generation point (ln (Gen)), taken to measure effects in percentages. $Month$ and $Country$ account for time-of-year and regional fixed effects, respectively.

$$ln(Gen) = \beta_0 + \beta_1 Time + \beta_2 Time * Category + \beta_3 CBX + \beta_4 CBX * Category + \beta_5 Category + \beta_6 Month + \beta_7 Country + \varepsilon \quad (2)$$

A parallel equation measuring the same variables' effects on price will complement this regression and provide insight into how carbon pricing changes the electricity price ($Price$), measured in euros, between the two country categories. For the advanced category, the carbon pricing would be expected to decrease the optimal price due to an influx of low-cost renewable generation, while it would be expected to increase the optimal price for the transitional category more reliant overall on fossil fuel generation. Equation (3), below, describes this regression using the same independent variables from equation (2).

$$Price = \beta_0 + \beta_1 Time + \beta_2 Time * Category + \beta_3 CBX + \beta_4 CBX * Category + \beta_5 Category + \beta_6 Month + \beta_7 Country + \varepsilon \tag{3}$$

Finally, the third equation uses the same independent variables to analyze changes in total carbon output (tCO_2), measured in thousand tons of carbon dioxide, providing insight into how merit order shifts from equations (2) and (3) affected carbon emissions. If the overall hypothesis of this study holds, then the signs on the advanced and transitional categories should be reversed from each other or nearly so, as the carbon output decrease in advanced countries should be offset by a weak increase in transitional ones. This trend should be particularly evident when looking at the coefficients on the carbon price (β_3 and β_4) and time (β_1 and β_2), as if the carbon price holds a different effect on the transitional category than on the advanced one, this trend should also be evident over time. Equation (4), below, describes this regression, which uses the same variables as those in equations (2) and (3).

$$tCO_2 = \beta_0 + \beta_1 Time + \beta_2 Time * Category + \beta_3 CBX + \beta_4 CBX * Category + \beta_5 Category + \beta_6 Month + \beta_7 Country + \varepsilon \tag{4}$$

A side-by-side comparison of these three regressions will provide insight into not only how carbon pricing has affected electricity prices, generation, and carbon output individually, but also how such changes in electricity markets affect carbon output. The three indicator variables will not be included in each other's regressions to prevent simultaneity bias in the estimated coefficients. Differential carbon price responses in the EU ETS would happen most noticeably if the effects of the carbon price and time differ significantly between the transitional and advanced categories. Thus, as the EU ETS aims to reduce carbon output in the most efficient possible way, then studying these effects on carbon dioxide emissions alongside those on electricity supply will help to analyze how the electricity sectors of the two blocks altered carbon output due to the EU ETS policy.

VI. Results

Before analyzing these three regressions, it is also important first to see how generation, price, and carbon emissions have changed both over time and from carbon pricing individually. Furthermore, as this study focuses primarily on the effect of carbon pricing on all three measurements, these preliminary regressions will independently analyze these effects to provide initial insights into the different carbon price responses. This study hypothesizes that the carbon price should increase renewable production or reduce carbon-intensive production in the advanced bloc, thereby decreasing its carbon output. Conversely, the transitional bloc should see a price increase alongside little generation or emissions changes due to the potentially prohibitive capital costs needed to switch to renewable generation.

For time-based changes in generation, price, and carbon output, a stark difference between the advanced and transitional categories appears even without carbon price effects. Table D, below, presents the findings of three regressions that regress the natural log of optimal generation, optimal price, and emissions with month and country providing time-of-year and regional fixed effects. Notably, the generation point for both economies decreases by around 0.5% per month, although this decline could be explained by a simultaneous increase in the price point from carbon pricing, resulting in a leftwards shift in observed optimal generation. On the other hand, transitional price points decrease over time despite the carbon price increase over the four-year period, with no significant change in long-run electricity prices for the advanced bloc. It is important to note, however, the sign and magnitude of carbon emissions between the two classifications reflects two distinct time-based responses, with an advanced category decrease of around 18.4 thousand metric tons per month and a transitional category increase of around 2.6 thousand metric tons per month. While transitional economies do have lower total carbon output, this trend in itself supports the claim that only the advanced bloc seems to decrease electricity sector emissions while the transitional bloc increases at a relatively slow rate. If no significant

	ln(Opt. Generation) **Model 1**	**Opt. Price** **Model 2**	**Thousand Tons CO_2** **Model 3**
Time	-0.005^{***}	0.152	-18.410^{***}
	(0.002)	(0.100)	(3.758)
Transitional	-0.405^{***}	34.047^{***}	-749.630^{***}
	(0.107)	(6.594)	(249.004)
Transitional: Time	-0.002	-0.311^{**}	21.050^{***}
	(0.002)	(0.129)	(4.861)
Country	*Yes*	*Yes*	*Yes*
Month	*Yes*	*Yes*	*Yes*
Constant	9.056^{***}	2.354	1183.109^{***}
	(0.089)	(5.485)	(207.123)
N	1068	1068	1068
R-squared	0.916	0.202	0.962
Adj. R-squared	0.913	0.174	0.961
Residual Std. Error (df = 1031)	0.458	28.372	1071.319
F Statistic (df = 36; 1031)	313.182^{***}	7.239^{***}	729.969^{***}

$^{***}p < .01$; $^{**}p < .05$; $^{*}p < .1$

Table D: Effect of time and carbon pricing on the natural log of generation, price, and carbon emissions differences existed in electricity sector emissions changes over time, the advanced and transitional blocs should show similar responses. However, the distinct coefficient differences indicate that the advanced and transitional blocs have drastically different time-based responses in the European electricity sector.

Analyzing instead the effect of the carbon index, Carbix, on the advanced and transitional blocs reflects the above time-based findings, supporting the differential response hypothesis. Carbon pricing does have a significant correlation with the optimal generation point, decreasing it by 1.3% per month in the advanced bloc and by 3.5% in the transitional one. This difference can likely be attributed to the greater dependence on fossil fuels in the transitional category than in the advanced one. On the other hand, the carbon price has an overall positive correlation (€0.67 per carbon price €) on the advanced bloc's electricity prices and an overall negative correlation (€-.58 per carbon price €) on the transitional bloc's electricity prices. This reversed correlation between economies strongly explains why, similar to the model of change over time, transitional economies have a relatively weak carbon output growth (6.6 thousand metric tons per carbon price €) while advanced economies have a relatively strong carbon output decline (-52.1 thousand metric tons per carbon price €). The vastly different carbon price correlations on electricity prices may drive this carbon output difference, as the positive price correlation on the advanced bloc would incentivize a carbon emissions reduction while a negative price correlation on transitional economies would incentivize the opposite. Table E, above, provides a summary of this regression.

	ln(Opt. Generation) **Model 1**	**Opt. Price** **Model 2**	**Thousand Tons CO_2** **Model 3**
Carbix	-0.013^{***}	0.668^{**}	-52.074^{***}
	(0.004)	(0.284)	(10.764)
Transitional	-0.269^{***}	37.281^{***}	-742.207^{***}
	(0.104)	(6.575)	(249.063)
Transitional : Carbix	-0.022^{***}	-1.252^{***}	58.662^{***}
	(0.006)	(0.363)	(13.742)
Country	*Yes*	*Yes*	*Yes*
Month	*Yes*	*Yes*	*Yes*
Constant	9.028^{***}	0.306	1189.165^{***}
	(0.087)	(5.496)	(208.192)
N	1068	1068	1068
R-squared	0.920	0.206	0.962
Adj. R-squared	0.917	0.179	0.961
Residual Std. Error (df = 1031)	0.448	28.289	1071.679
F Statistic (df = 36; 1031)	329.613^{***}	7.449^{***}	729.459^{***}

$^{***}p < .01$; $^{**}p < .05$; $^{*}p < .1$

Table E: Effect of carbon price on the natural log of generation, price, and carbon output

These two analyses inform the results of the final regression that includes both carbon pricing and time alongside the country category and fixed effects by time-of-year and country. Table F, below, provides a summary of this output. In this model, several similar instances of distinct correlation differences between the advanced and transitional categories emerge,

	ln(Opt. Generation) Model 1	Opt. Price Model 2	Thousand Tons CO_2 Model 3
Time	-0.005**	0.003	-11.512**
	(0.002)	(0.128)	(4.827)
Transitional : Time	0.005**	-0.041	13.364**
	(0.003)	(0.169)	(6.366)
Carbix	-0.004	0.661*	-31.288**
	(0.006)	(0.366)	(13.820)
Transitional : Carbix	-0.032***	-1.178**	34.176*
	(0.008)	(0.476)	(17.987)
Country	*Yes*	*Yes*	*Yes*
Month	*Yes*	*Yes*	*Yes*
Transitional	-0.310***	37.597***	-844.078***
	(0.106)	(6.706)	(253.332)
Constant	9.060***	0.240	1268.512***
	(0.088)	(5.568)	(210.356)
N	1068	1068	1068
R-squared	0.920	0.206	0.962
Adj. R-squared	0.918	0.177	0.961
Residual Std. Error (df = 1029)	0.447	28.315	1069.659
F Statistic (df = 38; 1029)	313.459***	7.047***	693.834***

***p < .01; **p < .05; *p < .1

Table F: Effect of time and carbon pricing on the natural log of generation, price, and carbon emissions

particularly in the model analyzing carbon output. Both the time and carbon price correlations are all reversed between the two categories for this model, indicating a different carbon price effect on the two categories. Trends in generation and price mirror these correlations, further supporting the theory that the two blocs responded to carbon pricing differently between 2015 and 2018. These differences indicate that while the advanced bloc has focused on increasing renewable generation, the transitional bloc has not had a similar focus, having likely not faced similar incentives to decrease carbon emissions from the cap-and-trade system.

The results in these three regressions support the overall hypothesis of this study that the advanced bloc faces the greater incentive to reduce electricity sector carbon emissions through the EU ETS. While the advanced bloc decreased the optimal generation point by 0.5% per month, coupled by a 11.5 thousand metric ton monthly carbon emissions decline, the transitional bloc increased the optimal generation point by 0% per month, mirrored by a low 1.9 thousand metric ton monthly carbon emissions growth. This difference indicates that as advanced countries shift to low-carbon or renewable generation, transitional countries have maintained stable fossil fuel generation levels, resulting in a weak carbon emissions increase. Although this study hypothesized that an increase in the optimal generation level would reflect an increased deployment of renewable energy, the negative sign on the emissions level coupled with a negative sign over time for the advanced bloc suggests that it has either reduced electricity demand, reduced the use of fossil fuel generators, increased renewable electricity generation, or a combination of all three to decrease carbon output. Conversely, the stagnant growth in generation coupled by a growth in emissions over time and a positive value for the Carbix (2.9 thousand metric tons per €) in the transitional bloc suggests that transitional economies have responded to carbon pricing by neither reducing fossil fuel output nor increasing renewable generation. Instead, it appears that a negative incentive to increase emissions may exist in this category based on the effect on the optimal price point.

Electricity prices as measured by the price point interestingly have fewer significant effects from the other two variables measured. However, the results from this model do still indicate that the transitional category has not faced an incentive to deploy renewable or low-carbon technology. This study hypothesized that a decrease in the optimal price point would indicate an increased deployment of renewable generation. However, while the carbon price decreased the price point for transitional economies by €0.517 per carbon price €, the increase in emissions for transitional economies from carbon pricing (2.9 thousand metric tons per €) suggests that the reduced cost may have instead prevented renewable electricity generators from entering the market. A lowered electricity price would disincentivize or slow renewable investment, as the potential profit from such plants lessens, increasing the time taken to recover capital costs. The reverse effect appears for the advanced category, where a positive effect on price from Carbix (€0.661 per carbon price €) coupled with a negative effect on emissions (-31.3 thousand tons per carbon price €) indicates that the increased price induced a competitive switch to renewable electricity. Thus, as the two blocs appear to respond to the carbon price in drastically different ways, these results show that the EU ETS induces different incentives for the advanced and transitional blocs to alter carbon output in the electricity sector. The advanced bloc has the incentive to reduce strongly by developing more renewable generation, while the transitional bloc has the incentive to increase emissions weakly by limiting the potential profits of new renewable electricity investments.

The effect of carbon pricing on emissions provides the most concrete way to analyze how electricity sector carbon emissions have changed between the advanced and transitional blocs due to carbon pricing. The positive correlation with the electricity price point for the advanced bloc mirrored by a negative correlation with emissions suggests that competitive switch to low-cost renewables through increased costs from carbon pricing for competing fossil fuel generators possibly occurred. On the other hand, as the transitional bloc generally has a larger percentage of total electricity generation from fossil fuels, the negative correlation with carbon pricing potentially reduced this competition between generators by reducing the electricity price enough to decrease the profit incentive of potential renewable generation investors. This lesser potential profit could prevent investors from seeking long-term investment in transitional electricity systems, as the time spent to recover capital costs would be relatively greater than in advanced economies. This finding suggests that the incentive for the transitional bloc may have been insufficient to induce a competitive switch to renewable technology from fossil fuels, showing a positive overall emissions growth over time despite generally lower total carbon emissions.

While also potentially effected by domestic policies of individual countries, partially controlled by country-specific fixed effects in the model, the correlations from these three models indicate that the total effect of carbon pricing has not been equal between the transitional and advanced blocs. Further studies that analyze the effects of domestic energy policies on carbon emissions alongside the carbon price could bolster insight into the EU ETS' direct causal effect on electricity sector carbon emissions. Nonetheless, as the carbon price reflects not only electricity sector carbon abatement costs but also those of manufacturing, industry, and other carbon-intensive sectors, correlations found in this study should provide some clarity into the potentially different responses between the advanced and transitional electricity generation. As emissions and generation move in opposite directions over time for both categories, with a strong negative effect for the advanced bloc and a weak positive effect for the transitional bloc, these trends could reflect only structural changes to electricity generation outside the EU ETS market. Advanced economies may have reduced energy consumption, thus decreasing generation and emissions, while demand in transitional economies may have remained stable, requiring no change from current fossil fuel generation. However, this theory ignores carbon pricing correlations, indicating that transitional countries may not have chosen to increase renewable energy generation due to a negative price correlation. This differential effect could create a potential long-term consequence for the latter category as the incentive exists not to invest in renewable energy or to modernize electricity infrastructure to accommodate its future growth exists. This potential effect could also explain why transitional countries tend to have fewer domestic initiatives to increase renewable generation than do advanced ones. Thus, carbon pricing effects on electricity systems indicates a potentially insufficient to nonexistent incentive for transitional economies to increase renewable generation, potentially undermining the overall success of the EU's long-term carbon neutrality goals.

Although a relatively small decrease, generation in advanced economies appears to decline over time while prices remain stable due to the impact of carbon permits on renewable energy development. Furthermore, carbon pricing has nearly reverse correlations on electricity pricing as measured by the optimal generation point between the two categories, indicated by a weak carbon emissions growth in the transitional category and a strong decline in the advanced category over time. This result reflects the policy differences between the two blocs, as Germany, the United Kingdom, and Denmark, all advanced economies, notably have highly publicized and praised renewable energy investment policies, while most transitional countries, excluding Spain, do not. This model thus provides greater insight into how different electricity sectors respond to carbon pricing based on the country-specific economic development status.

VII. Discussion

If the EU ETS ultimately aims to reduce EU-wide carbon emissions with a market-based approach, the central theory to the cap-and-trade policy, then the results of this study should not be important in the short run. While emissions do rise in the transitional bloc and fall in the advanced one, net electricity sector emissions do nonetheless decrease. As electricity generators face carbon price uniformity across all member states, then electricity producers should be expected to find the most cost-effective way to incorporate this price effect pursuant to their existing generators, access to capital, and need to provide unhindered electricity access. Renewable energy initiatives are more prevalent in the advanced bloc, with notable examples in the German *Energiewende*, British offshore wind development, and French nuclear dominance highlighting this greater renewable energy prioritization. Conversely, in the transitional bloc, the stronger reliance on carbon-intensive production, notably in Poland, may prevent the long-term energy transition to renewable or low-carbon generation because the dismantling of a more extensive fossil fuel-based electricity system may be prohibitively expensive in the short run. Significant challenges, such as high sunk costs from early fossil fuel generator retirement, infrastructure renovations to accommodate new renewable generation, and intermittency issues of solar and wind generation would make a total switch more difficult for transitional economies that have had relatively shorter periods of renewable energy programs, if any.

The EU ultimately aims to become carbon-neutral by 2050, noted by the long-term strategy presented by the European Commission in November 2018, and to maintain the Paris Agreement's objective of keeping global temperature increases below 2ºC above pre-industrial levels. According to this study, the EU ETS's effects on the electricity sector suggest that the different reduction measures could become more problematic and costly for transitional countries than for advanced ones in the long run. As advanced countries invest more heavily in renewable generation, the share of carbon-free generation as a percentage of overall electricity generation should also increase, providing a better long-run trajectory towards electricity sector carbon neutrality while also inducing renewable infrastructure investment to accommodate future renewable energy growth. On the other hand, the relatively slower to nonexistent development of renewables in the transitional bloc provides long-run challenges to these nations, particularly from the desire to recover a fossil fuel generator's sunk costs before deploying new renewable generation that would price such plants out of the market. Thus, the relatively weaker trajectory of renewable energy generation in the transitional bloc may increase its long run costs, as such generators will need to be replaced and the infrastructure to accommodate potential renewable generators will need to be expanded to achieve carbon neutrality in the electricity sector from the EU ETS.

This observation provides a source of potential improvements to the EU ETS for its fourth phase that will begin in 2021. Firstly, if access to capital is indeed a constraint on the transitional bloc's ability to finance large-scale renewable production, an intra-EU method to mitigate this restriction should be considered to facilitate a faster growth of renewable generation in relatively poorer regions. Wealth transfer mechanisms already exist in several international climate agreements, notably in the Kyoto and Paris Agreements, to facilitate renewable energy development in significantly poorer nations, although the transitional countries of the EU are relatively wealthier than these intended transfer recipients. Several transitional states in this study have domestic access to strong, unused renewable energy potential, notably with high offshore winds in the Baltic states, high geothermal heat in Hungary and Poland, and high solar radiation in Greece, Bulgaria, and Romania. The greater incorporation of an EU-specific sustainable finance program could provide transitional countries the necessary capital to more quickly increase renewable generation from these relatively untapped sources. As this study indicates a negative carbon price effect on electricity prices for the transitional bloc, the incentive to shift to low-cost renewable generation does not currently exist, and restricted access to capital, access to capital with prohibitively high interest rates, or inadequate electricity infrastructure may exacerbate this problem. Future studies should focus on whether access to capital for electricity companies in transitional economies have prevented renewable energy financing possibly desired by such companies or countries to provide greater insight into this potential effect.

While intra-EU electricity trade does exist at a relatively limited scale, the construction of high-voltage transmission lines between advanced and transitional economies could also reduce the short-run use of fossil fuel generators in transitional countries. Such transmission lines would theoretically liberalize the European electricity market, thereby increasing competition between electricity providers and incentivizing investment in the lower-cost renewable generation in transitional countries. This approach could either mirror or be further integrated into the existing European Single Market that already provides for free movement of goods, capital, labor, and services. Inducing a single electricity market with minimal barriers to entry by increasing transmission line coverage would also provide access to areas with greater renewable energy production currently inaccessible to some nations. A landlocked country could, in theory, gain access to offshore wind generation, while a northern country could gain access to southern solar generation. While the ENTSO-E does aim to eventually integrate the overall European electricity market further, this goal should be coupled with Phase IV of the EU ETS or with reforms to the European Single Market in order to prioritize a faster competitive switch to renewable generation both in transitional economies and across the EU. Direct investment both into the electricity sector as a means to reduce overall carbon emissions in the long run and into electricity transmission infrastructure to induce EU market liberalization should incentivize this competitive transition to low-cost renewable generation. These reforms should be coupled with EU ETS reforms to keep prices high enough to induce necessary short-term reforms, such as efficiency improvements and carbon abatement technology, a common criticism of its relatively low price in the early years of Phase III. A study into the effects of increased renewable deployment in advanced economies on the oversupply of low-cost permits in the market would greatly complement this carbon price reform.

This study highlights both the different effects and limits to Phase III of the EU ETS on advanced and transitional European Union member states. Firstly, the carbon price seems to have a relatively lesser effect on the merit order than likely desired, providing the transitional bloc little incentive to increase renewable electricity. The different effects on generation, price, and carbon emissions between advanced and transitional economies indicate that the two categories react to the EU ETS carbon price in drastically different ways, resulting in a strong carbon emission decline in the advanced bloc and a weak carbon emission growth in the transitional bloc. Advanced economies have strongly decreased carbon emissions through renewable electricity development and through reducing the use of existing fossil fuel generators, while transitional economies have weakly increased carbon emissions by maintaining fossil fuel generation. These different effects indicate that the EU ETS needs to increase its focus on renewable energy investment in transitional countries to reach the goal of EU carbon neutrality by 2050. By improving such investment, carbon-free generation may increase in transitional economies and potentially mitigate some of the lost sunk costs of early retirement fossil fuel plant retirement. This mechanism should provide a more equitable means to reduce EU-wide carbon emissions than the sole reliance of carbon market-based mechanisms that ignores its potential long-term consequences on electricity generation in transitional economies.

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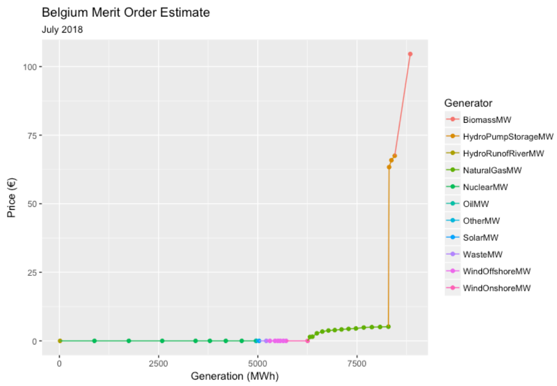
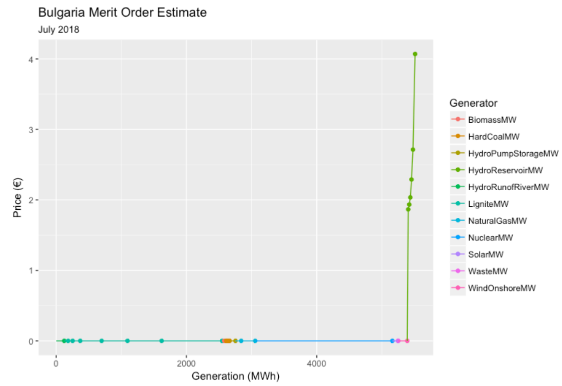
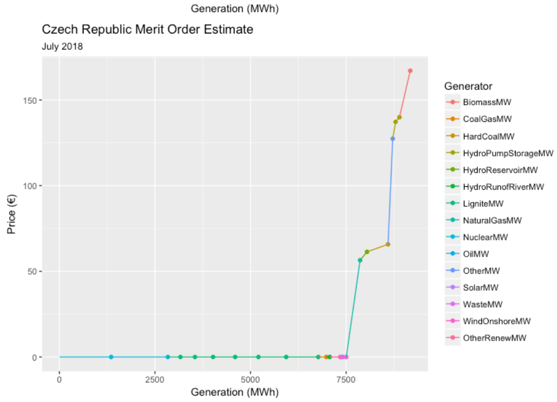
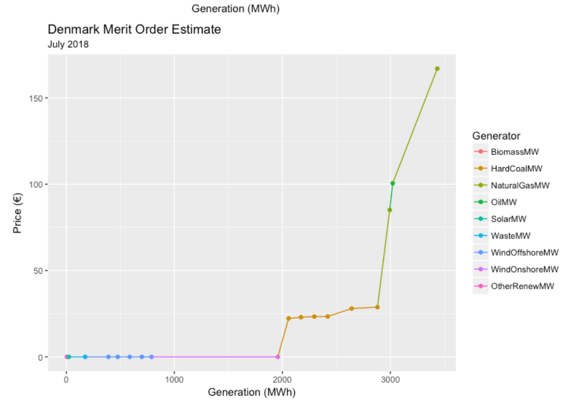
Appendix A: Sample Merit Order Estimates

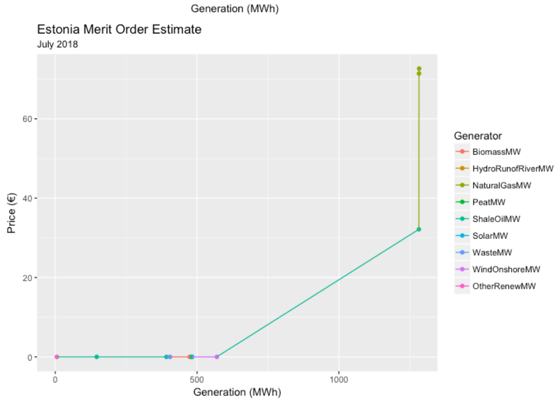
Each of these curves, listed in alphabetical order by country name in English, represents the estimated merit order for the 24 countries in this study in July 2018.

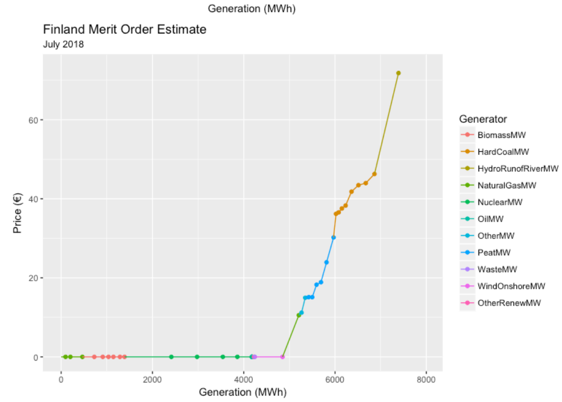


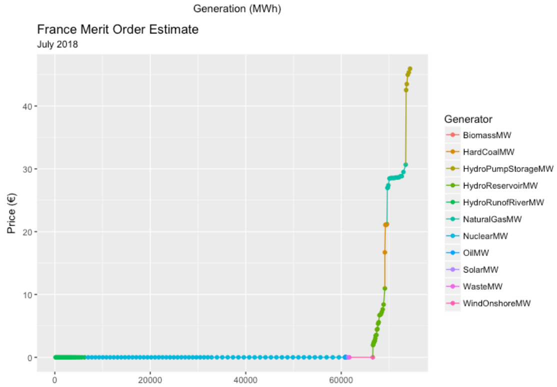


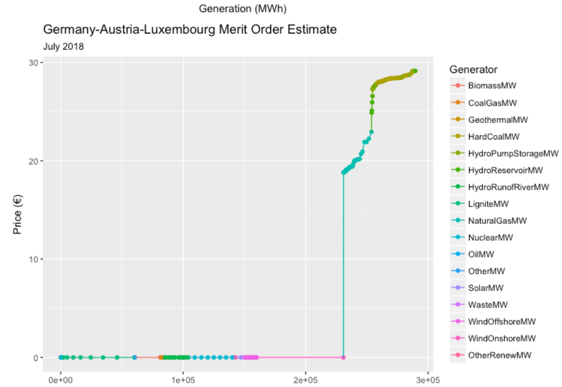




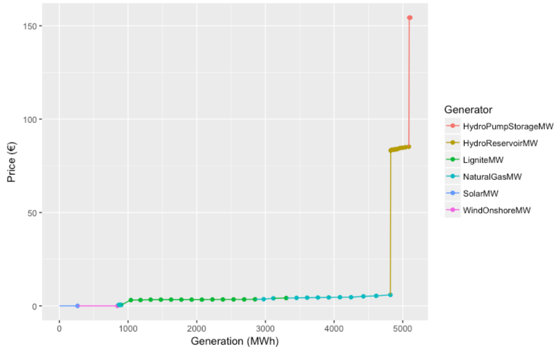




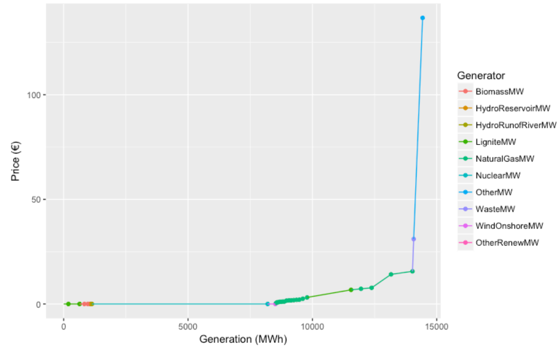




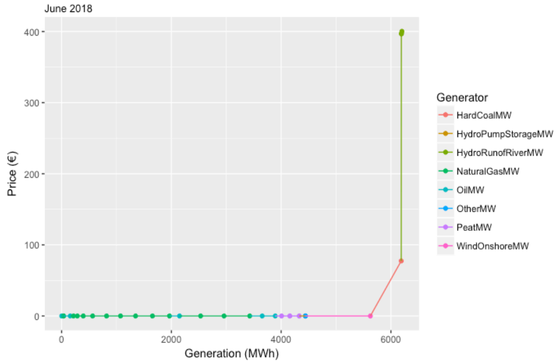
Greece Merit Order Estimate
July 2018



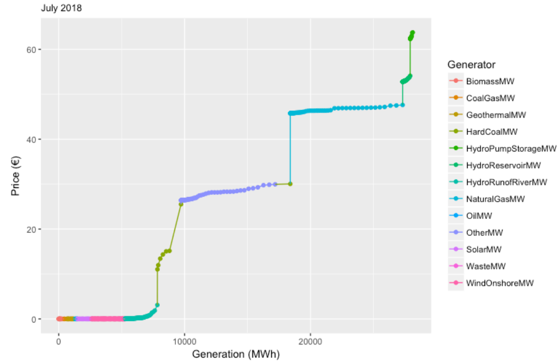
Hungary Merit Order Estimate
July 2018



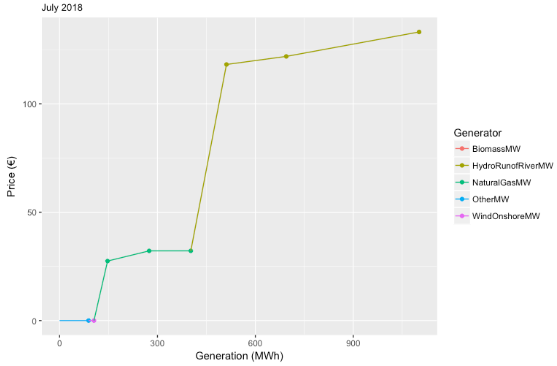
Ireland Merit Order Estimate
June 2018



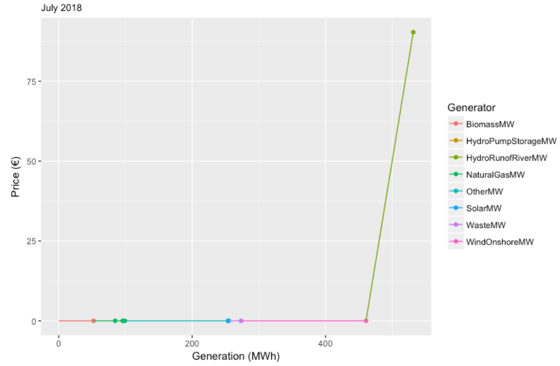
Italy Merit Order Estimate
July 2018



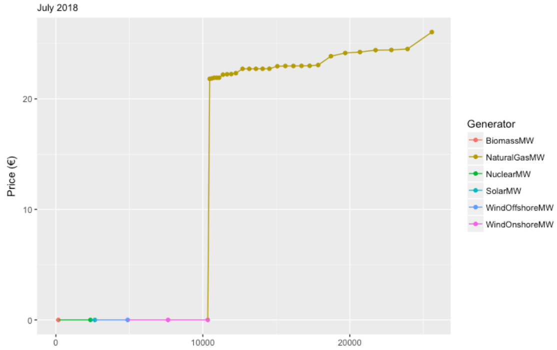
Latvia Merit Order Estimate
July 2018



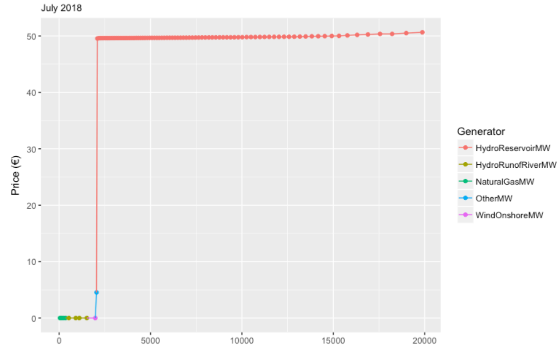
Lithuania Merit Order Estimate
July 2018

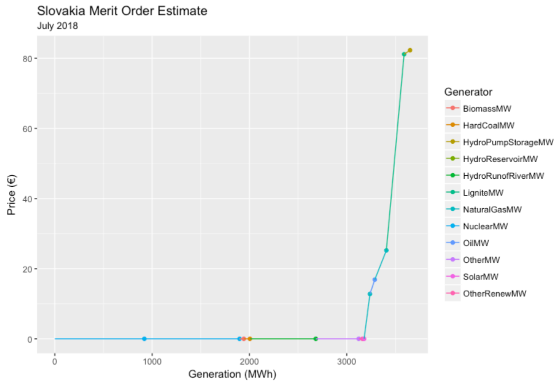


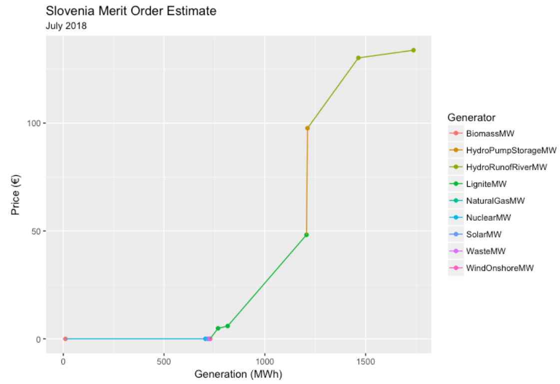
Netherlands Merit Order Estimate
July 2018

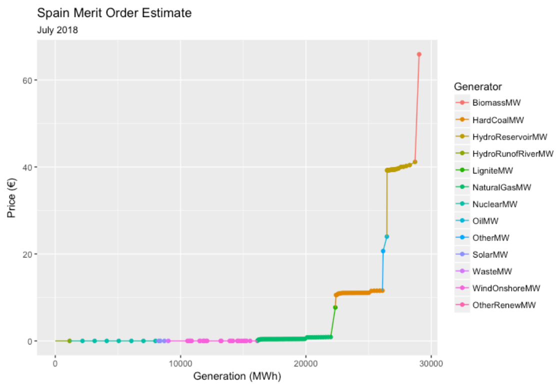


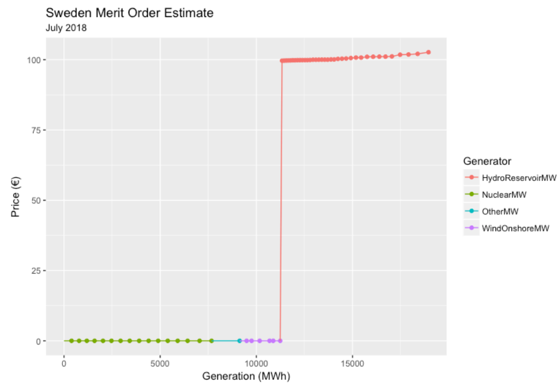
Norway Merit Order Estimate
July 2018

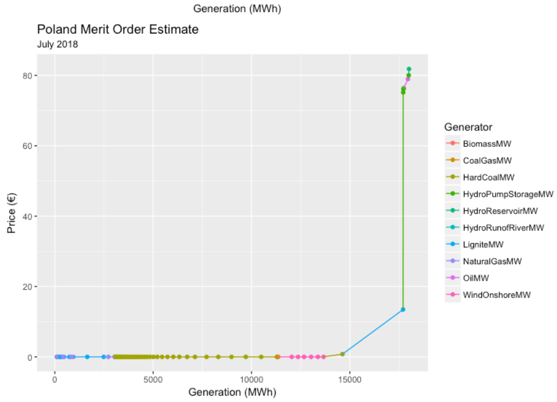


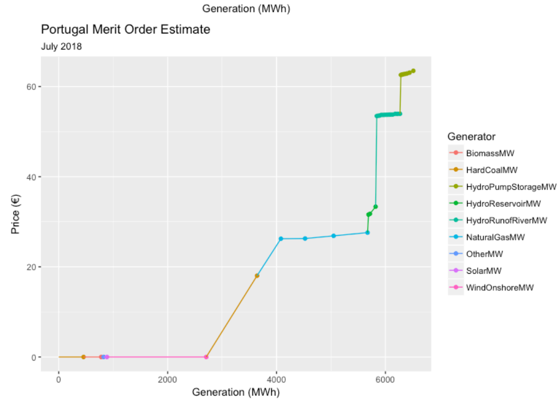

Slovakia Merit Order Estimate
July 2018
Price (€)
Generation (MWh)
Generator
BiomassMW
HardCoalMW
HydroPumpStorageMW
HydroReservoirMW
HydroRunofRiverMW
LigniteMW
NaturalGasMW
NuclearMW
OilMW
OtherMW
SolarMW
OtherRenewMW

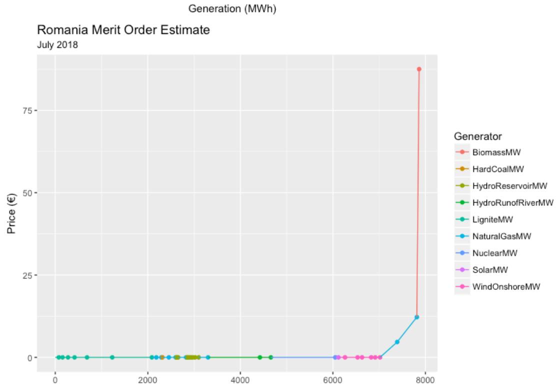

Slovenia Merit Order Estimate
July 2018
Price (€)
Generation (MWh)
Generator
BiomassMW
HydroPumpStorageMW
HydroRunofRiverMW
LigniteMW
NaturalGasMW
NuclearMW
SolarMW
WasteMW
WindOnshoreMW

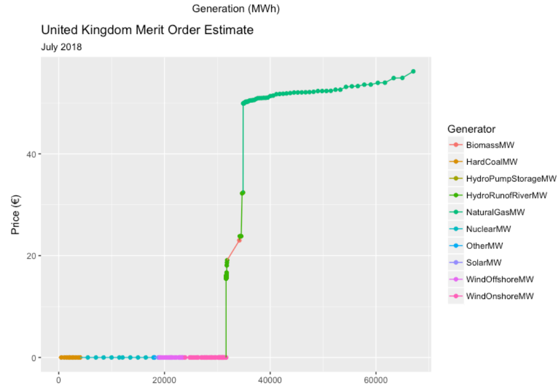

Spain Merit Order Estimate
July 2018
Price (€)
Generation (MWh)
Generator
BiomassMW
HardCoalMW
HydroReservoirMW
HydroRunofRiverMW
LigniteMW
NaturalGasMW
NuclearMW
OilMW
OtherMW
SolarMW
WasteMW
WindOnshoreMW
OtherRenewMW


Sweden Merit Order Estimate
July 2018
Price (€)
Generation (MWh)
Generator
HydroReservoirMW
NuclearMW
OtherMW
WindOnshoreMW


Poland Merit Order Estimate
July 2018
Price (€)
Generation (MWh)
Generator
BiomassMW
CoalGasMW
HardCoalMW
HydroPumpStorageMW
HydroReservoirMW
HydroRunofRiverMW
LigniteMW
NaturalGasMW
OilMW
WindOnshoreMW


Portugal Merit Order Estimate
July 2018
Price (€)
Generation (MWh)
Generator
BiomassMW
HardCoalMW
HydroPumpStorageMW
HydroReservoirMW
HydroRunofRiverMW
NaturalGasMW
OtherMW
SolarMW
WindOnshoreMW


Romania Merit Order Estimate
July 2018
Price (€)
Generation (MWh)
Generator
BiomassMW
HardCoalMW
HydroReservoirMW
HydroRunofRiverMW
LigniteMW
NaturalGasMW
NuclearMW
SolarMW
WindOnshoreMW


United Kingdom Merit Order Estimate
July 2018
Price (€)
Generation (MWh)
Generator
BiomassMW
HardCoalMW
HydroPumpStorageMW
HydroRunofRiverMW
NaturalGasMW
NuclearMW
OtherMW
SolarMW
WindOffshoreMW
WindOnshoreMW

Appendix B: ENTSO-E Data Summary Statistics

Appendix B.1: Prices and Total Generation

All price values indicated in this table are rounded to the nearest hundredth to reflect values given on an hourly basis in the ENTSO-E data in euro (€) per MWh. All generation values give the mean and standard deviation of monthly generation per country per year in MWh. Values given by a dash (-) indicate that no data were available for that particular country.

Country	Year	Mean Price	Standard Deviation	Mean Generation	Standard Deviation
Belgium	2015	44.72	21.56	4,069,820	707,548
	2016	35.58	23.53	3,746,490	616,607
	2017	44.58	21.62	4,313,101	970,532
	2018	55.27	23.54	5,775,117	810,699
Bulgaria	2015	-	-	-	-
	2016	41.05	16.45	3,744,752	500,987
	2017	34.91	14.04	3,767,993	433,042
	2018	40.36	37.12	3,863,180	480,972
Czech Republic	2015	32.33	12.33	6,464,546	717,242
	2016	31.04	13.01	6,449,807	603,145
	2017	36.45	17.42	6,723,697	825,423
	2018	46.02	17.07	6,837,778	547,490
Denmark	2015	23.34	11.00	2,353,634	603,799
	2016	27.47	10.34	2,393,010	613,087
	2017	30.57	10.74	2,446,759	627,883
	2018	44.68	15.05	2,468,912	716,850
Estonia	2015	31.08	14.38	712,749	126,185
	2016	33.06	12.81	816,289	159,737
	2017	33.20	9.54	882,189	105,884
	2018	47.07	15.28	803,791	143,531
Finland	2015	29.66	14.46	5,334,301	609,562
	2016	32.43	13.15	5,336,060	888,023
	2017	33.19	9.61	5,157,505	842,179
	2018	46.80	15.12	5,287,294	1,027,768
France	2015	38.45	12.99	44,828,911	6,358,626
	2016	36.70	24.44	43,383,604	6,710,277
	2017	44.97	20.23	43,270,407	6,531,643
	2018	50.20	18.46	44,763,595	6,387,267
Germany-Austria-Luxembourg	2015	31.82	12.48	192,304,774	12,622,728
	2016	28.98	12.48	193,543,142	12,326,916
	2017	34.19	17.66	198,924,900	12,866,322
	2018	44.62	17.72	178,381,524	31,404,877
Greece	2015	51.93	11.02	3,320,978	502,412
	2016	42.85	8.80	3,402,749	581,667
	2017	54.68	16.82	3,723,424	615,811
	2018	60.40	11.35	3,646,566	395,552
Hungary	2015	40.60	15.39	9,249,968	1,100,308
	2016	35.43	13.11	9,539,265	791,523
	2017	50.36	21.10	9,865,651	1,046,819
	2018	51.00	19.01	9,464,349	1,087,350
Ireland	2015	48.92	23.97	1,958,043	1,496,105
	2016	39.54	11.68	4,361,853	302,150
	2017	45.69	19.86	2,776,758	1,845,192
	2018	61.93	22.70	4,017,403	1,901,867
Italy	2015	52.12	13.10	20,549,223	1,603,311
	2016	18.85	18.43	19,825,099	1,102,668

Country	Year	Mean Price	Standard Deviation	Mean Generation	Standard Deviation
	2017	35.70	18.65	21,380,490	1,823,414
	2018	60.96	14.59	21,309,657	1,242,345
Latvia	2015	41.85	18.05	444,119	110,137
	2016	36.10	16.40	517,619	166,268
	2017	34.68	10.35	608,083	177,335
	2018	49.90	16.91	539,865	195,156
Lithuania	2015	41.92	18.13	341,491	28,682
	2016	36.53	16.91	266,855	64,083
	2017	35.13	10.81	273,805	34,790
	2018	50.00	17.14	269,363	71,893
Netherlands	2015	40.06	10.84	12,308,983	2,999,823
	2016	32.25	11.32	13,577,921	2,821,264
	2017	39.31	12.76	16,958,506	2,768,411
	2018	52.53	15.18	17,678,417	3,899,106
Norway	2015	20.05	7.45	11,860,055	1,640,958
	2016	25.70	7.13	12,413,311	2,020,480
	2017	28.36	4.45	12,267,915	1,740,154
	2018	43.41	9.20	12,157,816	2,251,350
Poland	2015	-	-	-	-
	2016	37.31	14.74	12,434,976	962,765
	2017	36.81	12.25	12,675,542	883,519
	2018	52.21	16.33	12,626,242	841,808
Portugal	2015	50.48	12.20	4,024,523	345,947
	2016	39.44	14.90	4,669,062	430,175
	2017	52.48	11.73	4,555,720	360,461
	2018	57.45	12.31	4,607,623	451,619
Romania	2015	36.37	14.33	5,359,607	409,151
	2016	33.18	12.94	5,300,789	595,769
	2017	48.07	23.96	5,188,760	548,769
	2018	46.41	21.36	5,275,960	466,281
Slovakia	2015	33.58	13.76	2,170,293	205,431
	2016	31.56	13.34	2,255,692	245,335
	2017	40.94	21.85	2,288,166	169,505
	2018	48.47	19.15	2,210,425	236,468
Slovenia	2015	41.41	16.29	1,162,513	164,404
	2016	35.62	13.48	1,278,639	149,548
	2017	49.53	21.64	1,256,036	78,599
	2018	51.16	18.76	1,257,585	121,296
Spain	2015	50.32	12.37	20,916,577	1,507,105
	2016	39.67	14.90	20,016,602	1,279,788
	2017	52.23	12.28	17,882,098	1,230,776
	2018	57.29	12.80	20,390,130	1,298,544
Sweden	2015	21.68	8.90	12,250,716	1,120,420
	2016	29.08	11.83	7,237,437	1,419,036
	2017	31.18	7.52	6,597,273	702,659
	2018	44.65	11.91	6,558,346	1,302,779
U.K.	2015	55.25	15.08	46,118,821	4,270,392
	2016	49.15	36.59	46,823,759	5,140,295
	2017	51.71	14.38	45,345,108	5,808,900
	2018	64.70	14.66	44,313,612	4,418,067

Appendix B.2: Fossil Fuel Generation

This table gives the average production in MWh by year for eight fossil fuel generation methods in the ENTSO-E data. Production from waste, although not defined as a fossil fuel, is also included. Values given are rounded to the nearest integer, mirroring the data in the ENTSO-E data, while values given with a dash (-) represent years where data were not available.

Country	**Year**	**Lignite**	**Coal Gas**	**Natural Gas**	**Hard Coal**	**Oil**	**Shale Oil**	**Peat**	**Waste**	**Other**
Belgium	2015	0	0	2369	0	0	0	0	184	567
	2016	0	0	2302	0	0	0	0	181	551
	2017	0	0	2408	0	0	0	0	185	580
	2018	0	0	2529	0	0	0	0	181	619
Bulgaria	2015	-	-	-	-	-	-	-	-	-
	2016	2468	0	0	0	0	0	0	0	0
	2017	2560	0	230	69	0	0	0	4	0
	2018	2238	0	225	68	0	0	0	4	0
Czech Republic	2015	3687	230	205	562	6	0	0	15	45
	2016	3788	230	368	557	9	0	0	21	77
	2017	3796	204	380	489	9	0	0	16	111
	2018	3852	190	383	398	6	0	0	17	115
Denmark	2015	0	0	456	867	24	0	0	178	0
	2016	0	0	489	1088	25	0	0	160	0
	2017	0	0	238	619	93	0	0	147	0
	2018	0	0	326	735	24	0	0	142	0
Estonia	2015	0	0	6	0	0	812	5	15	0
	2016	0	0	3	0	0	966	5	15	0
	2017	0	0	2	0	0	1034	4	15	0
	2018	0	0	4	0	0	960	4	14	0
Finland	2015	0	0	596	591	2	0	433	29	212
	2016	0	0	454	812	2	0	441	34	182
	2017	0	0	473	668	2	0	416	24	129
	2018	0	0	571	682	2	0	488	28	160
France	2015	0	0	2627	1018	261	0	0	200	0
	2016	0	0	4088	902	268	0	0	191	0
	2017	0	0	4675	1181	277	0	0	241	0
	2018	0	0	3417	732	217	0	0	231	0
Germany-Austria-Lux.	2015	60863	863	8277	39695	921	0	0	896	24274
	2016	59559	1866	10706	36813	853	0	0	1261	18232
	2017	59115	1882	12009	30624	869	0	0	2392	18930
	2018	59867	1848	19088	33621	206	0	0	3087	1851
Greece	2015	2242	0	959	0	0	0	0	0	0
	2016	1729	0	1562	0	0	0	0	0	0
	2017	1918	0	1893	0	0	0	0	0	0
	2018	1738	0	1740	0	0	0	0	0	0
Hungary	2015	2726	0	1946	0	10	0	0	66	353
	2016	2506	0	2483	0	6	0	0	47	339
	2017	2210	0	3134	0	19	0	0	50	339
	2018	2181	0	2851	0	3	0	0	54	306
Ireland	2015	0	0	2392	1173	0	0	570	0	0
	2016	0	0	2660	1080	538	0	571	0	6
	2017	0	0	2658	890	606	0	541	0	4
	2018	0	0	2707	491	488	0	511	0	5
Italy	2015	0	56	6084	1238	265	0	0	45	10711
	2016	0	225	6600	1141	142	0	0	47	9608

Country	Year	Lignite	Coal Gas	Natural Gas	Hard Coal	Oil	Shale Oil	Peat	Waste	Other
	2017	0	206	8196	2119	150	0	0	40	9302
	2018	0	221	8496	2952	112	0	0	38	6848
Latvia	2015	0	0	232	0	0	0	0	0	83
	2016	0	0	252	0	0	0	0	0	87
	2017	0	0	164	0	0	0	0	0	90
	2018	0	0	303	0	0	0	0	0	80
Lithuania	2015	0	0	210	0	24	0	0	15	14
	2016	0	0	104	0	21	0	0	16	14
	2017	0	0	54	0	13	0	0	16	13
	2018	0	0	30	0	0	0	0	16	32
Netherlands	2015	0	0	9418	1532	0	0	0	0	265
	2016	0	0	11673	75	0	0	0	0	312
	2017	0	0	15699	64	0	0	0	0	338
	2018	0	0	16089	58	0	0	0	0	355
Norway	2015	0	0	339	0	0	0	0	0	47
	2016	0	0	343	0	0	0	0	0	30
	2017	0	0	334	0	0	0	0	0	44
	2018	0	0	350	0	0	0	0	0	129
Slovakia	2015	201	0	100	53	42	0	0	0	373
	2016	187	0	112	58	51	0	0	0	358
	2017	180	0	133	81	48	0	0	0	370
	2018	154	0	162	93	51	0	0	0	336
Slovenia	2015	451	0	32	0	0	0	0	13	0
	2016	514	0	35	0	0	0	0	15	0
	2017	495	0	31	0	0	0	0	12	0
	2018	474	0	32	0	0	0	0	10	0
Spain	2015	515	0	5058	5349	330	0	0	223	78
	2016	381	0	5143	3654	286	0	0	258	60
	2017	545	0	5611	4334	295	0	0	298	49
	2018	352	0	5814	3701	283	0	0	299	53
Sweden	2015	0	0	0	0	0	0	0	0	766
	2016	0	0	0	0	0	0	0	0	824
	2017	0	0	0	0	0	0	0	0	918
	2018	0	0	0	0	0	0	0	0	915
Poland	2015	-	-	-	-	-	-	-	-	-
	2016	5306	63	591	9018	197	0	0	0	0
	2017	5398	72	685	8908	198	0	0	0	0
	2018	5103	62	991	9097	180	0	0	0	0
Portugal	2015	0	0	1127	1593	0	0	0	0	41
	2016	0	0	1325	1337	0	0	0	0	38
	2017	0	0	2021	1556	0	0	0	0	36
	2018	0	0	1649	1275	0	0	0	0	38
Romania	2015	1305	0	1085	795	0	0	0	0	0
	2016	1643	0	1131	193	0	0	0	0	0
	2017	1803	0	1220	162	0	0	0	0	0
	2018	1668	0	1222	136	0	0	0	0	0
U.K.	2015	0	0	19524	17636	1	0	0	0	1982
	2016	0	0	28966	6378	0	0	0	0	3230
	2017	0	0	27220	4690	0	0	0	0	2794
	2018	0	0	26303	3507	0	0	0	0	163

Appendix B.3: Renewable and Nuclear Generation

These two tables give the average generation in MWh by year by type of zero-carbon generation. The first table consists of biomass, geothermal, solar, onshore and offshore wind, and other renewable generation. The second table consists of nuclear and hydroelectric generation. For the purposes of this overall study, these two are considered renewable energy due to their near-zero carbon output.

Country	Year	Biomass	Geothermal	Solar	Offshore Wind	Onshore Wind	Other Renew.
Belgium	2015	340	0	184	294	283	0
	2016	343	0	181	272	255	0
	2017	362	0	185	332	301	0
	2018	349	0	181	401	339	0
Bulgaria	2015	-	-	-	-	-	-
	2016	28	0	152	0	154	0
	2017	35	0	151	0	162	0
	2018	29	0	138	0	145	0
Czech Republic	2015	264	0	256	0	68	287
	2016	235	0	243	0	55	298
	2017	233	0	246	0	64	283
	2018	257	0	266	0	69	272
Denmark	2015	44	0	69	553	1014	12
	2016	51	0	85	521	835	8
	2017	496	0	87	581	1079	5
	2018	440	0	110	508	1088	3
Estonia	2015	60	0	0	0	72	7
	2016	58	0	1	0	60	7
	2017	64	0	1	0	80	6
	2018	64	0	1	0	72	6
Finland	2015	884	0	0	0	236	37
	2016	841	0	0	0	326	42
	2017	812	0	0	0	470	41
	2018	732	0	0	0	615	37
France	2015	219	0	803	0	2237	0
	2016	285	0	909	0	2234	0
	2017	348	0	878	0	2608	0
	2018	398	0	1110	0	3061	0
Germany-Austria-Lux.	2015	17074	35	16307	3716	33768	247
	2016	19195	23	15823	5429	32118	446
	2017	19530	16	16909	7954	42018	566
	2018	19534	14	19473	7738	43808	540
Greece	2015	0	0	409	0	405	0
	2016	0	0	411	0	428	0
	2017	0	0	416	0	483	0
	2018	0	0	389	0	555	0
Hungary	2015	361	0	0	0	326	33
	2016	374	0	0	0	324	33
	2017	401	0	0	0	349	46
	2018	416	0	0	0	272	52
Ireland	2015	0	0	0	0	162	0
	2016	0	0	0	0	175	0
	2017	0	0	0	0	210	0
	2018	0	0	0	0	234	0
Italy	2015	280	660	2104	0	1664	0
	2016	277	667	1941	0	1929	0

Country	Year	Biomass	Geothermal	Solar	Offshore Wind	Onshore Wind	Other Renew.
	2017	344	661	2234	0	2006	0
	2018	398	651	2037	0	1981	0
Latvia	2015	78	0	0	0	12	0
	2016	81	0	0	0	13	0
	2017	83	0	0	0	14	0
	2018	75	0	0	0	12	0
Lithuania	2015	17	0	7	0	82	0
	2016	12	0	7	0	112	0
	2017	17	0	7	0	135	0
	2018	44	0	8	0	129	0
Netherlands	2015	147	0	478	598	3074	0
	2016	158	0	702	1022	2808	0
	2017	157	0	859	1659	3361	0
	2018	141	0	142	1617	3385	0
Norway	2015	0	0	0	0	270	0
	2016	0	0	0	0	241	0
	2017	0	0	0	0	304	0
	2018	0	0	0	0	386	0
Slovakia	2015	53	0	61	0	0	33
	2016	45	0	59	0	0	36
	2017	49	0	59	0	0	39
	2018	69	0	57	0	0	42
Slovenia	2015	8	0	31	0	0	0
	2016	9	0	34	0	0	0
	2017	9	0	33	0	0	0
	2018	9	0	28	0	0	0
Spain	2015	492	0	1457	0	5478	69
	2016	366	0	1406	0	5416	81
	2017	341	0	1400	0	4969	95
	2018	337	0	1378	0	5603	98
Sweden	2015	0	0	0	0	1895	0
	2016	0	0	0	0	1680	0
	2017	0	0	0	0	1867	0
	2018	0	0	0	0	1876	0
Poland	2015	-	-	-	-	-	-
	2016	215	0	0	0	1322	0
	2017	150	0	0	0	1634	0
	2018	206	0	0	0	1406	0
Portugal	2015	299	0	87	0	1294	0
	2016	305	0	89	0	1388	0
	2017	320	0	96	0	1367	0
	2018	317	0	94	0	1410	0
Romania	2015	61	0	143	0	761	0
	2016	51	0	143	0	729	0
	2017	48	0	155	0	834	0
	2018	40	0	154	0	712	0
U.K.	2015	0	0	1070	3219	4089	0
	2016	0	0	2162	2843	4203	0
	2017	1365	0	2321	3347	5673	0
	2018	3670	0	2557	3525	6015	0

Country	Year	Hydro Pumped Storage	Hydro Run-of-River	Hydro Reservoir	Marine	Nuclear
Belgium	2015	113	9	0	0	3098
	2016	108	10	0	0	4202
	2017	108	8	0	0	4181
	2018	115	7	0	0	3114
Bulgaria	2015	-	-	-	-	-
	2016	122	0	396	0	1797
	2017	96	105	261	0	1775
	2018	29	186	390	0	1840
Czech Republic	2015	142	83	133	0	2890
	2016	136	95	144	0	2593
	2017	132	94	104	0	3052
	2018	119	85	114	0	3224
Denmark	2015	0	2	0	0	0
	2016	0	2	0	0	0
	2017	0	2	0	0	0
	2018	0	50	0	0	0
Estonia	2015	0	4	0	0	0
	2016	0	3	0	0	0
	2017	0	3	0	0	0
	2018	0	3	0	0	0
Finland	2015	0	1772	0	0	2546
	2016	0	1642	0	0	2536
	2017	0	1573	0	0	2464
	2018	0	1430	0	0	2499
France	2015	829	4424	1778	0	47425
	2016	1070	4808	1711	0	43583
	2017	1091	4010	1428	0	43164
	2018	1102	4892	2019	0	44728
Germany-Austria-Lux.	2015	4371	14817	1657	0	38517
	2016	5272	20682	2443	0	36562
	2017	5247	19105	2381	0	32980
	2018	6364	18074	2522	0	32355
Greece	2015	104	0	512	0	0
	2016	70	0	482	0	0
	2017	49	0	348	0	0
	2018	75	0	501	0	0
Hungary	2015	0	40	52	0	6803
	2016	0	45	56	0	6896
	2017	0	39	47	0	6928
	2018	0	38	44	0	6761
Ireland	2015	184	155	0	0	0
	2016	188	145	0	0	0
	2017	157	171	0	0	0
	2018	162	108	0	0	0
Italy	2015	325	3872	0	0	0
	2016	328	3446	0	0	0
	2017	298	3037	0	0	0
	2018	365	4102	0	0	0
Latvia	2015	0	167	330	0	0
	2016	0	278	0	0	0
	2017	0	484	0	0	0
	2018	0	270	0	0	0
Lithuania	2015	77	35	0	0	0
	2016	65	41	0	0	0

Country	Year	Hydro Pumped Storage	Hydro Run-of-River	Hydro Reservoir	Marine	Nuclear
	2017	66	57	0	0	0
	2018	60	50	0	0	0
Netherlands	2015	0	0	0	0	2513
	2016	0	0	0	0	2088
	2017	0	0	0	0	2122
	2018	0	0	0	0	1953
Norway	2015	0	1402	14183	0	0
	2016	0	1286	15052	0	0
	2017	0	1330	14788	0	0
	2018	0	1144	14639	0	0
Slovakia	2015	36	408	19	0	1727
	2016	31	459	19	0	1680
	2017	40	435	20	0	1719
	2018	40	361	19	0	1692
Slovenia	2015	32	419	0	0	615
	2016	32	499	0	0	621
	2017	31	428	0	0	681
	2018	21	521	0	0	627
Spain	2015	0	874	2531	0	6250
	2016	0	1023	3383	0	6511
	2017	0	777	1605	0	6384
	2018	0	1224	2907	0	6086
Sweden	2015	0	0	8190	0	6190
	2016	0	0	7851	0	6795
	2017	0	0	7864	0	6328
	2018	0	0	7785	0	7098
Poland	2015	-	-	-	-	-
	2016	78	179	15	0	0
	2017	81	218	16	0	0
	2018	72	168	12	0	0
Portugal	2015	211	707	185	0	0
	2016	389	1081	427	0	0
	2017	294	392	158	0	0
	2018	355	835	340	0	0
Romania	2015	0	1197	764	0	1328
	2016	0	1308	763	0	1287
	2017	0	1120	531	0	1314
	2018	0	1244	779	0	1299
U.K.	2015	650	934	0	0	14988
	2016	689	770	0	0	15188
	2017	671	903	0	0	14942
	2018	582	731	0	0	13828

Appendix C: European Covenant of Mayors Emissions Factors

This table gives the conversion from megawatt-hour to metric ton of CO_2 used in this study.

Fuel	Emissions Factor (tCO_2 per MWh)
Hard Coal	0.354
Lignite	0.364
Natural Gas	0.202
Oil Shale	0.385
Peat	0.382
Fuel Oil	0.279