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Pass-Through Rates of Emission Costs in the Iberian Electricity Market

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Abstract

We investigate the pass-through of emission costs to electricity prices on the Iberian electricity market from 2017 to 2021. Using an IV specification that requires few assumptions on the functional forms of the supply and demand curve we find an average pass-through rate of 110%, which is higher than previous estimates for Spain. To understand this beyond-complete pass-through rate, we quantify pass-through rates during periods of high and low demand, as well as differences in pass-through during periods when carbon prices increase and decrease. Contrary to previous findings from the same geographical context, we do not observe a difference in pass-through during periods of high and low demand. Our results suggest that emission cost decreases are passed through at a greater rate than increases. These findings provide insight into the behavior of firms operating in a market with emission costs.

Keywords: Pass-through rate; Emission cost; Iberia; Electricity market; Asymmetric
JEL: D44, L13, L94, Q02

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1 Introduction

The EU emissions trading system (EU ETS) is a cap-and-trade scheme that covers 45% of the EU's greenhouse gas emissions. It affects a large share of the global population and is an important part of the legislation to reduce greenhouse gas emissions. The EU ETS has set a price on carbon in Europe that varies with demand and supply for energy, world commodity markets, the total available emission allowances as decided by the regulator, and changes to wider macroeconomic trends. Ideally, the number of ETS Allowances (EUA)[1] are set such that the price of an allowance will equalise the marginal abatement cost across all firms. This means that the price of emitting an additional tonne of CO_2 is equal to the operational or investment cost associated with the prevention of another tonne of CO_2 being emitted. This can, in theory, lead to an equalization of aggregate marginal damage and aggregate marginal abatement costs, in which case there is no deviation from the optimal point of emissions.

Phases I to III of the EU ETS (2005-2008, 2008-2013, 2013-2020) had significant over-allocation of allowances to gently introduce the market to firms and avoid disruption. The commitment from the EU to decrease the number of allowances over time to curb carbon emissions should naturally lead to higher European Emission Allowance prices. Of course, this assumption can break during recessions or other times of low demand for energy, as we have already seen from the financial crisis of 2008 when EUA prices decreased significantly. Not only will the reduction of total allowances have a positive effect on the price of one emission allowance, it will also reduce total emissions, by definition. In the period that we study in this paper, 2017 to 2021, the ETS is in the end of its third and beginning of its fourth phase, and EUA futures prices are within the same range as in the first two phases up until 2020, after which prices increase significantly into the end of 2021 as shown in Figure 1.

[1] We will refer to EU ETS allowances as EUAs, carbon permits, and carbon allowances interchangeably. Their prices can be referred to as carbon prices, allowance prices, and EUA prices.

Figure 1: EUA Price 2005 - 2021

Notes: Carbon allowance prices from the start of the EU ETS in 2005 until the end of 2021. Data from European Energy Exchange (no date)

The pass-through of carbon to electricity prices is the change in electricity prices in response to a unit change in the carbon price. We are interested in quantifying the pass-through rate of carbon prices to electricity prices on the Iberian electricity market from 2017 to 2021. Even if near full pass-through rates have been observed during phase I across Europe and in Spain (Fabra and Reguant 2014; Sijm, Neuhoff, and Chen 2006; Fell 2010), our setting is of interest because carbon future prices see significant volatility and increases over the time period rising to levels of great cost implication. In other words, as the ETS matures and prices rise, conclusions from previous studies may not hold anymore.

The study of pass-through rates in this context is relevant because of the size and novelty of the EU emissions trading system. In addition to quantifying the size of the average pass-through rate, we also aim to test for the existence of asymmetric pass-through rates. Asymmetric pass-through occurs when the timing or level of pass-through is different for positive and negative cost shocks, and their existence has often been associated with significant market power. Given that our sample consists of a set of firms for which the four largest set the price in 68% of the hourly auctions in our sample, market power may play a role in pass-through rates. There are also policy implications associated with the existence of asymmetric pass-through rates. If emission costs are passed through such that cost decreases lead to a lesser price reaction than cost increases, then putting a price on carbon has effectively enabled short-term profits that would otherwise not exist. These profits come at the expense of consumers.

Fossil fuel powered electricity generators have non-zero carbon dioxide emissions and almost all such plants in the EU have to participate in the auctioning of emissions permits since the beginning of phase III. Some free allocations still exist within lower-income EU member states and can be awarded to generators for investments into modernisation or clean energy. In the early phases of the scheme most permits were allocated free of charge but limited in number, which generated a positive price for permits. Their scarcity generated an opportunity cost of using them when they could instead be sold. In our setting, the Iberian peninsula between 2017 and 2021, electricity generators are mandated to acquire permits through auctions. With the introduction of auctioning, thermal plants stopped receiving so called 'windfall profits' from free allocation of allowances. The price value of permits were instead transferred to the regulator. Emission-free electricity generators still receive windfall profits when the electricity auction price is decided by a thermal plant which has passed through some part of their emission costs.

The switch from free allowances to auctioning, and thus the removal of windfall profits for emissions positive electricity generators, could lead to new pass-through strategies. While with free allowances there is political risk associated with complete pass-through of emission costs since the regulator has the ability to reduce future allowances, this risk does not exist when the acquisition of allowances incurs a cash expense. Our results indicate that coal and gas plants pass-through emission costs to a rate of 110% on average. This is in contrast to a previous study in the same geographical context but during a period of free allowances which found average pass-through rates below 100% (Fabra and Reguant 2014).

There are some notable events during the period we study. First, carbon futures began to increase towards the end of phase III around the time of the amendments by directive (EU) 2018/410 in April 2018 to the market stability reserve which intended to restrict the oversupply of EUAs. Second, the Covid-19 pandemic caused a drop in demand for energy in 2020 and carbon futures fell, even if only for a short time. Third, from mid-2020 to the end of 2021, carbon futures prices increased more than twofold. This provides significant variance in prices which we can use to investigate asymmetric pass-through rates of EUA prices to electricity prices. Finally, given that most studies on the same topic take place during Phase I and Phase II, we believe it is relevant to conduct a study on pass-through prices during later phases of the scheme. Electricity markets are suitable for the study of pass-through rates because they provide surprisingly granular data on demand and supply. Bid and ask curves can be constructed with data from power exchanges for every hour of every trading day, and emission rates for different technologies are usually available and don't exhibit a lot of variance across time. Carbon and fuel prices are transparent, and weather data is readily available.

In this study, we focus on the pass through of emission costs to electricity prices among gas and coal plants in the Iberian electricity market during the period 2017-2021. We use an instrumental variables approach to quantify the average pass-through rate of emission costs to electricity prices and find consistent estimates of 110%. Then, we test for differences in pass-through rates under varied circumstances: high versus low demand and periods of rising versus falling carbon prices. We fail to reject the null of equal pass-through rates in periods of high and low demand, and we reject the null that emission costs are passed through symmetrically when carbon prices increase and decrease.

The rest of the paper is structured as follows. Section 2 discusses previous research on pass-through rates both inside and outside electricity markets. Section 3 provides information on electricity markets, pass-through rates and the Iberian market for electricity. In section 4 we show how we construct our dataset. Section 5 introduces our model, section 6 discusses the results of our three main analyses, section 7 shows results from a robustness check and section 8 concludes.

2 Literature Review

This paper builds upon a plethora of literature regarding pass-through rates in a variety of contexts. One strand of literature is evaluating the pass-through rates of carbon prices on wholesale electricity prices as we aim to do. Much of the existing literature in this strand provides evidence of high pass-through rates, though almost all of the studies that we found focus on early implementation periods of cap-and-trade carbon programs such as phase I and phase II of the EU ETS when carbon permits were allocated to producers for free.

The most directly relevant study to this paper is Fabra and Reguant (2014) as we both build upon their empirical framework and study the same market, though in a different time period. They investigate the pass-through of emissions cost in Spain between 2004 and 2006, at the start of the EU ETS. They estimate that pass-through rates were, on average, between 79 to 86% during their sample. They hypothesise that generators deviate from optimal bidding behavior during periods of low demand due to invisible costs such as ramping costs that occur when a generator has to change its rate of production. Instead of adjusting production to optimal levels during periods of low demand, generators may maintain a certain level of maintenance production and sell their electricity at prices below marginal costs, thus avoiding the costs associated with ramping up or down. When the authors analyse periods of high and low demand, they find that emission costs are indeed passed through to a lower extent when demand is low. The estimate for periods of high demand is roughly 100% while for low demand it is between 44 and 64%. They also create a structural framework to estimate how much demand, supply, and markup adjustments contribute to the bid made by an electricity producer in the auction market for electricity. They find that emissions costs accurately capture the true cost shock that firms suffer when carbon prices change and that these shocks are common to all firms.

Papers studying pass-through rates in electricity markets across other EU countries and in Australia find similar evidence of high pass-through rates. Sijm, Neuhoff, and Chen (2006) estimate pass-through rates in Germany and Netherlands from 2004 to 2006 to be between 60 and 100%. Fell (2010) use a cointegrated vector auto-regression model to study the relationship between EUA and electricity prices in the Nordic market for wholesale electricity and finds a pass-through rate close to 100% when coal-generated electricity is at the margin. Nazifi (2016) looks into the Australian National Electricity market from July 2010 to October 2013 and finds that carbon costs were indeed fully passed on to wholesale electricity spot prices resulting in higher electricity prices for consumers and potential windfall profits for some generators. Dagoumas and Polemis (2020) study Greek electricity markets through a portion of the third phase of the EU ETS (2014-2018) and also see almost complete pass-through, revealing that retailers fully internalize the cost of CO_2.

Another closely related strand of literature deals with evidence around asymmetric pass-through rates of carbon allowance prices onto market electricity prices. These papers tend to utilize time series methods to determine that electricity prices are more affected by upward movements in the carbon price than downward movements, sometimes referred to with a rocket and feather analogy where prices rocket up in response to a cost increase, but drift down slowly like a feather when costs decrease. Zachmann and Hirschhausen (2008) look at weekly average carbon spot prices and weekly average electricity futures prices in Germany from 2005-2006, the first two years of the EU ETS regime, and reject the null hypothesis of symmetric pass-through in off-peak hours. Mokinski and Wölfing (2014) confirms the findings of Zachmann and Hirschhausen (2008) with new data and a more nuanced identification strategy. On top of confirming the existence of asymmetric pass-through rates, they also find that these disappeared after the German competition authority clamped down on the electricity industry for passing through EUA prices to electricity prices too aggressively. Outside of the EU, Apergis (2018) examine the New Zealand market from January 2001 to March 2014 using a nonlinear autoregressive distributed lag model and find that there are indeed long-run asymmetric pass-through rates. In fact, they conclude that only positive changes in carbon price lead to complete pass-through of carbon prices onto electricity prices. Overall, asymmetries have not received as much attention as the quantification of pass-through rates agnostic to the direction of EUA price movements, but despite this selection in research there are multiple instances showing evidence of asymmetries. We intend to contribute to this literature.

Pass-through rates have also been studied extensively outside of electricity markets with a range of resulting estimates. Excise taxes on products such as soda, alcohol, and tobacco have been widely researched, as has the pass-through of exchange rates onto the price of imported goods.

Much of the literature on soda and alcohol excise taxes point to manufacturers over-shifting the tax burden onto consumer prices (Dubois, Griffith, and O'Connell 2020; Shrestha and Markowitz 2016; Kenkel 2005; Young and Bielińska-Kwapisz 2002). For instance, Dubois, Griffith, and O'Connell (2020) find that in the UK, a sugar tax of 25 pence per liter led to a price increase of 28 pence per liter - a pass-through rate greater than 100%. In the US beer industry, the results from Shrestha and Markowitz (2016) also suggest over-shifted taxes onto prices leading to consumers bearing the full burden of tax increases; a 10 cent increase in beer taxes raise retail prices by 17 cents according to their analysis. The only time that soda and alcohol taxes are not fully passed through is when cross-border shopping in a market that faces lower taxes is an option for buyers. Cawley and Frisvold (2017) utilize a difference-in-differences models to evaluate a soda tax that passed in one municipality, but failed in neighboring areas and found the pass-through rate to be 43%, significantly lower than the over-100% rates other studies, but in line with research regarding cross-border shopping. As Iberian electricity is a good that has limited ability to travel due technological transmission constraints as well as being surrounded by other markets that are also subject to the EU ETS, cross-border effects should not play a factor in our results.

The tobacco industry is another interesting strand of literature that stands out due to cross-border shopping, the use of marketing efforts, and lower price alternatives to avoid full pass-through of excise taxes. Harding, Leibtag, and Lovenheim (2012) find that cigarette taxes on the border with lower tax states are 49%. This means that the cigarette tax is not always fully reflected in consumer prices leading to consumers and producers splitting the burden of the tax. Cross-border shopping between areas with differing levels of tobacco taxes drives this result as the pass-through rate is positively correlated with the distance from the border. Apollonio and Glantz (2020) back up this finding and conclude that tobacco manufacturers are able to increase prices less than the amount of the tax both by encouraging buyers to purchase in places with lower taxes and by lowering manufacturer pricing. The pass-through rate of tobacco may in fact be heterogeneous as Xu et al. (2014) discuss. Their study finds that smokers of premium brands actually face more than full pass-through rates, but generic brand users and carton purchaser faced lower pass-through rate of 30-80%.

A large number of studies have also measured the pass-through rate of exchange rates on imported goods and have generally found low rates. One example is in the coffee market where Nakamura and Zerom (2010) find that 33% of retail and wholesale increases in commodity costs due to exchange rates are passed on to retail prices even in the long-run. Both Gopinath, Itskhoki, and Rigobon (2010) and Campa and Goldberg (2005) find that short run pass-through of U.S. imports is approximately 25%. These papers are representative of the literature regarding exchange rate impacts on imported goods prices that overwhelmingly support partial pass-through.

Pass-through rates have been studied in a lot of contexts with some cost increases leading to price increases that exceed the cost while in other areas, the pass-through rate is less than full. Previous literature on the relationship between carbon prices and market electricity prices have generally found very high, if not full, pass through rates, with some studies also finding evidence of asymmetric pass-through rates. Excise taxes on soda and alcohol generally lead to taxes that are over-shifted where prices rise by more than the change in the tax. Tobacco excise taxes fall between 30-80% due to cross-border shopping and marketing efforts by tobacco companies. Exchange rates also tend to have quite low pass-through rates.

3 Background

Electricity is a requisite part of society. As a commodity however, electricity faces the unique challenge that it cannot be stored for long periods. As such, supply and demand need to constantly be balanced between producers and consumers of electricity. This is accomplished by day-ahead and intraday auctions where market participants enter their bids for buying or selling electricity at specific times; their bids consist of the volume and price at which they are willing to buy or sell. Nominated electricity market operators aggregate these bids into aggregate supply and demand curves to determine a market clearing price. The market clearing price is the point at which the aggregate supply and demand curves intersect, and this is the price that is applied to all buyers and sellers. Sellers who submitted a bid below the market clearing price receive the market clearing price and buyers who submitted a bid above the market clearing price also receive the market clearing price. The overall purpose of the electricity market operators who run these daily auctions is to protect the security of energy supply, increase competitiveness, and ensure that consumers can buy energy at affordable prices (Council of European Union 2015).

The supply curve for the auction is also known as the merit order curve. Renewable generation sources have close to zero marginal cost as wind and solar are free and thus sit at the bottom of the merit curve. Nuclear follows as the cheapest non-renewable power source. Historically, in periods of high demand, gas plants have often been the last dispatched unit, setting the price of electricity on the wholesale market as they sit atop the merit curve. Although this has been the case for a long time, as carbon prices increase, coal plants, which have been sitting below gas plants in the merit order, will experience a steeper increase in emission costs because their emission rates are higher, and thus, eventually, increasing carbon prices will force the gas and coal plants to switch places in the merit order. When this happens, coal plants will more often be the last dispatched unit during periods of high demand. One report has estimated the point at which this switch occurs to be at around $30/t$CO_2$ (Léger et al. 2018).

3.1 Pass-Through Rates

The purpose of the ETS is to establish a cost of emissions and to increase carbon emission abatement. Pass-through rates are important because the pass-through of emission costs by an auction-winning electricity generator creates additional profits for units with zero emission costs, thus incentivizing investment in technologies with fewer or zero emissions. Furthermore, the pass-through of emission costs signals the value of emissions in the production of goods, or conversely, the cost associated with using emissions as a production input, which has normative value.

Theory offers suggestions for the possible determinants of pass-through rates, such as the shape of demand and supply curves and the number of firms. The cases most relevant to our situation are the theoretical analyses of pass-through rates under variable supply and demand curves. As summarized by Sijm, Chen, and Hobbs (2012), these can be divided into linear demand and supply, iso-elastic demand and supply, or a combination of iso-elastic and linear supply and demand. If a market is characterised by linear demand and constant supply, the pass-through rate increases with the number of firms. Full Cournot competition brings a pass-through rate of 100% versus 50% in a monopoly setting. Under iso-elastic demand and constant marginal costs, on the other hand, less competition can lead to pass-through rates of above 100%. In this case, the pass-through rate will depend on the elasticity of demand and the number of firms, as given by the following equation:

$$PTR = \frac{dP}{dCC} = \frac{N\varepsilon}{N\varepsilon - 1}$$

Where PTR is pass-through rate, $\frac{dP}{dCC}$ is the derivative of price with respect to changes in the cost of carbon, ε is the price elasticity of demand, N is the number of Cournot firms.

When both demand and supply are linear, the pass-through of carbon costs to electricity prices will always be lower than the corresponding increase in costs. If demand is linear and supply is variable and iso-elastic, the pass-through is given by:

$$PTR = \frac{dP}{dCC} = \frac{1}{1 + \frac{1}{N} + \varepsilon b}$$

Where b is the constant elasticity of supply. If $\varepsilon < 1$, increases to the elasticity of supply will increase the pass-through rate. An increase in active firms N will always increase the pass-through rate.

When demand is iso-elastic and supply is linear, the pass-through rate defined as the derivative of electricity price with respect to carbon costs is given by:

$$PTR = \frac{dP}{dCC} = \frac{1}{(1 - \frac{1}{N\varepsilon}) + uP^{-\varepsilon-1}}$$

where u is the slope of the inverse linear supply curve. As the slope of the supply curve u or price P increase, the PTR decreases. The change to the PTR with respect to ε is ambiguous and depends on the value of uP. If instead defined as dP/dMC, the PTR is equal to:

$$\frac{N\varepsilon}{N\varepsilon - 1}$$

for which an increase in demand elasticity will lead to a lower pass-through rate. A monopolist will have a PTR higher than markets in which $N > 1$. This definition of the pass-through rate can be used when demand is iso-elastic, regardless of the supply scheme.

When both demand and supply are iso-elastic, the pass-through rate, here defined as dP/dCC, is equal to:

$$PTR = \frac{dP}{dCC} = \frac{1}{(1 - \frac{1}{N\varepsilon})(1 + \varepsilon b)}$$

The pass-through rate decreases as ε and or b increase. More firms N leads to a lower pass-through rate. By this definition, there exists combinations of ε and b such that the monopolist's $PTR > 1$.

When the pass-through rate is defined as $\frac{dP}{dCC}$, changes to the structure of the merit order also determines the pass-through rate of CO_2 to electricity prices. This is because changes to CO_2 prices can make different technologies change position inside the merit order. As that happens, the pass-through rate can deviate substantially from the previous trading period.

It is uncommon to observe complete pass-through rates, and theory does not cover all aspects of electricity markets. It is possible that firms deviate from profit maximizing behavior and employ strategies such as rules of thumb, market share targets or revenue targets (Sijm, Chen, and Hobbs 2012), and that these have an effect on the pass-through rate of emission costs. It is not certain how one should account for these deviations away from expected behavior, even though they are known to exist.

Another topic which has been proposed as a possible reason for incomplete pass-through rates is price rigidities. In our setting, these may not be of great concern as on the firm level near daily changes to bids have been observed (Fabra and Reguant 2014). Therefore, it is unlikely that electricity markets suffer from price rigidities that would in turn have an effect on the ability of generators to pass through emission costs.

All in all, there are many factors that affect the magnitude of pass-through rates. From a theoretical basis, market factors such as demand, supply, the number of active firms, strategic behaviour, and price rigidities all play a role in determining pass-through rates. Theory has shown that pass-through rates can be both below and above 100%.

3.2 Iberian Electricity

Spain produces around 5.5 times the amount of electricity as Portugal. In 2021, total production was 217TWh and 49TWh respectively with two-thirds of Spanish electricity coming from carbon free sources (47% renewable and 21% nuclear). In Portugal, the share of renewables was even higher in 2021, at 59.82%. From 2000 to 2022, the share of renewables has nearly doubled in both countries as can be seen in Figure 2. There has never been any electricity production using nuclear facilities in Portugal, and in Spain the share of nuclear generation has remained steady at around 20% of total generation from 2000 to 2022.

During the period we study, both countries have experienced significant decreases in the use of coal to produce electricity. In 2017, the production of electricity from coal in Spain accounted for 16.5% of total electricity generation whereas in 2021 only 1.8% of Spanish electricity was generated by coal. For Portugal, the corresponding numbers are 25.4% and 1.6%. Gas, on the other hand, has increased in the total share of

Figure 2: Renewables and Nuclear, Percentage of Total Electricity Generation

Notes: Evolution of low carbon electricity generation in Spain and Portugal from 2000 to 2021. Includes renewables (solar, wind, hydropower, biomass and waste, geothermal and wave and tidal) and nuclear. Data from Ritchie, Roser, and Rosado (2022)

electricity production over the same period. Gas accounted for 23.4% of total electricity generation in Spain in 2017 and 30.6% in 2021. Portugal used 32.7% gas for of its electricity generation in 2017 and 37.0% in 2021.

Another thing which has changed since the beginning of the EU ETS program is that the Portuguese and Spanish electricity markets are now integrated into a joint electricity market for the Iberian Peninsula called MIBEL which was launched in 2007. Inside MIBEL there are three types of markets: the day-ahead market which accounts for most of the volume traded, the intraday market, and the continuous intraday market. Buyers and sellers in the day-ahead market submit bids for each hour of the following trading day. Vendors can submit multiple bids for the same generating unit. Operador del Mercado Ibérico de Energia (OMIE) is the market operator that is responsible for running auctions in these markets. If the physical transmission capacity between Spain and Portugal is reached, Spain and Portugal will have two different electricity prices. As long as the transmission capacity is not reached, the price will be the same in both countries (Andrade et al. 2017).

Major changes to the Spanish electricity market that we have highlighted are the changes to the composition of sources in electricity generation and the formation of the integrated electricity market for Spain and Portugal. These are important to note as we compare many of our results to Fabra and Reguant (2014) who studied the Spanish electricity market in 2004 to 2006 when coal contributed more heavily to electricity generation and market integration had not yet been implemented.

4 Data

This section discusses the sources of data that we use in our analysis and provides summary statistics of these measures. The data comes from a range of sources including the Iberian electricity market operator, Operador del Mercado Ibérico de Energia (OMIE); the Spanish systems operator, Red Eléctrica; European Climate Assessment & Dataset Project; and commodity futures markets. Table 1 shows summary statistic for the variables in our dataset.

Table 1: Summary Statistics

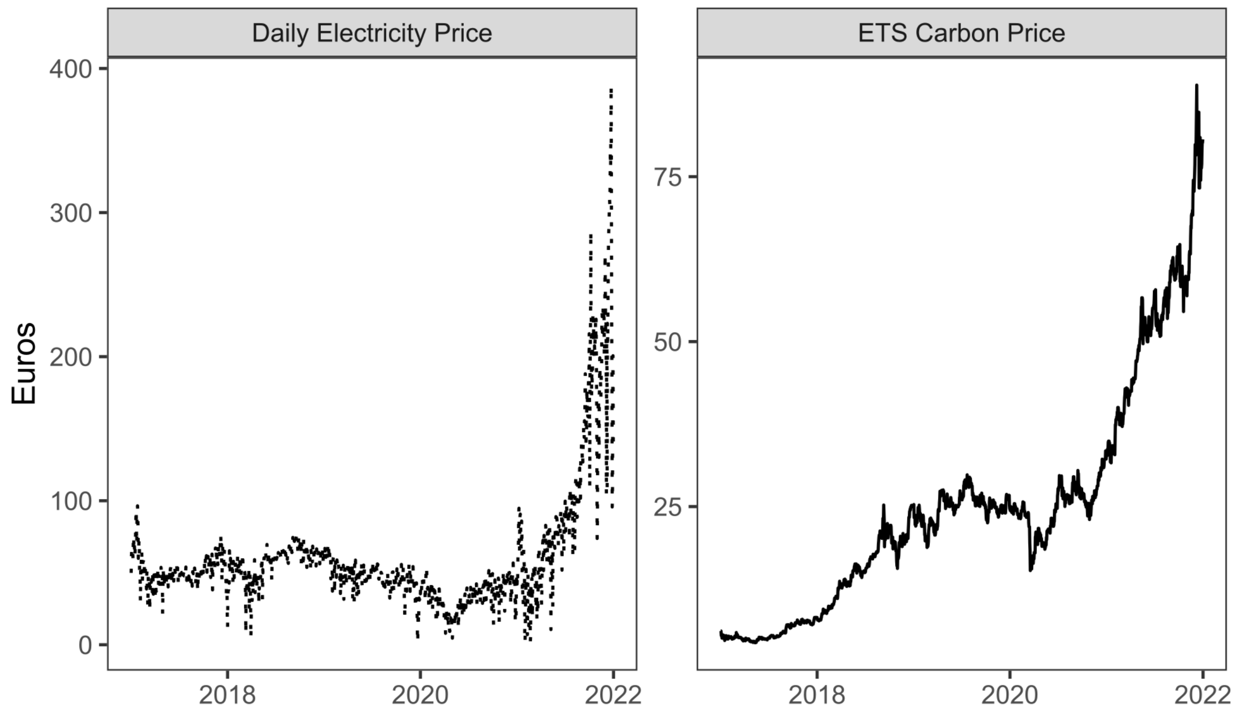
Variable	Mean	Std. Dev.	Min	Max
Emission Intensity (tCO2/MWh)	0.63	0.28	0.38	1
Electricity Price (€)	59	42	4.1	500
Carbon Price (€/tCO2)	23	17	4.3	89
Brent ($/barrel)	61	11	20	86
Gas (€/MWh)	21	19	3.1	182
Coal ($/tonne)	81	32	38	274
High Wind (0.1 m/s)	103	27	39	237
Rain (0.1 mm)	18	33	0	322
Sun (0.1 hr)	74	31	0	141
Avg Temp (0.1°C)	174	67	22	311
High Temp (0.1°C)	235	76	49	401
Humidity (%)	64	12	36	93

4.1 Carbon Prices

From the initiation of the EU ETS scheme, if has aimed to curb CO_2 emissions of power generators and other energy-intensive industries. During the first two phases from 2005 to 2012, emission allowances were given to almost all businesses for free, though this did establish a price for carbon. Starting in 2013, phase 3 of the program shifted free allocation to auctioning as the primary method of allowance allocation. The EU Commission estimates that 57% of general allowances were auctioned in phase 3 (European Commission no date). In the context of Iberian electricity generators, allowances have been allocated under auction since 2013. Outside of permit auctions, permits are readily tradable on different exchanges. We use EU allowance carbon futures prices from the European Energy Exchange in our data.

Historically, the price of carbon under the EU ETS was quite low. In fact, from 2012 – 2017, the price for carbon consistently stayed below €10/tCO_2. In 2018, the price of carbon started to dramatically rise and was above €90/tCO_2 at the end of 2021. The dramatic changes in carbon pricing makes 2017 to 2021 a compelling time period to study. The development of the EUA price over the entirety of the EU ETS is shown in Figure 1 while Figure 3 shows Iberian electricity prices trending upward with EUA prices during the time period that we are studying.

Figure 3: EU ETS Carbon Price and Daily Electricity Price: 2017-2021



Notes: Charts for daily electricity prices (left) as given by the winning bid in the day-ahead market for electricity, and ETS Carbon (EUA) Futures prices (right). The sample period begins in January 2017 and ends in December 2021. Data from OMIE (2021) and European Energy Exchange (no date)

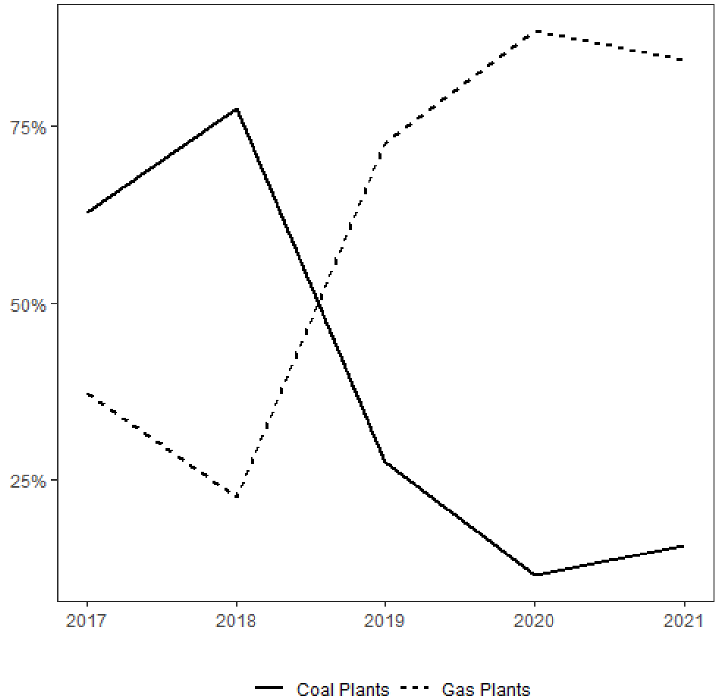
4.2 Electricity Prices and Auction Bid Data

The electricity market operator in the Iberian peninsula, OMIE, publicly publishes all of the data from the auctions including the generating units for supply bids. We focus only on the day-ahead market for electricity, because a majority of volume (85% in both 2020 and 2021) is sold there (OMIE 2021). We do not consider bilateral contracts, intraday auctions, or continuous intraday auctions.

To construct our data set of electricity auction winning bids, we simply find, for each hour, the data point with the highest accepted price. That gives the clearing price, together with information about the unit that submitted the winning bid. If markets are integrated at the time, the result is one observation per hour. If the markets are separated in a given hour, the result will be two observations, one for the Portuguese clearing price and one for the Spanish clearing price.

Figure 4 shows the evolution of coal and gas plant auction win rates over time and shows that coal plants win fewer electricity auctions than gas plants after the middle of 2018 until the end of the sample. This is likely due to a combination of coal and gas plants switching places in the merit order, carbon prices rising, and a decrease in coal used for electricity production over the time period.

Figure 4: Auction Winning Technology By Year



Notes: Proportion of hourly electricity auctions won by coal or gas plants relative to the other. Data from OMIE (2021)

4.3 Marginal Emissions Cost

We find the marginal emissions cost for power plants by dividing their carbon emissions by their electricity production and multiplying the resulting value with the price of carbon. Renewable and nuclear sources of electricity have negligible carbon emissions.

$$CO_{2cost} = \frac{CO_2}{MWh} \times \frac{EUR}{CO_2} = \frac{EUR}{MWh}$$

In the context of thermal power plants, the marginal cost of producing an additional unit of electricity can be decomposed into emissions costs and marginal input costs. Emissions costs depend on the emissions rate of the plant and the price of carbon. In our case, we have monthly data on emissions rates for two different types of thermal power plants: coal plants and combined cycle plants, but not plant specific emissions rates. These data are provided by Red Eléctrica, the Spanish systems operator.

For each of the two technologies that we are able to match to our electricity market data, we divide monthly emissions (tonnes of CO_2) with monthly electricity production (MWh) to construct emission rate averages. Combined cycle plants emit approximately 0.383 - 0.403 tCO_2/MWh while dirtier coal-fired plants emit on average 0.950 - 0.977 tCO_2/MWh over the duration of our sample. To check whether only using data on combined cycle plants and coal plants is representative of emissions emitting electricity generation, we can inspect total installed capacities by technology in the Spanish grid. In terms of total installed Spanish capacity, combined cycle plants represent between 23 to 25%, and coal plants 3% to 10% over our sample period (Red Eléctrica no date). Both Spain and Portugal have less installed coal capacity at the end of the sample period. The Spanish emissions-positive technologies that we are missing in our data represent about 8% of installed Spanish capacity. This means our data covers most of the emitting technologies.

In reality, the data on emission rates are more nuanced than our data demonstrates. For example, coal plants use different types of coal with associated variation in emission intensity. Due to only having average data on plant emission rates, we are not able to distinguish between variation of emission rates within each technology. Instead, we are estimating the pass-through rate for the average coal plant and the average combined cycle plant inside Spain, using monthly production and emissions data. This highlights another limitation of our data, namely that we do not have data on emission intensities of Portuguese coal and gas plants. There are in total 2 coal and 4 gas plants in Portugal over our sample. We assume that Spanish and Portuguese coal and gas plants are similar on average and fill in the missing emission intensity data for Portuguese electricity producers with our Spanish averages.

4.4 Commodities Prices and Weather

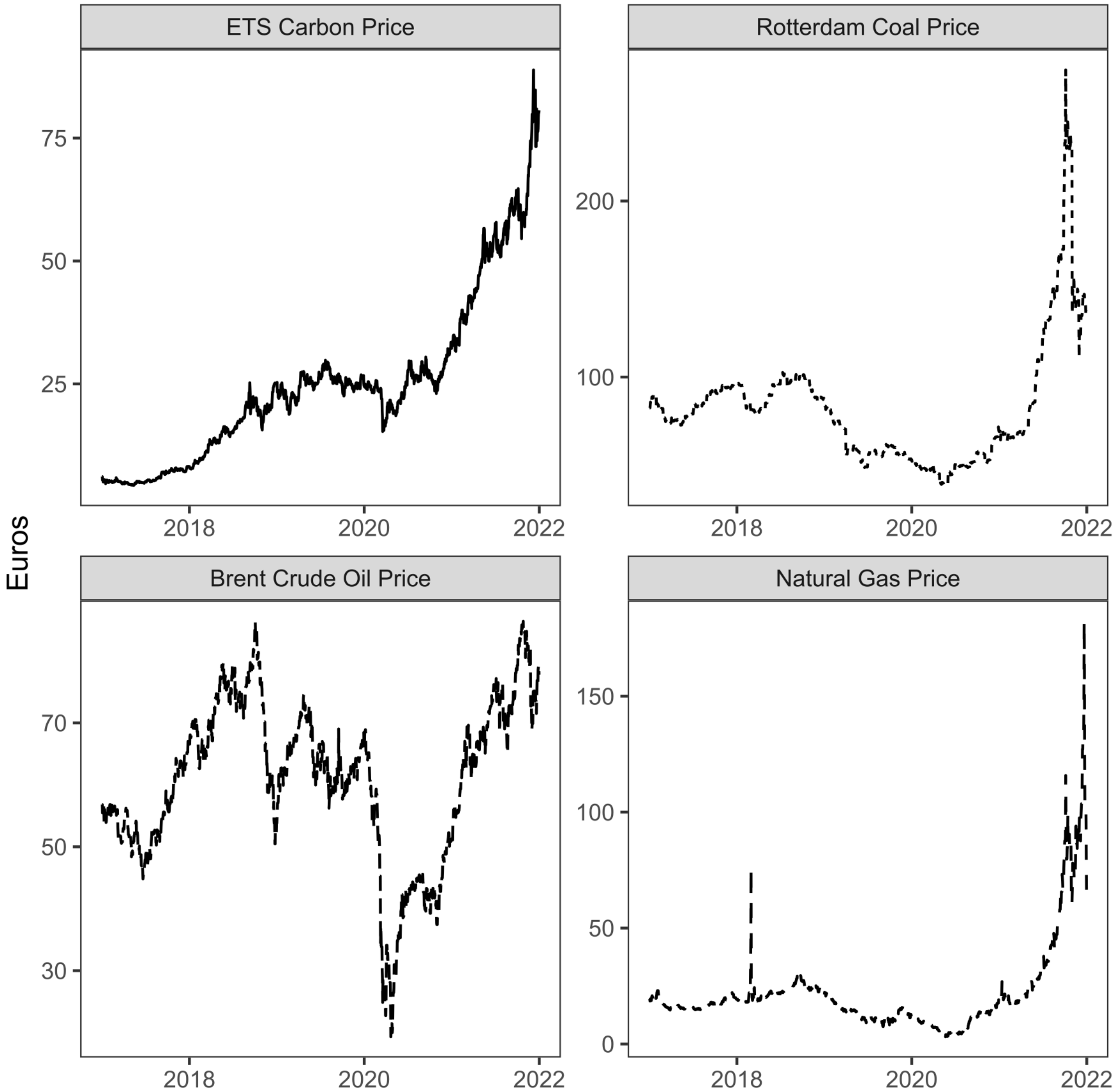
Electricity prices are also highly affected on the supply side by commodities such as coal, oil, and natural gas. We take Brent crude oil, Dutch TTF, and Rotterdam coal prices as the most regionally relevant prices for these commodities.

Most coal used in Portugal and Spain over the period 2017 to 2021 is imported (Ritchie, Roser, and Rosado 2022). Over 2017 to 2022, Spain has imported most of its coal from Colombia, Russia, USA, Indonesia, and Australia. In our sample, most of Portugal's coal imports came from Spain, Colombia, and USA (ITC 2018). Using Rotterdam coal futures as a proxy for coal costs may bring measurement error as coal may be imported from these trading partners using long term contracts that carry significant transportation costs. This means that coal acquisition costs may not closely follow that of the Rotterdam coal futures index. Spain has also had a history of subsidizing the production and consumption of coal, and although state aid for coal stopped in 2018, together with a decision to close most Spanish coal mines Rentier, Lelieveldt, and Kramer (2019), it is not clear whether the economic effects of such subsidies reach into our sample period, and if they do, for how long. The data that we use for coal is thus subject to some measurement error.

A summary of the evolution of EU ETS Allowance prices and commodities prices over our sample is featured in Figure 5.

Weather also plays a role in both energy demand for cooling and heating. We thus incorporate daily metrics for temperature and humidity across the region. Weather from Seville, Madrid, and Bilbao are averaged to represent the overall weather as these three cities capture the main regional climate areas across the peninsula. The data comes from the European Climate Assessment and Dataset project. As approximately a quarter of Spain and Portugal's electricity is generated from wind and solar power (Ritchie, Roser, and Rosado 2022), we also incorporate measures for sunshine hours and wind speed. This data comes from the same sources as the temperature and humidity data.

Figure 5: EU ETS Carbon Price and Commodity Prices: 2017-2021



Notes: Data from European Energy Exchange (no date) and Intercontinental Exchange (no date)

5 Model

We use an instrumental variable framework based on Fabra and Reguant (2014) to estimate the pass through rate of carbon prices (τ_t) into the spot electricity market in the Iberian Peninsula (p_{thz}).

$$p_{thz} = \rho \tau_t e_{thz} + X_t \beta_0 + X_t^D \beta_1 + X_t^S \beta_2 + \omega_{th} + \epsilon_{thz} \tag{1}$$

Our main independent variable is the marginal emissions cost for the plant which sets the price in the day ahead electricity auction in a given hour; the marginal emissions cost is found by multiplying the carbon price at a given day by the average emissions intensity of the market clearing plant. The marginal emissions cost is instrumented by the carbon price. The need for an instrument and discussion about the instrument will follow below.

Marginal emissions cost is a more targeted independent variable than the carbon price as the carbon price affects electricity producers differently - combined cycle plants are more carbon efficient than coal plants. The impact on electricity production costs that producers face is thus varied and must be accounted for at the plant level.

The final price of the electricity auction of day t, hour h and inside zone z is represented by p_{thz}, where z is either the integrated market or Portugal or Spain. τ_t is the price of emissions at day t, the EU ETS allowance price, e is the emissions rate of the generator that wins the uniform auction at day t hour h in zone z. $\tau_t e_{thz}$ is thus the hourly marginal emissions cost for the production unit that set the market clearing price in the day ahead market for zone z in hour h of day t. ρ is our variable of interest that we interpret as the unit-to-unit pass-through rate or the impact on electricity price of a one euro change in marginal emissions cost. The marginal emissions rate is instrumented by the carbon price τ_t as it is likely to be endogenous. The type of plant that wins the day ahead auction is a confounding variable. This is because the type of plant, for instance coal versus natural gas, have different emission intensities, e, and also different effects on price, p, as coal plants on average emit three times more CO_2 per MWh produced than natural gas plants, but have lower variable cost and therefore when they are the last dispatched unit, demand and electricity price are both likely to be low when the price of carbon is low. So, estimating the model as it is written above, without an instrument, may lead one to conclude that increasing emissions costs ($\tau_t e_{th}$) are associated with lower prices. This would naively indicate a negative pass-through rate.

The X_t, X_t^D, and X_t^S variables are vectors of controls where X_t includes coal, natural gas, and oil prices; X_t^D are covariates that affect the demand for electricity such as temperature and humidity; and X_t^S are covariates that affect the supply of electricity such as wind speed and sunshine hours in a day as the Iberian Peninsula has a significant amount of solar and wind generation. These controls are included because the dependent variable, price, is the equilibrium price, so it makes sense to include covariates that affect supply and demand. Furthermore, marginal costs for fossil fuel plants are influenced by the price of fuel, the heat rate of the plant, and variable operation and maintenance costs. While we cannot reconstruct plants' entire marginal costs, we can isolate the average variation in electricity prices due to emission costs with the stated controls as in the short run, heat rates and variable operation and maintenance costs are unlikely to be correlated to carbon prices. This does not hold in the long run, as we expect increasing carbon prices to incentivize investment into emission reducing technologies.

Lastly, ω_{th} are fixed effects for year, month, day of week, hour, and country that the plant is located in. The year, month, day of week, and hour fixed effects are in place to address seasonality concerns. An unobservable related to year can be effects on electricity consumption patterns due to the COVID-19 pandemic or year to year changes in sustainability attitudes as climate change concerns become more universal. Day of week fixed effects are necessary to account for differing patterns in behaviors on weekdays when people are typically going into their workplaces versus weekends when they may be pursuing leisure activities. Hour of day is important due to peak versus off-peak electricity consumption - people do not use much electricity in the middle of the night when they are sleeping. The country that the plant is located in is also included as a fixed effect to address time-invariant unobservables that are country specific. An example could be differing attitudes toward regulation between the Spanish and Portuguese governments.

We believe the ETS carbon price is a reasonable instrument for the hourly marginal emissions cost $\tau_t e_{thz}$ as it satisfies four key criteria: independence, exclusion, relevance, and monotonicity. These assumptions will allow us to interpret the coefficient ρ as a local average treatment effect (LATE).

To start, an independent instrument is one that is independent of potential outcomes. And, the carbon price instrument reasonably satisfy the exclusion assumption if it only affects the dependent variable, electricity price, through the marginal emissions cost. The ETS carbon price is set for the entirety of the EU and it covers multiple sectors in addition to electricity generation: heat generation, aviation, and other energy-intensive sectors such as oil refineries, steel works, metals productions, chemicals production, etc. Together, Spain and Portugal represent only approximately 10% of the overall European electricity market (Ritchie, Roser, and Rosado 2022). As this is a small portion of only one industry that comprises of the market for EU carbon permits, the electricity market in the the Iberian Peninsula should be exogenous to the carbon price after controlling for common macroeconomic factors such commodities prices. Thus, we believe the carbon price reasonably fulfills the independence and exclusion criteria.

Next, the instrument is relevant because the carbon tax is a main driver of the marginal emissions cost. The rate at which a plant emits carbon dioxide when it produces electricity is quite difficult to change due to technological constraints, thus the carbon price is driving the change in marginal emissions cost. Furthermore, F-test results presented later in the paper gives us no reason to believe that this is a weak instrument.

The last assumption of the LATE theorem is that the instrument be monotonic. In our application, this requires the carbon price to affect the marginal emissions cost in the same direction for all plants at all hours. This assumption holds by construction. The carbon price is a multiplicative factor in yielding the marginal emissions cost and thus marginal emissions cost and the carbon price will always move monotonically.

Given that our instrument reasonably satisfies the four conditions of independence, exclusion, relevance, and monotonicity, we can interpret our IV coefficient, ρ as a local average treatment effect. The IV regression using the ETS carbon permit price as an instrument on the marginal emissions cost for the market clearing power plant will estimate the causal effect of a one unit change in marginal emissions cost on the equilibrium price of electricity that is due to the exogenous change in the ETS carbon price in markets where the carbon price falls within the interval defined by the instrument.

6 Results

6.1 Reduced form estimates

$$p_{th} = \rho\tau_t + X_t\beta_0 + X_t^D\beta_1 + X_t^S\beta_2 + \omega_{th} + \epsilon_{th} \tag{2}$$

Our reduced form analysis results in Table 2 show that the carbon price is a statistically significant determinant of the price of electricity as determined by the gas and coal plants in our sample. We cannot draw too many conclusions from the reduced form regression as the specification itself suffers from the carbon price being endogenous. One reason for this is the reverse causality bias on the carbon price coefficient due to the relationship between the carbon price and the price of electricity. The price of electricity is one determinant of carbon prices. In turn, carbon prices impact marginal costs for electricity producers which then affects the price of electricity (Lovcha, Perez-Laborda, and Sikora 2022). This simultaneity results in correlation between the carbon price and the residual error term. An instrumental variable would help to address this problem.

Table 2: Reduced Form Estimates, OLS

	(1)
EUA price	0.533
	(0.123)
Temperature	−0.069
	(0.021)
Max Temperature	0.051
	(0.019)
Wind Speed	0.111
	(0.081)
Wind Speed^2	−0.006
	(0.001)
Sunshine Duration	−0.007
	(0.008)
Humidity	0.037
	(0.023)
Coal	0.033
	(0.026)
Gas	1.813
	(0.060)
Brent	0.013
	(0.021)

Table notes: Dependent variable is hourly wholesale electricity price. Specifications includes year of sample, month, weekday, hour, and country fixed effects; weather and demand controls (temperature, max temperature, humidity, sunshine); supply controls (commodity prices of coal, gas, and oil). Robust standard errors in parentheses. Number of observations: 11,331.

Although these results do not quantify how much of emissions costs are being passed through to electricity prices, it provides an indication that electricity prices are moved by carbon prices. Of course, the reverse is also true, which necessitates a method of estimation which is robust to this simultaneity. In section 7, we will present a robustness check to this reduced form analysis which uses the lagged carbon price as an instrument for carbon price.

6.2 Fossil Fuel Plant Pass-Through Rate

To estimate equation (1), we use 2SLS and the price of carbon as an instrument for the endogenous cost of emission. We only use gas and coal plants in these regressions because they are the only emitting generators that we have emission intensity data for. Renewables are excluded because their emission costs are zero. In Table 3 below, we outline the results from four different specifications. Each specification uses a different set of fixed effects. Our point estimates for the impact of a unit change in emissions cost on electricity price is roughly 1.1 across all specifications. This means that on average a €1 change in emissions cost that a fossil fuel plant faces leads to a €1.10 change in the electricity price and that emissions costs are more than fully passed through.

Table 3: Pass-through Rate of Emission Costs Onto Electricity Prices, IV 2SLS

	(1)	(2)	(3)	(4)
Marg. Emissions Cost	1.103	1.072	1.100	1.092
	(0.295)	(0.298)	(0.305)	(0.308)
Temperature	−0.087	−0.147	−0.150	−0.155
	(0.023)	(0.054)	(0.054)	(0.053)
Max Temperature	0.058	0.061	0.069	0.069
	(0.021)	(0.043)	(0.043)	(0.043)
Wind Speed	0.096	0.071	0.064	0.056
	(0.089)	(0.094)	(0.093)	(0.094)
Wind Speed^2	−0.006	−0.006	−0.006	−0.006
	(0.001)	(0.001)	(0.001)	(0.001)
Sunshine Duration	−0.011	−0.014	−0.012	−0.012
	(0.009)	(0.009)	(0.009)	(0.009)
Humidity	0.023	0.045	0.038	0.039
	(0.028)	(0.026)	(0.027)	(0.026)
Coal	0.023	0.021	0.026	0.022
	(0.030)	(0.032)	(0.033)	(0.034)
Gas	1.853	1.843	1.825	1.827
	(0.058)	(0.058)	(0.061)	(0.062)
Brent	0.042	0.100	0.094	0.094
	(0.023)	(0.026)	(0.027)	(0.027)
F-stat	451.0	466.3	449.1	447.2
Base FE	Yes	Yes	Yes	Yes
Month × Temp, Max Temp FE	No	Yes	Yes	Yes
Month × Hour FE	No	No	Yes	Yes
Month × Country FE	No	No	No	Yes

Table notes: Dependent variable is hourly wholesale electricity price. All specifications include year of sample, month, weekday, hour, and country fixed effects; weather and demand controls (temperature, max temperature, humidity, sunshine); supply controls (commodity prices of coal, gas, and oil). The marginal emissions cost is instrumented with the emissions price. Robust standard errors in parentheses. Number of observations: 11,331.

In our results table, we present F-statistics for the instrument and find these to be very high across all specifications indicating that the instrument is not weak. Another encouraging result is that the signs and magnitudes on control variables remain consistent across all specifications, with mostly expected signs. The coefficients on coal, gas, and oil are all positive; this is in line with the expectation that increased fuel costs push electricity prices up. Sunshine duration and humidity also have the expected signs: increased sunshine means more ability to produce solar power and thus lower electricity prices, while increased humidity is associated with more demand for electricity to provide cooling and has a positive correlation with electricity prices.

The wind speed estimates are a bit surprising. Wind speed is estimated to have a (not statistically significant) positive effect on electricity prices. Given that higher wind speed should provide more electricity and push prices down, there may be non-linear effects of wind speed on electricity prices. For example, at high wind speeds, wind mills may be forced to stand still as operational risk increases with wind speed.

Deviations from mean temperatures drive energy consumption through household heating and cooling. Using both average daily temperatures, represented by the Temperature variable, and max temperatures as controls in the regression lets us discover the nonlinear effect of temperature on electricity prices. Maximum temperatures are estimated to have a positive effect on electricity prices, which is in line with expectations as more electricity is needed for cooling when maximum temperatures are high. Average daily temperatures appear to be low enough to have have a net negative effect on electricity prices, an idea which becomes clearer as we add month-temperature fixed effects. Average temperatures in say December are lower and likely to generate more demand for heating, thus increasing electricity prices, than average temperatures in March or October. The reverse can be said for summer months like June during which average temperatures will be higher and drive demand for cooling, which will increase electricity prices. The $Month \times Temperature$ fixed effects applied to regressions (2)-(4) reduce the effects of these winter and summer months on the estimate of average temperature's effect on electricity prices. The result is a substantially lower estimates for Temperature in columns 2, 3 and 4.

Other fixed effects that we layer on are a $Month \times Hour$ fixed effect and a $Month \times Country$ fixed effect. The $Month \times Hour$ fixed effects helps to control for seasonality effects throughout the year such as daytime and night time electricity needs; 7p.m. during the winter is night time and that induces different electricity demands that 7p.m. during the summer when the sun is still out. $Month \times Country$ fixed effects account for any differences between Spain and Portugal at a more nuanced time scale.

The result that the average response of electricity prices due to changes in emission costs of Iberian coal and gas plants are consistently estimated at 110% per unit increase in emission costs suggests that wholesale electricity buyers pay for the entirety of emissions costs induced by the EU ETS, and then some.

Fabra and Reguant (2014) analyzed the Spanish market from 2004-2006 at the onset of the EU ETS and found pass-through rates of approximately 80%. Both our work and Fabra and Reguant (ibid.) find evidence of high pass-through rates, and while we arrive at a larger point estimate, the Fabra and Reguant (ibid.) estimate of 80% is within the 95% confidence interval of our estimates. Some potential causes of this variation between studies are that a lot of aspects in the market have changed over the last decade and a half. As we discussed in the Background section of the paper, electricity generation mixes have evolved, the Spanish market was integrated with the Portuguese market, EUA allowances are no longer allocated for free, and carbon prices skyrocketed over the time period of our paper. These changes are likely causes of the differing pass-through rate estimates.

6.3 Peak and off-peak

In this section, we investigate pass-through rates during peak versus off-peak hours. Previous literature from Fabra and Reguant (2014) and Zachmann and Hirschhausen (2008) have found differing pass-through rates between the two time periods during earlier phases of the EU ETS. Fabra and Reguant (2014) quantified pass-through rates in off-peak hours as 40% versus 100% in peak hours. They argue that this difference in peak and off-peak pass-through is due to the existence of ramping costs. Both combined cycle gas plants and coal plants have ramping costs, so if this truly is the reason, we should witness similar tendencies in our sample period, namely that peak and off-peak pass-through rates are different, as a consequence of ramping costs. If we reject the null that pass-through is similar in peak and off-peak then there is support for their statement in our sample. On the other hand, if we fail to reject the null hypothesis that peak and off-peak pass-through rates are equal, then there would be reason to think their explanation is incomplete.

We estimate the following equation to look for differences between peak and offpeak hours:

$$p_{thz} = \rho_1 \tau_t e_{thz} + \rho_2 (OP_h \times \tau_t e_{thz}) + X_t \beta_0 + X_t^D \beta_1 + X_t^S \beta_2 + \omega_{th} + \epsilon_{thz} \tag{3}$$

Where $OP_h = 0$ for hours between 8am and 8pm, and $OP_h = 1$ otherwise. This regression is estimated using 2SLS, just like previously, the only difference being that we now have two endogenous variables and require two instruments. The instruments used are τ_t and $\tau_{t-1} \times OP_h$. If we were using $\tau_t \times OP_h$ together with τ_t as the two instruments, we would run into issues since they are perfectly correlated when $OP_h = 1$. Additionally, the first lag of the carbon price, τ_{t-1} is still highly correlated with emissions costs. We multiply the lagged carbon price with the indicator for off-peak hours since that is the part of the carbon price series we are interested in. By the same arguments laid out in Section 5, we believe both these instruments fulfill the independence, exclusion, relevance, and monotonicity criteria. The results table for the off-peak, 4, analysis does not include the coefficients for the control variables featured in Table 3 because they retain their previous directions and magnitude.

Contrary to Fabra and Reguant (ibid.), who hypothesised that pass-through of emission cost in peak and off-peak hours could be different due to the existence of ramping costs, we are unable to reject the null that the estimates for peak and off-peak pass-through rates are equal. Our results highlight the possibility that coal and gas plants have changed their pricing behaviour between the period 2004-2006 and 2017-2021.

Given that ramping costs existed then and still exist today, we are interested in pursuing an alternative explanation to this difference in results. We believe that the switch from freely allocated allowances to auctioned allowances could have induced this change in behavior. Since rising pass-through rates increase producer surplus and decrease consumer surplus it may be politically risky to pass through the value of freely allocated allowances in its entirety. Generators could be careful in passing through emission costs too

Table 4: Peak vs. Off Peak Pass-Through

	(1)	(2)	(3)	(4)
Marg. Emissions Cost	1.039	1.001	1.030	1.023
	(0.304)	(0.308)	(0.315)	(0.317)
Marg. Emissions Cost × Offpeak	0.132	0.140	0.140	0.141
	(0.108)	(0.106)	(0.103)	(0.103)
Cragg-Donald	227.3	235.3	231.5	230.4
Base FE	Yes	Yes	Yes	Yes
Month × Temp, Max Temp FE	No	Yes	Yes	Yes
Month × Hour FE	No	No	Yes	Yes
Month × Country FE	No	No	No	Yes

Table notes: Dependent variable is hourly wholesale electricity price. All specifications include year of sample, month, weekday, hour, and country fixed effects; weather and demand controls (temperature, max temperature, humidity, sunshine); supply controls (commodity prices of coal, gas, and oil). The marginal emissions cost is instrumented with the emissions price. Robust standard errors in parentheses. Number of observations: 11,324.

aggressively since free allowances could technically be taken away from them in the future. If that is the case, one would have to ask when it is optimal for the generator to keep pass-through rates below 100%. The natural conclusion is that it is best to do so in periods of low demand, when aggregate profits for a firm will be lower.

This also makes sense given that most firms in our sample have several types of generation technologies in their portfolio. The 4 largest firms all have a mix of renewable and gas or coal generators. They benefit from their own pass-through of carbon prices if they hold renewables. Renewables are likely to be active, to a greater extent, in peak-hours. Raising the pass-through during peak hours is, therefore, yields higher returns. When permits are instead auctioned, there is no political risk to full pass-through, and the incentive will be to pass on the cost of emissions since these are now incurred as cash expenditures. This explanation needs further research to be validated, and that research is outside the scope of this paper.

The results in Table 4 lead us to conclude that there is no evidence for different pass-through rates of emission costs during periods of high and low demand in our sample.

6.4 Asymmetric Pass-Through

Zachmann and Hirschhausen (2008) mention two drivers of asymmetric pass-through. Firstly, there may be a period of learning associated with new costs which may delay pass-through. Secondly, market power may afford electricity generators the ability to pass through cost increases to a lesser extent, or more slowly. In our sample period, it would be difficult to argue that the existence of asymmetries, if proven, would be due to learning periods, given that the Iberian electricity market has already been participating in the ETS for 12 years at the start of our sample.

It is not obvious how bidders account for the changes in carbon prices that they face if they are truly behaving differently in response to the EUA price rising versus falling. We categorize our data into three distinct buckets: time periods when the carbon price has been increasing, time periods when it has been decreasing, and time periods when it has stayed the same. Creating these categories is not without its issues as the time frame that producers consider and the thresholds to which they respond are unknown. For instance, are producers responding simply to the carbon price today versus what it was yesterday, or are they considering carbon price changes over longer time periods. To this end, we try a few different ways to categorize price movements.

We calculate the change in carbon price in terms of both absolute euro changes and relative percentage changes. Then, we proceed to assign each day as having increasing, decreasing, or constant EUA prices by using a few different thresholds. First, we define carbon price movements within ± 3% as the price staying constant, with movements greater than or less than that threshold as price increasing or decreasing respectively. Secondly, we use an absolute movement of the carbon price as a threshold with price movements between ± €0.5 as the price remaining constant and movements outside of that being categorized appropriately based on the direction of movement. We calculate these price movements based on three different intervals. First, we look at price changes from one day to the next. Then the price difference today versus the average price over the past three days, and finally today versus the average price over the past seven days.

We extend equation (1) to include an interaction term between emissions costs and an indicator for prices increasing, as well as an interaction term between emissions costs and an indicator for prices decreasing:

$$p_{thz} = \rho_1 \tau_t e_{thz} + \rho_2(\Delta\tau_t^- \times \tau_t e_{thz}) + \rho_3(\Delta\tau_t^+ \times \tau_t e_{thz}) + X_t\beta_0 + X_t^D\beta_1 + X_t^S\beta_2 + \omega_{th} + \epsilon_{thz} \tag{4}$$

Where $\Delta\tau_t^-$ and $\Delta\tau_t^+$ are binary indicators for prices having decreased or increased.

In equation (4), ρ_1 is the pass-through rate when prices are constant, i.e. no deviation larger than 3% in any direction or no deviation larger than €0.5 in any direction. ρ_2 is the additional pass-through that occurs during times when prices have decreased, and ρ_3 is its analog for when prices have increased. We use three instruments to estimate equation (4): τ_t, $\Delta\tau_t^- \times \tau_{t-1}$, and $\Delta\tau_t^+ \times \tau_{t-2}$.

The results suggest the effect on electricity prices due to changes in emissions costs are different when the price of EUA allowances are going up compared to when they are going down. These results are consistent when looking at relative price movements of equal to or greater than 3% and absolute changes of €0.5. Regardless of carbon price movement, our estimates show pass-through rates to be consistently above 100%. Contrary to previous research that finds full pass-through rates when prices are increasing, but lower effects for decreasing prices, we see evidence for higher pass-through rates when prices are decreasing.

These results could be due to market power. Our sample is characterised by a few large firms with a competitive fringe of many small players. In fact, the 10 largest firms win around 90% of the auctions in our sample. What's more, these 10 largest firms have an even more dominant hold of fossil fuel plants accounting for roughly 10,500 of 11,348 coal and gas plant auction wins. Whereas a market characterised by close to full competition encourages fast and full pass-through of increased costs in order to maintain any margin, oligopolists may respond differently to increasing costs, which could be the driver of our results. Another

Table 5: Pass-Through Rate, Increasing/Decreasing EUA prices: Day to Day

	(1)	(2)	(3)	(4)
±3% Threshold				
Marg. Emissions Cost	1.229	1.221	1.267	1.265
	(0.298)	(0.303)	(0.312)	(0.314)
Marg. Emissions Cost × EUA Price Decreasing	0.382	0.442	0.456	0.455
	(0.110)	(0.113)	(0.112)	(0.111)
Marg. Emissions Cost × EUA Price Increasing	−0.069	−0.052	−0.068	−0.067
	(0.069)	(0.068)	(0.068)	(0.068)
Cragg-Donald	153.4	157.8	154.8	154.1
±0.5€ Threshold				
Marg. Emissions Cost	1.168	1.146	1.175	1.173
	(0.304)	(0.309)	(0.316)	(0.319)
Marg. Emissions Cost × EUA Price Decreasing	0.298	0.325	0.334	0.333
	(0.069)	(0.071)	(0.070)	(0.070)
Marg. Emissions Cost × EUA Price Increasing	−0.062	−0.042	−0.037	−0.038
	(0.055)	(0.055)	(0.055)	(0.056)
Cragg-Donald	152.0	157.2	154.7	154.0
Base FE	Yes	Yes	Yes	Yes
Month × Temp, Max Temp FE	No	Yes	Yes	Yes
Month × Hour FE	No	No	Yes	Yes
Month × Country FE	No	No	No	Yes

Table notes: Dependent variable is hourly wholesale electricity price. All specifications include year of sample, month, weekday, hour, and country fixed effects; weather and demand controls (temperature, max temperature, humidity, sunshine); supply controls (commodity prices of coal, gas, and oil). The marginal emissions cost is instrumented with the emissions price. Robust standard errors in parentheses. Number of observations: 11,316.

reason for these results could be that the market is characterised by different demand or supply schedules when prices decrease. For example, if the supplier faces more elastic demand during times when carbon prices increase, the pass-through rate may be lower, as given by the definition of pass-through rates under iso-elastic demand curves: $\frac{dP}{dMC} = \frac{N\varepsilon}{N\varepsilon - 1}$.

We have also looked at how timing might change asymmetric pass-through rates as it may take more persistent changes in the carbon price to induce producers to change their pricing strategy. In the appendix, we have featured results from analyses in which we categorise price changes by two alternative timings. In Table 10, days are categorized as carbon price increasing, decreasing, or remaining constant by comparing the price change between the mean price of the most recent three days to the mean price of the seven days prior. Then, in Table 11, we compare the mean price over the most recent seven days to the mean over the seven days prior. We choose to also look at these time frames because weekly and three-day averages should be less noisy than daily price changes and indicate a more persistent increase or decrease in the carbon price.

Table 6: Pass-Through Rate, Increasing/Decreasing EUA prices: Today vs. Previous 3 Day Average

	(1)	(2)	(3)	(4)
±3% Threshold				
Marg. Emissions Cost	1.235	1.227	1.270	1.266
	(0.296)	(0.302)	(0.310)	(0.313)
Marg. Emissions Cost × EUA Price Decreasing	0.309	0.363	0.364	0.364
	(0.086)	(0.090)	(0.087)	(0.088)
Marg. Emissions Cost × EUA Price Increasing	0.022	0.039	0.029	0.028
	(0.058)	(0.059)	(0.059)	(0.059)
Cragg-Donald	152.5	157.9	154.9	153.5
±0.5€ Threshold				
Marg. Emissions Cost	1.040	1.038	1.084	1.083
	(0.294)	(0.300)	(0.308)	(0.310)
Marg. Emissions Cost × EUA Price Decreasing	0.435	0.475	0.480	0.478
	(0.068)	(0.069)	(0.069)	(0.069)
Marg. Emissions Cost × EUA Price Increasing	0.159	0.166	0.158	0.158
	(0.054)	(0.053)	(0.053)	(0.054)
Cragg-Donald	153.9	159.0	155.3	154.6
Base FE	Yes	Yes	Yes	Yes
Month × Temp, Max Temp FE	No	Yes	Yes	Yes
Month × Hour FE	No	No	Yes	Yes
Month × Country FE	No	No	No	Yes

Table notes: Dependent variable is hourly wholesale electricity price. All specifications include year of sample, month, weekday, hour, and country fixed effects; weather and demand controls (temperature, max temperature, humidity, sunshine); supply controls (commodity prices of coal, gas, and oil). The marginal emissions cost is instrumented with the emissions price. Robust standard errors in parentheses. Number of observations: 11,316.

All of our results indicate that there is an asymmetry in pass-through rates when the carbon price has increased or decreased, but magnitudes and directions change depending on what time periods are being used. The ρ_1 estimates all lie within one standard error's distance from each other and are consistently estimated above 1.0. The same cannot be said about the estimates for ρ_2 and ρ_3 which vary between different specifications.

Our results indicate an asymmetry of pass-through, although the quantification of this asymmetry is highly dependent on timing. The finding that asymmetry is most often found in cases of decreasing prices is contrary to what other studies on asymmetric pass-through rates have found, and while we have tried to explain this finding with theory and insights from our data, we are wary that these results may lack external validity as carbon prices see such a dramatic and sustained increase over our sample period.

Table 7: Pass-Through Rate, Increasing/Decreasing EUA prices: Today vs. Previous 7 Day Average

	(1)	(2)	(3)	(4)
±3% Threshold				
Marg. Emissions Cost	1.458	1.475	1.543	1.542
	(0.288)	(0.294)	(0.303)	(0.305)
Marg. Emissions Cost × EUA Price Decreasing	0.195	0.244	0.252	0.256
	(0.070)	(0.074)	(0.073)	(0.073)
Marg. Emissions Cost × EUA Price Increasing	−0.157	−0.145	−0.161	−0.157
	(0.056)	(0.056)	(0.056)	(0.056)
Cragg-Donald	137.2	138.8	134.5	133.4
±0.5€ Threshold				
Marg. Emissions Cost	1.342	1.343	1.413	1.415
	(0.305)	(0.311)	(0.322)	(0.324)
Marg. Emissions Cost × EUA Price Decreasing	0.271	0.293	0.300	0.297
	(0.059)	(0.060)	(0.060)	(0.060)
Marg. Emissions Cost × EUA Price Increasing	−0.025	−0.024	−0.034	−0.034
	(0.055)	(0.053)	(0.054)	(0.054)
Cragg-Donald	132.3	136.6	132.3	131.9
Base FE	Yes	Yes	Yes	Yes
Month × Temp, Max Temp FE	No	Yes	Yes	Yes
Month × Hour FE	No	No	Yes	Yes
Month × Country FE	No	No	No	Yes

Table notes: Dependent variable is hourly wholesale electricity price. All specifications include year of sample, month, weekday, hour, and country fixed effects; weather and demand controls (temperature, max temperature, humidity, sunshine); supply controls (commodity prices of coal, gas, and oil). The marginal emissions cost is instrumented with the emissions price. Robust standard errors in parentheses. Number of observations: 11,316.

7 Robustness - Direct Impact of EUA price on electricity price

Thus far, we have specified and estimated a model to isolate the effect of a unit change in marginal emissions costs on the system electricity price in the day-ahead market. This analysis has been limited to the impact of emission costs on electricity pricing by carbon-emitting fossil fuel plants. It is also interesting to investigate the overarching effect of carbon allowance prices on electricity prices across all hours, irrespective of the type of generator that wins the day-ahead auction. To achieve this, we will return to our reduced form specification in (2) (repeated below) and estimate it using 2SLS with the first lag of the carbon price as an instrumental variable. This is to address the endogeneity caused by the simultaneity between carbon prices and electricity prices discussed in section 6.1.

$$p_{th} = \rho\tau_t + X_t\beta_0 + X_t^D\beta_1 + X_t^S\beta_2 + \omega_{th} + \epsilon_{th}$$

Table 8 shows the coefficient on the EUA price in the IV regression to be 0.819 which can be interpreted as a €1 increase in the EUA price leading to a €0.82 increase in the electricity price. Though this is still quite a high pass-through rate, it is a lower estimate than those found in earlier sections of the paper, in which the pass-through rate of carbon prices onto electricity prices was estimated to be around 1.1.

Table 8: Direct impact of EUA prices on electricity prices, all electricity generators

	OLS	IV
EUA price	0.629	0.819
	(0.053)	(0.052)
Temperature	−0.053	−0.051
	(0.011)	(0.011)
Max Temperature	0.015	0.011
	(0.010)	(0.010)
Wind Speed	−0.333	−0.349
	(0.035)	(0.035)
Wind Speed^2	−0.002	−0.002
	(0.000)	(0.000)
Sunshine Duration	−0.001	−0.001
	(0.005)	(0.005)
Humidity	0.000	−0.001
	(0.011)	(0.011)
Coal	0.038	0.043
	(0.012)	(0.012)
Gas	1.894	1.838
	(0.029)	(0.028)
Brent	0.014	−0.015
	(0.011)	(0.011)
F-stat		536,046

Table notes: Dependent variable is hourly wholesale electricity price. All specifications include year of sample, month, weekday, hour, and country fixed effects; weather and demand controls (temperature, max temperature, humidity, sunshine); supply controls (commodity prices of coal, gas, and oil). The EUA price is instrumented with the prior day's EUA price. Robust standard errors in parentheses. Number of observations: 45,335.

Hydro generators are a likely driver of the difference between these estimates. Table 9 shows the number and percentage of hourly day ahead auction wins have been won by each production technology from 2017-2021. About half of all of the auctions are won by hydro generators. Because hydro generators have the ability to store the energy that they have produced, their marginal costs are a function of the opportunity cost associated with storing water and so their pricing strategies are different to producers who submit bids based purely on marginal costs plus a markup. Their bids are likely to vary with the cost of carbon simply because other producer's bids do so, and their bids become part of the opportunity cost incurred by energy-storing water reservoirs. Other renewable producers such as solar and wind have significantly lower and less varying marginal costs than fossil fuel plants and hydro plants. Therefore, each additional auction won by such a plant will decrease the estimated effect of carbon prices on electricity prices, throughout the entirety of our sample.

Table 9: Auction Wins by Production Technology

Technology	Auction Wins	Percent of Auctions Won
Hydro	25244	55.0%
Gas Combined Cycle	6646	14.5%
Coal	4702	10.2%
Thermal	3826	8.3%
Wind	3686	8.0%
Solar	1256	2.7%
Other	544	1.2%

Notes: Hourly auction wins on the day ahead electricity market run by OMIE between 2017-2021 in the Iberian Peninsula

8 Conclusion

The EU ETS is the world's largest cap-and-trade scheme for emissions. It has set a price on carbon and forced producers to integrate the cost of emissions into their production functions. The success of the scheme in reducing consumption of emissions among electricity producers rests to a significant extent on the transfer of emissions costs to consumers such that incentives for investment into abatement technologies able to capture windfall profits grow. Electricity generators outside of lower-income member countries have been forced to participate in the auctioning of emission allowances since the start of the third phase in 2013. Electricity markets therefore provide ample opportunity to understand how the introduction of emission costs affects equilibrium prices.

In this study, we have quantified the pass-through rate of emission costs onto electricity prices in the Iberian electricity market between the start of 2017 and end of 2021, a period during which the price of carbon allowances increased dramatically. Using an instrumental variables approach, our results show consistent estimates of pass-through rates of around 110%. To understand this near-complete pass-through rate, we looked at pass-through rates during periods of high and low demand, as well as differences in pass-through during periods when carbon prices increase and decrease.

Contrary to previous findings from the same geographical context, we do not observe a difference in pass-through during periods of high and low demand. While such a difference has previously been observed and hypothesised to be due to technological ramping costs, we think our results indicate another mechanism; namely political risk of high pass-through rates under free allowances. We believe that in early phases of the EU ETS, pass-through rates could have been reduced during periods of low demand to protect the generators from losing future free allowances and with them, windfall profits. When allowances are auctioned and paid for in full, as in the time frame that we study, there is no longer any political risk to passing through their costs entirely during both periods of high and low demand.

We find evidence of asymmetries in pass-through rate, with fossil fuel plants tending to pass-through emission costs more when carbon prices are decreasing versus when they are constant or increasing. This asymmetry is in the opposite direction than typically seen. We have proposed some explanations to these findings but further research is required to better understand underlying mechanisms. Our asymmetry analysis is also not agnostic to timing and may have limited external validity as carbon prices are for the most part increasing during our sample period. We recommend that future research tackles this question with different methodologies that may uncover the nature of asymmetric pass-through with more clarity.

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Appendix

Table 10: Pass-Through Rate, Increasing/Decreasing EUA prices: 3 Day Average vs. Prior 7 Day Average

	(1)	(2)	(3)	(4)
±3% Threshold				
Marg. Emissions Cost	1.340	1.348	1.423	1.414
	(0.284)	(0.288)	(0.298)	(0.300)
Marg. Emissions Cost × EUA Price Decreasing	−0.003	0.023	0.031	0.030
	(0.055)	(0.056)	(0.056)	(0.056)
Marg. Emissions Cost × EUA Price Increasing	−0.125	−0.130	−0.147	−0.144
	(0.052)	(0.052)	(0.052)	(0.052)
Cragg-Donald	126.2	130.0	125.5	125.0
± 0.5€ threshold				
Marg. Emissions Cost	1.304	1.305	1.372	1.360
	(0.327)	(0.332)	(0.344)	(0.348)
Marg. Emissions Cost × EUA Price Decreasing	−0.108	−0.093	−0.089	−0.094
	(0.056)	(0.058)	(0.057)	(0.057)
Marg. Emissions Cost × EUA Price Increasing	−0.134	−0.140	−0.154	−0.153
	(0.059)	(0.060)	(0.060)	(0.060)
Cragg-Donald	114.9	119.0	114.7	114.0
Base FE	Yes	Yes	Yes	Yes
Month × Temp, Max Temp FE	No	Yes	Yes	Yes
Month × Hour FE	No	No	Yes	Yes
Month × Country FE	No	No	No	Yes

Table notes: Dependent variable is hourly wholesale electricity price. All specifications include year of sample, month, weekday, hour, and country fixed effects; weather and demand controls (temperature, max temperature, humidity, sunshine); supply controls (commodity prices of coal, gas, and oil). The marginal emissions cost is instrumented with the emissions price. Robust standard errors in parentheses. Number of observations: 11,316.

Table 11: Pass-Through Rate, Increasing/Decreasing EUA prices: 7 Day Average vs. Prior 7 Day Average

	(1)	(2)	(3)	(4)
±3% Threshold				
Marg. Emissions Cost	1.202	1.208	1.271	1.268
	(0.286)	(0.288)	(0.297)	(0.301)
Marg. Emissions Cost × EUA Price Decreasing	0.138	0.209	0.227	0.227
	(0.072)	(0.073)	(0.072)	(0.072)
Marg. Emissions Cost × EUA Price Increasing	−0.002	−0.003	−0.011	−0.011
	(0.044)	(0.043)	(0.043)	(0.043)
Cragg-Donald	139.2	143.5	139.0	138.2
± 0.5€ threshold				
Marg. Emissions Cost	1.195	1.198	1.259	1.256
	(0.312)	(0.314)	(0.324)	(0.328)
Marg. Emissions Cost × EUA Price Decreasing	0.183	0.246	0.268	0.263
	(0.062)	(0.062)	(0.064)	(0.064)
Marg. Emissions Cost × EUA Price Increasing	0.022	0.026	0.022	0.021
	(0.042)	(0.041)	(0.041)	(0.041)
Cragg-Donald	115.9	120.6	116.2	115.0
Base FE	Yes	Yes	Yes	Yes
Month × Temp, Max Temp FE	No	Yes	Yes	Yes
Month × Hour FE	No	No	Yes	Yes
Month × Country FE	No	No	No	Yes

Table notes: Dependent variable is hourly wholesale electricity price. All specifications include year of sample, month, weekday, hour, and country fixed effects; weather and demand controls (temperature, max temperature, humidity, sunshine); supply controls (commodity prices of coal, gas, and oil). The marginal emissions cost is instrumented with the emissions price. Robust standard errors in parentheses. Number of observations: 11,316.