Rising electricity prices in Europe: The impact of gas and carbon prices

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Abstract

This paper provides an empirical assessment of the impact of rising gas and carbon prices on European electricity prices. Using a comprehensive data set of hourly power market data of 24 European countries, we estimate the impact of gas and carbon prices on electricity prices for the years 2015 to 2021. We find that a gas price increase of 1€/MWh leads to an electricity price increase of 0.3-2.2€/MWh. Correspondingly, a carbon price increase of 1€/tCO_2 leads to an electricity price increase of 0.2-1.0 €/MWh. The magnitude of these impacts mainly depends on a country's production portfolio: Countries with a gas-based power market are more heavily affected by increasing gas prices; whereas the carbon price impact is higher for countries with a high coal share. Finally, we find that the rising gas price was mostly responsible for the electricity price increase between 2019 and 2021. We show that the gas price lead to an increase in yearly average electricity prices of up to 70€/MWh; whereas the increase attributed to the carbon price only amounted to a maximum of 25€/MWh. Thus, our analysis contributes to the current policy debate on reasons and consequences of rising energy and carbon prices across Europe.

Keywords: Electricity prices, natural gas prices, carbon pricing

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1. Introduction

At the end of 2021 Europe experienced a huge increase in energy prices. Most of all, gas prices increased from below 20 to more than around 180€/MWh within a couple of months, but also the price for CO_2 within the European Emission Trading System (EU ETS) experienced an all time high of more than 80€/t CO_2 in winter 2021. As a consequence, electricity prices rose up from weekly averages of around 50€/MWh to more than 300€/MWh.

This paper sheds light on these recent developments from the perspective of European power markets - and disentangles the different factors that led to these high power prices. Specifically, we estimate the impact of gas and carbon prices on electricity prices for 24 European countries. We make use of a large data set of hourly electricity market data from the years 2015 to 2021 including electricity prices, load, generation by technology, as well as daily fuel and carbon prices. We answer three main questions: (1) What is the marginal impact of gas and carbon prices on electricity prices? (2) What determines the magnitude of these impacts? (3) To what extent were coal and gas prices responsible for the increase in electricity prices between the years 2019 and 2021?

The main mechanisms that drive price setting in a power market are well understood: In a perfectly competitive market, the electricity price is set by the marginal cost of the marginal generator. Given the mixed plant portfolio of most European power markets, in many cases either coal or gas plants are marginal and thus set the price. As a consequence, fuel prices are one of the main drivers of electricity prices. In addition, the carbon price puts a price tag on emissions and thus makes dirtier production relatively more expensive. This implies that mostly lignite and hard coal production, but to a lower extent also gas generation, become more expensive, again leading to higher electricity prices.

These general mechanisms are the same for all countries. Also, fuel prices are determined on international markets and thus nearly uniform across Europe. The same is true for the carbon price which is determined by the EU ETS' allowance price (EUA). However, the impacts of gas and carbon prices on electricity prices are highly heterogeneous across countries due to very different pplant portfolios: In each hour, the heat efficiency and carbon emissions of the marginal generator determine the impacts of gas and carbon prices, respectively. The size of the *average price impact* additionally depends on how often each plant is marginal. In other words, a country with a high gas share is likely to be heavily affected by increases in the gas price, while a country with a high coal share is likely to be more affected by an increase in the carbon price. While the driving mechanisms are clear, empirical assessments of gas and carbon price impacts are scarce.

To the best of our knowledge, our study provides the first empirical assessment of the impact of recent gas and carbon price developments on electricity prices. Our results can by summarized by three main points. First, a gas price increase of 1€/MWh leads to an electricity price increase of 0.3 €/MWh in Sweden up to 2.2 €/MWh in Italy. Correspondingly, a carbon price increase of 1€/tCO_2 leads to an electricity price increase of 0.2 €/MWh in Italy and Portugal up to 0.8-1.0 €/MWh in Germany, Czech Republic, Estonia and Ireland.

Second, the magnitude of the gas price impact mainly depends on the share of gas generation, i.e., we show that countries with a high level of gas generation are more heavily affected by increasing gas prices. In contrast, the carbon price impact is mainly driven by the share of coal generation, or more generally, by the carbon emissions of electricity generation. Thus, countries with carbon intensive electricity generation are more affected by an increase in carbon prices. Furthermore, a higher share of non-fossil generation lower the impact of both, gas and carbon prices; whereas the impact of a higher import share is ambiguous.

Third, the gas price increase was the main driver of electricity prices between 2019 and 2021. Our calculations show that in some countries the gas price lead to an increase in yearly average electricity prices of up to around 70€/MWh. In contrast, the increase that we can attribute to the carbon price increase only amounts to a maximum of around 25 €/MWh.

With our study we contribute to the growing literature on the empirical assessment of climate and energy policy in two main ways.

First, the beginning of last decade was characterized by low carbon prices but an extensive support of renewable energies. Consequently, there was a substantial strand of literature, focusing on the decreasing price effect of RE promotion (merit-order effect). Studies have looked at domestic price impacts of RE promotion (e.g. Wuerzburg et al., 2013; Cludius et al., 2014; Abrell et al., 2019) as well as on cross-border impacts (e.g. Abrell & Kosch, 2022; Phan & Roques, 2015; Haxhimusa, 2018; Gugler & Haxhimusa, 2019). Only recently carbon prices - at least within the EU ETS - have increased to a level that has a substantial impact on electricity prices. We thus contribute by analyzing the impact of carbon pricing on the electricity price.

Second, in the past few studies have looked at the impact of fuel and carbon prices on European electricity prices. Freitas & da Silva (2015) analyze the impact on Spanish electricity prices for the second and third phase of the EU ETS. The impact of the third phase is additionally analyzed by Ahamada & Kirat (2015) for Germany and France and by Wolff & Feuerriegel (2019) for Germany. Hirth (2018) provides a comprehensive decomposition analysis of factors that caused the price drop between 2008 and 2015 with a focus on Germany and Sweden. Also related is the literature on the cost pass-through of fuel and carbon prices that analyzes to what extent electricity producers pass their input cost to consumers. In the past, this has been investigated for several countries (e.g. Hintermann, 2016; Fabra & Reguant, 2014; Guo & Gissey, 2021; Bai & Okullo, 2021; Jouvet & Solier, 2013; Ahamada & Kirat, 2018). Our contribution to this literature is twofold. On the one hand, this is - to the best of our knowledge - the first study that empirically analyzes fuel and carbon price impacts for (almost) all European countries. On the other hand, we look at a very recent period with increasingly high fuel and carbon prices by constructing a comprehensive data set with hourly market data for each country.

Next to the contributions to the academic literature our analysis is also relevant for the political debate. Primarily, we provide the first comprehensive empirical analysis that provides a quantitative assessment to what extent the increase in electricity prices between 2019 and 2021 can be attributed to gas and carbon prices respectively. Furthermore, we show that these impacts vary significantly between countries. Specifically, we find that countries with higher shares of non-fossil generation are generally less affected by rising gas and carbon prices. This implies that reducing the dependency from fossil electricity generation can make an economy less vulnerable to changes in international fuel prices. On the contrary, a higher dependency on gas generation, as currently intended in some countries as a consequence of coal and nuclear phase-outs, will increase this vulnerability. Finally, our findings are important regarding the distributional implications between and within European countries: In countries with high impacts consumer are negatively affected - the higher the price increase the more they suffer. In contrast, sub-marginal producers, such as nuclear or renewable generators, can benefit from substantially higher profits.

The remainder of this paper proceeds as follows. In the next section we provide some context on the development in European electricity markets and show how the electricity price is affected by changes in gas and carbon prices. Section 3 presents our empirical specifications and robustness checks. Section 4 presents the marginal impacts of gas and carbon prices on the electricity price, analyzes the main factors that drive the level of these impacts and attributes the increase in electricity prices between 2019 and 2021 to the increase in gas and carbon prices respectively. Section 5 concludes.

2. Context

2.1. European power markets from 2015 to 2021

Looking at the development of electricity prices in Europe within the last six years[1] (upper panel of Figure 1), mostly the drastic increase in 2021 jumps to the eye. Within less than a year, weekly average prices rose from around 50 up to almost 350€/MWh. A somewhat closer look shows that already in former years electricity prices have been volatile. As shown by the lower panel of Figure 1, also fuel and carbon prices have undergone substantial ups and downs.[2] A visual comparison of the two Figures shows that fuel and carbon prices seem to be closely correlated with the electricity price, most pronounced in the case of gas.

However, while the developments of gas and carbon prices have been the same for all countries, there are substantial differences in the electricity price curves for different power markets. For example, for Sweeden we see a much lower increase as compared to Germany or Italy.

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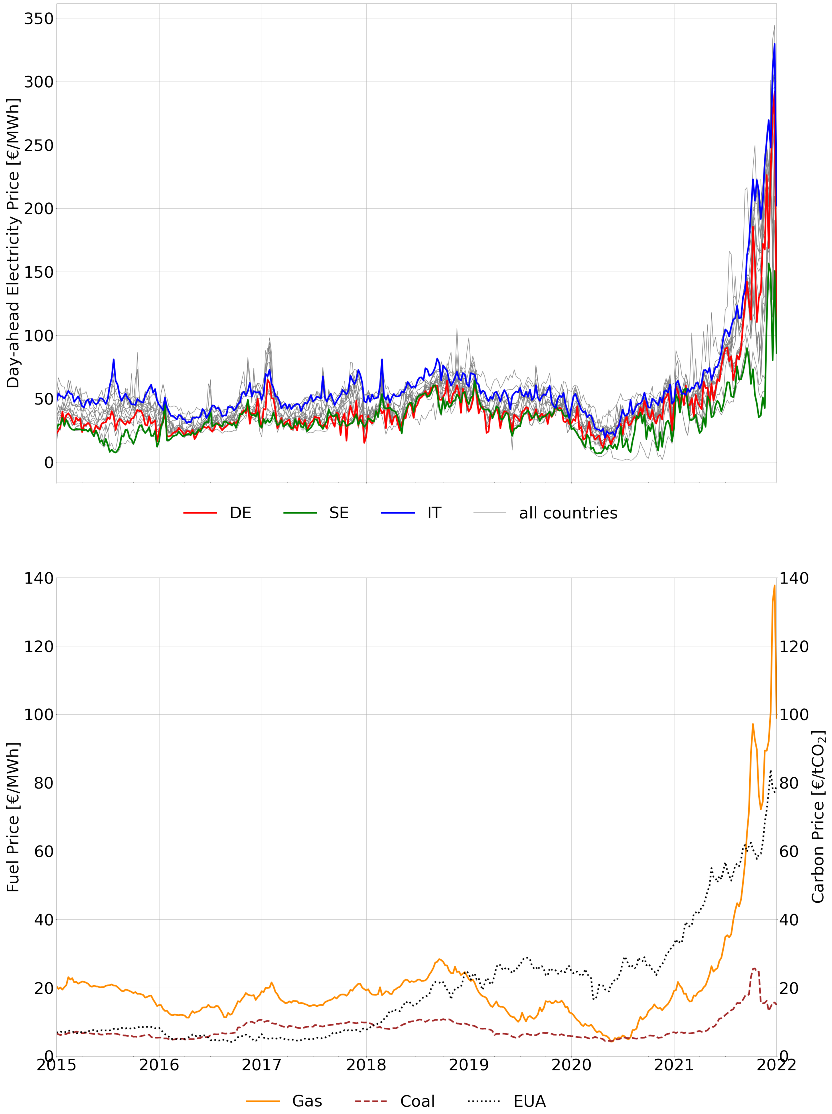
[1] Hourly day-ahead electricity prices are obtained from the European Network of Transmission System Operators for Electricity ENTSO-E (2021) transparency platform. For Poland, ENTSO-E prices are incomplete and we thus additionally used day-ahead prices from EIKON (2017).

[2] Gas prices show the front month price of Dutch TTF natural gas futures (downloaded from https://tradingeconomics.com/commodity/eu-natural-gas and https://data.nasdaq.com/data/CHRIS/ICE_TFM1-endex-dutch-ttf-gas-base-load-futures-continuous-contract-1-tfm1-front-month); coal prices show the front month price of Rotterdam Coal futures (downloaded from https://de.tradingview.com/symbols/ICEEUR-ATW1%21/ and https://data.nasdaq.com/data/CHRIS/ICE_ATW1-rotterdam-coal-futures-continuous-contract-1-atw1-front-month). As coal prices are provided in $/t, we convert them to €/MWh using a conversion factor of 8.141 MWh/t and historical exchange rates (www.excelrates.com/historical-exchange-rates/USD-EUR). Carbon prices show the front month prices of European Allowances (EUA) futures (downloaded from https://tradingeconomics.com/commodity/carbon and https://data.nasdaq.com/data/CHRIS/ICE_C1-ecx-eua-futures-continuous-contract-1-c1-front-month).

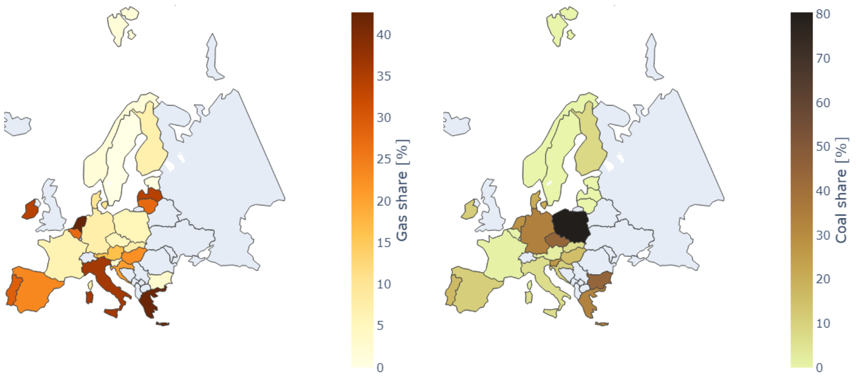
Figure 1. Electricity, fuel and carbon prices



Notes: The upper panel show weekly means of hourly day-ahead electricity prices The lower panel shows weekly averages of daily fuel prices (measured on the left axis) and the carbon price (right axis). Data sources are provided in the text.

Gas and carbon prices influence the electricity price via their impact on fossil power producers. Thus, electricity markets are likely to be differently affected depending on their production portfolio. Intuitively, we expect that markets with a gas-based portfolio are highly affected by the gas price increase, while

Figure 2. Share of fossil generation



(a) Gas share (b) Coal share

Notes: Coal includes hard coal and lignite. Percentages are calculated over the whole sample period, i.e. from 2015 to 2021, by dividing the sum of a technology's production by the country's total power generation.

markets with a generally high carbon intensity (mostly lignite and coal but also gas generation) are affected by the carbon price increase. Figure 2 thus shows the share of coal and gas production compared total generation. The share is calculated using hourly generation data over the whole sample period provided by ENTSO-E (2021).

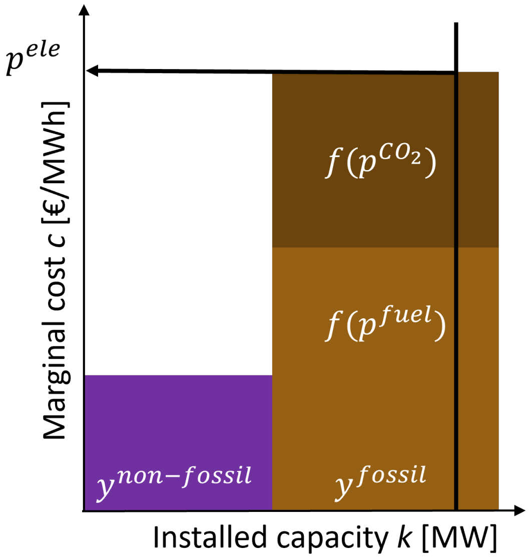
Indeed, coming back to the three examples above, we find that Italy with a high gas share experienced a substantial increase while Sweden with a basically carbon neutral electricity generation shows a less pronounced increase. However, the fact that also the increase in Sweden is clearly visible points at the high interconnection of power markets through international transmission lines.

Already this descriptive analysis shows that the impact of fuel and carbon prices on the electricity price is highly heterogeneous across countries and depends on many market characteristics such as the power plant portfolio or the international integration. In the following, we use a stylized merit order model to disentangle the individual impacts on the electricity price and later develop an empirical model to estimate the gas and carbon price impact for each country.

2.2. The impact of carbon prices on the electricity price

Figure 3 shows a stylized merit order curve with one non-fossil and one fossil technology. Assuming perfect competition (and consequently a 100 % cost pass-through of fuel and carbon cost to electricity consumers), the electricity price (p^{ele}) is given by the marginal cost of the marginal generator (mc^{*}). The latter is determined by fuel and carbon costs of electricity generation (other marginal cost are lower and thus neglected here):

FIGURE 3. Stylized merit order model



$$p^{ele} = mc^* = \frac{1}{\eta^*}(p^{fuel^*} + \theta^* p^{CO_2}), \tag{1}$$

where p^{fuel} and p^{CO_2} are the fuel and carbon price, η^* is the heat efficiency[3] of the marginal generator and θ^* the emission factor of the fuel. By deriving the electricity price by the CO_2-price or the gas price, we get the marginal impact of the respective price on the electricity price:

$$\frac{\partial p^{ele}}{\partial p^{CO_2}} = \frac{\theta^*}{\eta^*} = e^* \tag{2}$$

$$\frac{\partial p^{ele}}{\partial p^{gas}} = \frac{1}{\eta^*} \tag{3}$$

where e^* is the emission coefficient of the marginal generator, i.e., the amount of CO_2 that is emitted by producing one MWh of electricity. Thus, *in each hour*, the marginal generators' emission coefficient determines the carbon price impact on the electricity price, while—in case the marginal generator is a gas plant—the heat efficiency determines the gas price impact. Consequently, the *average* electricity price impacts over a period of time are given by the *average* of the

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[3] The heat efficiency determines how much electrical energy is produced per input of thermal energy, i.e., it is given as $\frac{\mathrm{MWh_{el}}}{\mathrm{MWh_{therm}}}$. The inverse of the heat efficiency is called heat rate.

marginal emission coefficients and the *average* of heat efficiencies[4], respectively.

Thus, how strong a country's electricity price is affected by changes in the carbon price depends on two main factors: First, how often are fossil plants marginal? I.e., in a country with a high share of non-fossil generation, the probability of a fossil plant being marginal is lower. Also, a country with high import capacities might have the opportunity of importing more cheaper non-fossil electricity, and might thus be less affected by an increase in the carbon price. Second, how "dirty" is the fossil generation? I.e., in a coal-based power market with high average emissions of fossil generation, the marginal plant is likely to have a high emission coefficient.

Correspondingly the impact of gas price changes depends on similar factors: First, how often are gas plants marginal? Of course, gas-based power markets are likely to be more affected by changing gas prices. Second, how efficient are the gas plants the respective electricity market? If the plant fleet is highly efficient, the impact on the electricity price is lower as less fuel is needed to produce the electricity.

3. Empirical Model

3.1. Empirical Specification

In the econometric approach we are interested in estimating how gas and carbon prices affect the electricity price. To estimate their respective impacts we use a reduced form model based on the stylized merit order model introduced above. Our main regression specification takes the following form[5]:

$$\begin{aligned} p_{tr}^{ele} = \alpha_r + \beta_{1r} p_t^{EUA} + \beta_{2r} p_t^{gas} + \beta_{3r} p_t^{coal} \\ \gamma_{1r} d_{tr} + \gamma_{2r} r_{tr} + \gamma_{3r} h_{tr} + \gamma_{4r} n_{tr} + \boldsymbol{F}_t \boldsymbol{\delta}_r + \epsilon_{tr} \,. \end{aligned} \tag{4}$$

where β_1 and β_2 are our main coefficients of interest measuring the impact of carbon and gas prices on the electricity. Together with the coal price p_t^{coal}, they are the main components of marginal costs in electricity production. In addition, we control for factors that determine the marginal generator, i.e., demand (d) and generation of non-fossil plants such as renewable energies (r, i.e wind and solar), hydro (h), and nuclear (n). In some alternative specifications (see Section 3.3 for more details), we add month-of-year and hour-of-day fixed effects ($\boldsymbol{F}_t$) to control for seasonal and daily cycles.[6] In our main specification t denotes the

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[4] For the hours when not gas but some other technology is marginal, the impact needs to be set to zero.

[5] For a formal derivation of the estimation model, we refer to Abrell et al. (2019).

[6] One short-coming of our current specification is that it does not include available capacities as these data are not available on a daily basis. However, in a next version of the paper we intend to address this issue. Furthermore, we will provide more additional specifications including more flexible functional forms as well as semi-parametric specifications. Finally, due to limited data availability, we currently use the same gas and coal prices for all countries.

day-of-sample, i.e., we estimate the impacts on the daily average price; in some alternative specifications t denotes the hour-of-sample or week-of-sample.

Table 1 gives an overview of all variables included in the estimation. Our sample includes the years 2015 to 2021.

Table 1. Estimation variables

Variable	Description
p_{tr}^{ele}	Hourly electricity price in country r [€/MWh]
p_t^{EUA}	Daily price of European Emissions Allowances [€/tCO$_2$]
p_t^{gas}	Daily gas price [€/MWh$_{\text{th}}$]
p_t^{coal}	Daily coal price [€/MWh$_{\text{th}}$]
d_{tr}	Hourly system demand in country r [GWh]
r_{tr}	Hourly RE production in country r [GWh]
n_{tr}	Hourly nuclear production in country r [GWh]
h_{tr}	Hourly hydro production in country r [GWh]
$month$	Month-of-year fixed effects
$hour$	Hour-of-day fixed effects

Notes: MWh$_{\text{th}}$ refers to thermal energy. Demand for each country is constructed as the sum of total generation plus net-imports. Further details on data sources and construction are provided in Section 2.1.

3.2. Identification, exogeneity assumptions and temporal resolution

To consistently estimate the model and identify our main coefficients of interest, all explanatory variables need to be independent:

Gas and coal prices are determined on international markets, thus individual countries are too small to significantly affect these prices. The main determinants of the EUA price are an ongoing item of political and academic discussions. While some argue that it is driven by fundamentals such as coal and gas prices, others argue that it is mostly determined by political regulations and financial markets. In any case, it can be assumed as exogenous from the short-run perspective of hourly price setting in electricity markets. In other words, electricity producers take the carbon price as a given input cost, when they announce their hourly bids.

To ensure the exogeneity of demand, we rely on the assumption of inelastic electricity demand. Given the short-run nature of our approach, this assumption seems to be plausible, as in the short-run demand is mainly determined by economic activities and weather conditions and does hardly react to changes in the wholesale market price.

Furthermore, we assume that base load and renewable generation are exogenous: Wind and solar generation have near zero marginal cost, thus once installed, their generation depends on weather conditions, the same is true for run-of-river hydro generation. Nuclear generation has very low marginal cost and is always dispatched before fossil generators.

Finally, some countries have a substantial share of storage and pump-storage hydro production which can be dispatched depending on the price, i.e., are not completely exogenous. To address this issue we re-sample our hourly data set to average daily data for our main specification[7] and also use weekly average values as a robustness check: As hydro generation is merely shifted to other hours, the short-run impacts of hydro power on the electricity price are eliminated if we look at longer time horizons. A more detailed discussion on the reasons for different temporal resolutions as well as other robustness checks is provided in Section 3.3.

3.3. Alternative Specifications

To analyze the robustness of our results we perform three types of sensitivity analyses: First, we vary the temporal resolution of our data. Second, we use different sets of time fixed effects. Third, we estimate the impact without controlling for the coal price. Table 2 gives an overview of all the models (M01-M10), and in the following we explain the reasons for each type of robustness check.

Table 2. Overview alternative specifications

	M01	M02	M03	M04	M05	M06	M07	M08	M09	M10
Temporal res.										
hourly				x	x	x	x	x		
daily	x	x	x							
monthly									x	x
Fixed effects										
hour					x		x			
month		x				x	x			x
Other										
no coal price			x					x		

Notes: M01 denotes our main model. More detailed descriptions of all specifications are in the text.

TEMPORAL RESOLUTION—For our main model (M01), we use a daily temporal resolution for the whole data set. To test the sensitivity of the results to the temporal resolution, we additionally estimate a set of models with hourly resolution (M04-M08) and a set of models with weekly resolutions (M09-M10). There are several reasons for or against different temporal resolutions: Generally, it is preferable to use the whole observed variation in the data, i.e., hourly values. However, in countries with a substantial share of dispatchable hydro generation, e.g., storage or pump-storage plant, these estimates are then potentially biased, as hydro generators are able to shift their production from times with low prices to times with higher prices, i.e., they also influence the electricity price. However, these effects largely balance out over the course of a day or week, which is a reason to use a lower temporal resolution such as weekly data.

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[7] Another reason for the choice of daily resolution is that gas and carbon prices, our main variables of interest are observed on a daily level.

To address this trade-off, we decided to show the results for hourly, daily and weekly data. For the main model, we decided to use daily data, also because our main variables of interest, i.e., gas and carbon prices, are also available daily.

TIME FIXED EFFECTS—–To control for daily or seasonal variation in unobserved variables we additionally estimate a set of models with different time fixed effects. In the case of daily and weekly resolution, we only use monthly fixed effects (M02 and M10, respectively); in the case of hourly resolution, we use hourly fixed effects (M05), monthly fixed effects (M06) or both (M07).

NO COAL PRICE—–Our main results show, that the coal price impact in most cases is statistically insignificant, indicating that the coal price does not affect the electricity price (after controlling for all other impacts). This could theoretically be the case when coal is never the marginal technology. However, for coal-based countries this scenario is very unlikely. The more plausible explanation is that coal costs actually paid for by the electricity producers might (in the short term) only be weekly correlated with international coal prices. A possible reason are higher transport and storage costs for coal (as compared to gas) which make daily trading much less attractive. Thus, electricity producers either have long term contracts at fixed prices or even own their own coal mines. To take these possibility into account, we estimate two models where we do not include the coal price as a control variable (M03 and M08).

4. Results

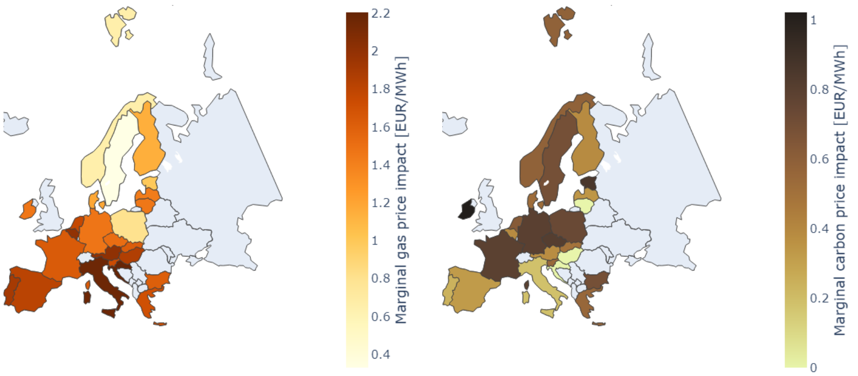
Following our guiding research questions we now look at the following results: First, we show the marginal impacts of gas and carbon prices on the individual electricity prices. Second, we determine the factors that drive the level of impact. Third, we analyze, to what extent the increase in electricity prices between the years 2019 and 2021 can be explained by the raise in gas and carbon prices.

4.1. Marginal impacts of gas and carbon prices on electricity price

The left panel of Figure 4 shows the marginal impacts of gas prices on the electricity price, i.e., the change in the electricity price induced by a gas price increase of 1 €per MWh of thermal energy (all coefficients and standard errors are shown in Tables A.1 to A.3 in Appendix A). We find that in all countries the impact is positive. However, the differences are substantial across countries, i.e., the impact ranges from 0.3 €/MWh in Sweden to 2.2 €/MWh in Italy.

Let's put these numbers in perspective: In equation (3) we established that whenever gas is the marginal technology, the expected impact corresponds to the inverse of the thermal heat efficiency of the marginal power plant. Given that the heat efficiency of gas generation mostly lies somewhere between 30-60% this would imply an increase of around 2-3€/MWh. Thus, in a gas-based electricity market such as Italy, an estimate at the lower bound of this range is expected, as gas is often but not always the marginal generator. In contrast, Sweden's power generation is carbon neutral. Thus, a low impact of the gas price on the electricity price is no surprise. A more systematic analysis of the drivers of these impacts for all countries follows in Section 4.3.

FIGURE 4. Marginal impacts on electricity prices



(a) Gas price impact (b) Carbon price impact

Notes: Regression results of our main model (see equation 4). The left panel shows the coefficient on the gas price (β_{2r}), the right panel shows the coefficient on the carbon price (β_{1r}). Standard errors are provided in Tables A.1 to A.3.

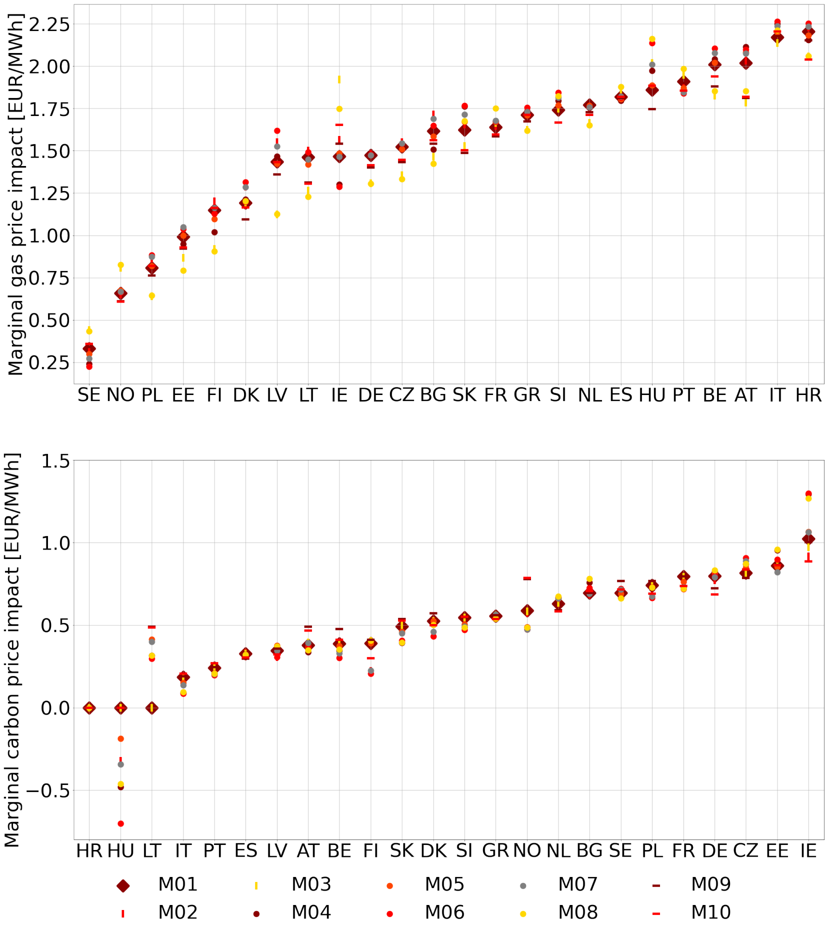
The right panel of Figure 4 shows the marginal impacts of carbon prices on the electricity price, i.e., the change in the electricity price induced by a carbon price increase of 1 € per ton of CO_2 (coefficients and standard errors are shown in Tables A.1 to A.3 in Appendix A)). The impacts are positive in all countries, except for Hungary, where the coefficient is not statistically significant. Again, there is a substantial range from from 0.2€/MWh in Italy and Portugal to 0.8-1.0€/MWh in Germany, Czech Republic, Estonia and Ireland.

Again, we put these results into perspective: As established in equation 2, the impact corresponds to the emission coefficient (emission per MWh of electricity production) of the marginal generator. These lie around 0.5 t/MWh for gas, 1.0 for coal and 1.2 for lignite. Consequently, for coal-based power markets such as Germany or the Czech Republic, an impact of the carbon price close to 1.0 would be expected. The power generation in Estonia is to a large extent based on oil shale and thus highly carbon intense, thus a large impact of the carbon price is very likely. Ireland's electricity generation is mostly gas-based, thus the high value is somewhat surprising. However, as there is little interconnection to other countries, there are few alternative options and it is likely that high prices of inefficient peak plants directly influence the electricity price. Again, a more systematic analysis of the drivers of these impacts for all countries follows in Section 4.3.

4.2. Robustness Checks

Figure 5 shows the coefficients of coal and carbon prices for all models. For the sake of clarity, the figures only show the coefficient without the standard deviation, furthermore statistically insignificant coefficients have been set to zero. All coefficients including standard errors as well as the respective R^2 for each model are shown in Tables B.4 to B.8 in Appendix B.

Figure 5. Robustness checks results



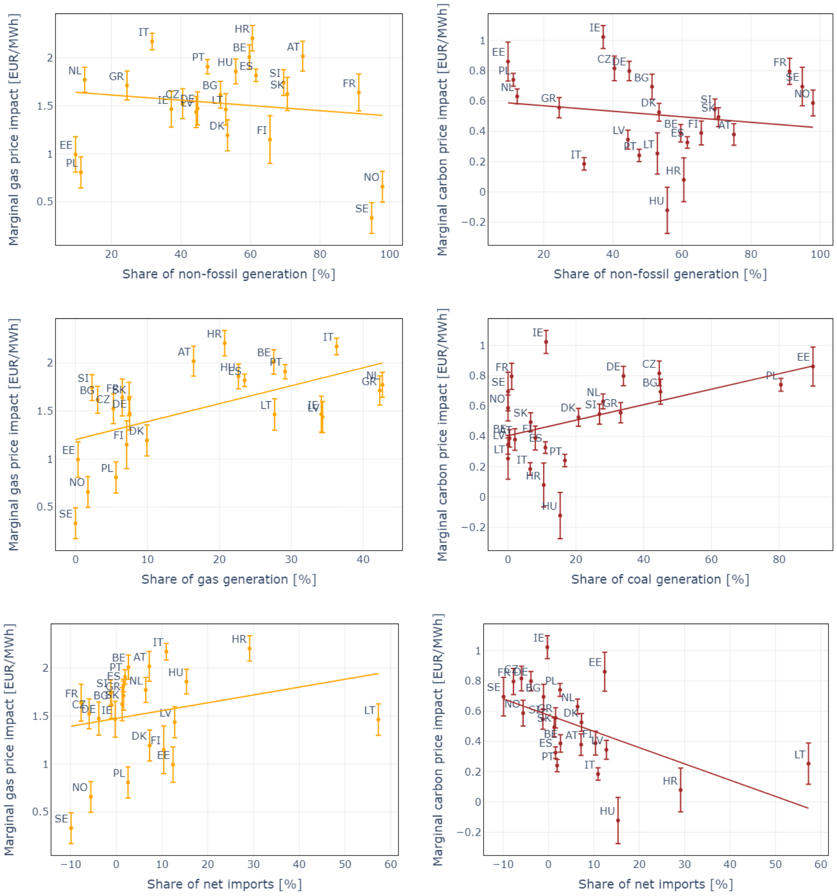
Notes: Detailed information on the individual models is provided in Table 2 and Section 3.3.

Regarding the robustness of our results we can draw the following conclusions: First, the results seem generally robust to the different specifications.

Second, the carbon price impact seems to be slightly affected by different temporal resolutions in the case of Lithuania, Finland, Norway and Ireland. This might be due to high hydro shares in Norway and Finland, and a high import share in Lithuania. For Ireland the possible reason is less obvious and needs to be further analyzed. In the case of Hungary we even observe negative values for the carbon price impact in the case of hourly resolution. This needs to be looked at in more detail.

Third, the estimated gas price impact slightly changes when we do not control for the coal price. It increases for most, but also decreases for some coun-

Figure 6. Drivers of gas and carbon price impacts on the electricity price



Notes: Non-fossil includes renewable, hydro and nuclear generation; net-import are calculated as imports minus exports; in Estonia we add the oil shale generation to the coal share as it is very carbon intense. Percentages are calculated over the whole sample period, i.e. from 2015 to 2021, by dividing the sum of a technology's production by the country's total power generation.

tries. Regarding changes due to different temporal resolution or fixed effects, again the largest variations can be observed for Norway, Ireland and Hungary.

4.3. What determines the impacts?

In Section 2.2 we established that the impact of fuel and carbon prices on the electricity price depends on the technology, heat efficiency, and carbon emissions of the marginal plant.

Thus, the average marginal gas price impact depends on (i) how often gas is the marginal technology and (ii) the heat efficiency of the marginal gas plants.

The average marginal carbon price impact, in turn, depends on (i) how often a fossil technology is marginal and (ii) the carbon emission coefficient of this marginal plant. As we do not observe the marginal power plants, we cannot directly assess whether our results verify the theory. However, in the following we use some observed market characteristics to assess the drivers that determine whether a country is more or less affected by changes in gas and carbon prices. To this end we look at the correlation of marginal gas and carbon price impacts with (i) the share of non-fossil generation, (ii) the share of gas and coal generation, and (iii) the import share.

NON-FOSSIL GENERATION——The uppermost panels of Figure 6 show that the impact of gas and carbon prices are slightly negatively correlated with the share of non-fossil generation, i.e., the higher the non-fossil generation, the lower the impact of gas and carbon prices on the electricity price. This negative correlation is expected as a higher non-fossil generation share reduces the chances of a fossil plant being marginal. In fact, the electricity price of an isolated fossil-free power market, would not be affected at all by gas and carbon prices. However, currently, even countries without fossil generation on their own, such as Sweden, are affected by changes in gas and carbon prices through their cross-border trade.

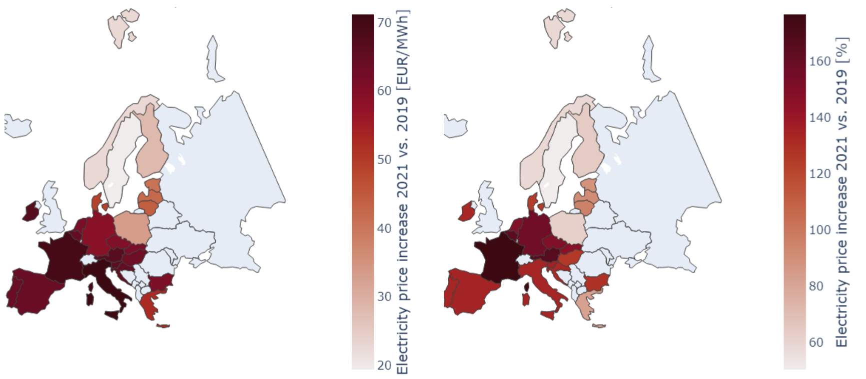
GAS AND COAL GENERATION——The middle panels of Figure 6 show that the impact of gas prices is positively correlated with the gas share; and the impact of the carbon price is positively correlated with the coal share. In case of the gas price impact it is straightforward to see that a country with a higher gas share is likely to be more heavily affected by changes in the gas price. In case of the carbon price impact, it is basically the emission factor that determines the impact. As emissions are generally highest for coal generation (the figure includes both, hard coal and lignite), a high coal share increases the possibility that a carbon intensive coal plant is marginal and leads to a high carbon price impact.

IMPORTS——The lowest panels of Figure 6 show that the impact of gas prices is positively, and the impact of carbon prices is negatively correlated with the net import share of a country. In fact, the role of imports is ambiguous. On the one hand, countries that import can to some extent choose their imports and try to minimize their electricity cost by buying the cheapest possible imports. Thus, to some extent they can avoid higher fuel and carbon cost. On the other hand, they might need to rely on imports to fulfill their demand. Thus, at some times they need to import electricity even at high cost.

4.4. Main drivers of the increase in electricity prices 2021

Between 2019 and 2021 electricity prices have risen substantially all over Europe, peaking at the end of 2021. In terms of yearly average prices, the increase was lowest in Sweden with less than 20 €/MWh and largest in Italy

Figure 7. Price increase from 2019 to 2021



(a) Absolute difference

(b) Relative difference

Notes: The absolute difference (left panel) shows the increase in yearly average electricity from 2019 to 2021. The percentage increase (right panel) shows the relative increase based on the year 2019.

with around 70€/MWh (Figure 7).[8] Generally, we find a lower increase in Scandinavia (SE, NO, FI, DK), Poland and the Baltic states (EE, LV, LT), a slightly larger increase in Eastern European states (CZ, BG, SK, HU) as well as Greece, Germany and Holland, and the highest increase in the rest of western Europe.

To assess to what extent this increase can be attributed to different determinants of the electricity price, we use our estimation results as well as the differences in prices and electricity generation between the years 2019 and 2021:

$$\begin{aligned}\Delta p_r^{ele} = \beta_{1r}\Delta p^{EUA} + \beta_{2r}\Delta p^{gas} + \beta_{3r}\Delta p^{coal} \\ \gamma_{1r}\Delta d_r + \gamma_{2r}\Delta r_r + \gamma_{3r}\Delta h_r + \gamma_{4r}\Delta n_r + \mathrm{R}_r\,,\end{aligned} \tag{5}$$

where R describes the residual and Δ describes the differences in yearly means (e.g. $\Delta p_r^{ele} = \overline{p}^{ele}_{2021,r} - \overline{p}^{ele}_{2019,r}$). Thus we calculate the total gas price impact per country r as $\beta_{2r}\Delta p^{gas}$, and the carbon price impact as $\beta_{1r}\Delta p^{eua}$.

Figures C.1 to C.3 in Appendix C show these results for each country individually. We can draw the following main conclusions. First, our results confirm that the electricity price increases can largely be explained by the higher gas and carbon prices. Second, the impact of the gas price was substantially higher compared to the carbon price. Third, the impacts of coal prices as well as changes in load or non-fossil generation were very low between 2019 and

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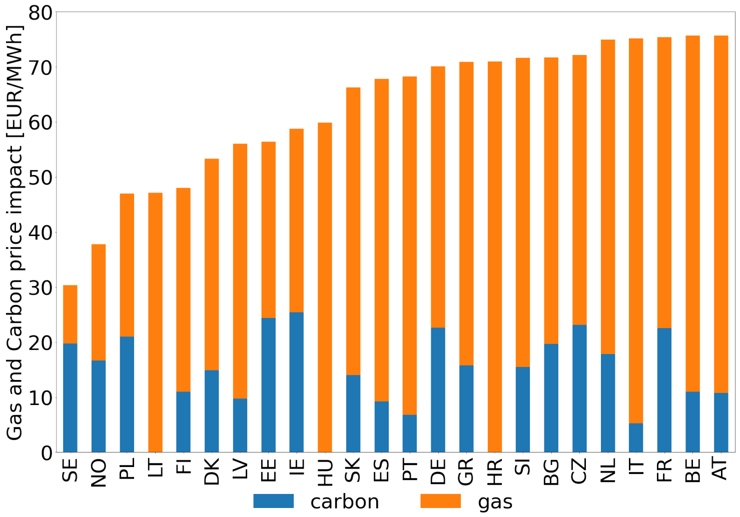
[8] Note that Italy consists of several different price zones. Here we report an (unweighted) average of the different price zones.

Figure 8. Impact of gas and carbon price increase on electricity price



Notes: The bars show the impacts of the gas and carbon price increases between 2019 and 2021 on the electricity prices; the calculation is described by equation (5).

2021. Fourth, the negative residual (R) in most countries indicate, that our calculations seem to slightly overestimate the total impact on the electricity prices.

Figure 8 compares the estimated gas and carbon price impacts across countries. We find that the combined effect varies between 20€/MWh in Sweden to more than 70€/MWh in the Netherlands, Italy, France, Belgium and Austria. The gas price impact alone ranges from 10€/MWh in Sweden to almost 70€/MWh in Italy. In comparison, the carbon price impact is lower but still substantial for some countries: It varies from around 5€/MWh in Italy[9] to more than 20€/MWh in Estonia and Ireland.

5. Conclusions

This paper uses a comprehensive data set of hourly electricity market data of 24 European countries to estimate the impact of gas and carbon prices on the electricity price for the years 2015 to 2021. We answer three main questions:

First, what is the marginal impact of gas and carbon prices on electricity prices? We find that the marginal impact of gas prices ranges from 0.3€/MWh in Sweden to 2.2€/MWh in Italy; while the marginal impact of carbon prices range from 0.2€/MWh in Italy and Portugal to 0.8-1.0€/MWh in Germany, Czech Republic, Estonia and Ireland.

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[9] For Lithuania, Hungary and Croatia we did not find any statistically significant impact.

Second, what determines the size of these impacts? The main drivers are the shares of gas and coal generation, respectively. I.e., countries with a high share of gas generation are more affected by changes in the gas price; while countries with a high share of coal generation are more affected by changes in the carbon price. Generally, a larger share of non-fossil generation decreases the impact of both, gas and carbon prices.

Thrid, to what extent were coal and gas prices responsible for the increase in electricity prices between the years 2019 and 2021? We find that the gas price increase was mostly responsible for the electricity price increase between 2019 and 2021. Our calculations show that in some countries the gas price lead to an increase in yearly average electricity prices of up to around 70€/MWh. In contrast, the increase that we can attribute to the carbon price increase only amounts to a maximum of around 25€/MWh.

Finally, our analysis contributes to the current debate on reasons and consequences of rising energy prices as it sheds light on the respective impacts of gas and carbon prices for 24 European power markets.

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Appendix A. Estimation results

Table A.1. Results main model (I)

	AT	BE	BG	CZ	DE	DK	EE	ES
p^{EUA}	0.38***	0.39***	0.69***	0.82***	0.80***	0.53***	0.86***	0.33***
	(0.07)	(0.06)	(0.08)	(0.08)	(0.06)	(0.06)	(0.13)	(0.04)
p^{gas}	2.02***	2.01***	1.62***	1.52***	1.47***	1.19***	0.99***	1.82***
	(0.16)	(0.13)	(0.14)	(0.16)	(0.17)	(0.16)	(0.18)	(0.07)
p^{coal}	-1.42**	-1.18**	-0.86	-1.08*	-1.04*	-0.03	-0.82	0.30
	(0.59)	(0.51)	(0.65)	(0.59)	(0.62)	(0.71)	(0.73)	(0.28)
d	3.95***	6.16***	3.72**	4.89***	1.08***	7.31***	17.13***	2.08***
	(0.81)	(0.51)	(1.56)	(0.63)	(0.08)	(1.37)	(3.54)	(0.17)
r	-4.73***	-9.87***	-21.39***	-13.29***	-1.34***	-9.44***	-87.66***	-2.62***
	(0.75)	(1.13)	(4.95)	(3.71)	(0.11)	(1.06)	(13.40)	(0.17)
n		-3.81***	-4.36*	-7.96***	-2.02***			-1.68***
		(0.49)	(2.31)	(1.36)	(0.45)			(0.56)
h	0.79	6.12	-17.07***	16.19***	1.11*		1392.35	-2.12***
	(0.51)	(6.41)	(4.00)	(4.93)	(0.67)		(1216.96)	(0.27)
R^2	0.89	0.88	0.85	0.86	0.89	0.81	0.73	0.94

Notes: Regression results of equation (4): d refers to demand, r, n and h to renewable, nuclear and hydro generation respectively. Heteroscedasticity-autocorrelation robust standard errors are shown in parentheses. *, **,***: Significant at the 10%, 5% and 1% levels, respectively.

Appendix B. Robustness Checks

TABLE A.2. Results main model (II)

	FI	FR	GR	HR	HU	IE	IT	LT
p^{EUA}	0.39***	0.80***	0.56***	0.08	-0.12	1.02***	0.18***	0.25*
	(0.08)	(0.09)	(0.07)	(0.14)	(0.15)	(0.08)	(0.04)	(0.14)
p^{gas}	1.15***	1.64***	1.71***	2.21***	1.86***	1.47***	2.17***	1.46***
	(0.25)	(0.19)	(0.15)	(0.13)	(0.13)	(0.19)	(0.09)	(0.16)
p^{coal}	-1.43	0.14	-0.58	-1.29	1.06**	1.80***	-0.20	-1.34*
	(0.94)	(0.73)	(0.59)	(0.90)	(0.54)	(0.50)	(0.37)	(0.73)
d	6.86***	1.67***	6.67***	27.25***	12.86***	3.52*	0.90***	3.59
	(1.12)	(0.18)	(0.81)	(4.67)	(1.73)	(1.93)	(0.08)	(2.43)
r	-19.02***	-2.73***	-10.79***	-9.53*	-22.67***	-12.65***	-2.39***	-54.68***
	(2.82)	(0.31)	(1.28)	(5.08)	(7.75)	(1.26)	(0.25)	(7.12)
n	-16.75***	-1.67***			-13.01***			
	(3.09)	(0.24)			(3.81)			
h	-12.69***	-0.97***		-7.74**	-10.88	41.72***	-0.20	34.07***
	(2.93)	(0.33)		(3.04)	(62.51)	(9.19)	(0.27)	(8.36)
R^2	0.63	0.90	0.91	0.92	0.89	0.88	0.96	0.73

Notes: Regression results of equation (4): d refers to demand, r, n and h to renewable, nuclear and hydro generation respectively. Heteroscedasticity-autocorrelation robust standard errors are shown in parentheses. *, **,***: Significant at the 10%, 5% and 1% levels, respectively.

TABLE A.3. Results main model (III)

	LV	NL	NO	PL	PT	SE	SI	SK
p^{EUA}	0.34***	0.63***	0.59***	0.74***	0.24***	0.70***	0.55***	0.49***
	(0.06)	(0.05)	(0.09)	(0.04)	(0.04)	(0.13)	(0.07)	(0.06)
p^{gas}	1.44***	1.77***	0.66***	0.81***	1.91***	0.33**	1.74***	1.62***
	(0.16)	(0.13)	(0.16)	(0.16)	(0.07)	(0.16)	(0.14)	(0.17)
p^{coal}	-1.98***	-0.69	0.93	-1.06*	0.26	0.69	0.03	-0.60
	(0.70)	(0.47)	(0.69)	(0.57)	(0.30)	(0.83)	(0.55)	(0.68)
d	23.01***	4.22***	2.19***	2.49***	6.73***	2.94***	20.57***	0.29
	(2.81)	(0.41)	(0.50)	(0.22)	(0.53)	(0.84)	(3.37)	(0.29)
r	-418.44***	-7.48***	-13.42***	-5.39***	-8.20***	-6.79***	-23.62	-32.18*
	(56.58)	(0.97)	(1.72)	(0.66)	(0.56)	(1.15)	(35.62)	(18.41)
n		-1.71				-0.37	-6.34*	0.42
		(1.98)				(0.83)	(3.54)	(2.18)
h	-19.81***	0.00	-0.67	-9.63**	-5.00***	-3.01***	-20.33***	-12.45***
	(2.47)	(0.00)	(0.41)	(4.50)	(0.60)	(1.04)	(3.47)	(3.31)
R^2	0.73	0.93	0.74	0.86	0.93	0.62	0.88	0.83

Notes: Regression results of equation (4): d refers to demand, r, n and h to renewable, nuclear and hydro generation respectively. Heteroscedasticity-autocorrelation robust standard errors are shown in parentheses. *, **,***: Significant at the 10%, 5% and 1% levels, respectively.

Table B.4. Results sensitivity analyses (I)

		M01	M02	M03	M04	M05	M06	M07	M08	M09	M10
AT	p_{eua}	0.38***	0.38***	0.39***	0.34***	0.36***	0.37***	0.39***	0.35***	0.49***	0.47***
		(0.07)	(0.07)	(0.08)	(0.02)	(0.03)	(0.02)	(0.02)	(0.03)	(0.10)	(0.09)
	p_{gas}	2.02***	2.03***	1.79***	2.12***	2.08***	2.10***	2.08***	1.85***	1.81***	1.82***
		(0.16)	(0.15)	(0.13)	(0.08)	(0.08)	(0.08)	(0.08)	(0.06)	(0.20)	(0.16)
	R^2	0.89	0.90	0.88	0.84	0.84	0.85	0.85	0.83	0.93	0.94
BE	p_{eua}	0.39***	0.33***	0.40***	0.35***	0.37***	0.30***	0.33***	0.35***	0.48***	0.41***
		(0.06)	(0.05)	(0.06)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.08)	(0.06)
	p_{gas}	2.01***	2.09***	1.83***	2.04***	2.02***	2.10***	2.08***	1.85***	1.88***	1.94***
		(0.13)	(0.13)	(0.11)	(0.07)	(0.07)	(0.06)	(0.07)	(0.05)	(0.12)	(0.11)
	R^2	0.88	0.88	0.88	0.80	0.80	0.80	0.81	0.79	0.93	0.93
BG	p_{eua}	0.69***	0.69***	0.74***	0.76***	0.71***	0.73***	0.69***	0.78***	0.70***	0.71***
		(0.08)	(0.07)	(0.08)	(0.05)	(0.05)	(0.05)	(0.05)	(0.04)	(0.08)	(0.08)
	p_{gas}	1.62***	1.71***	1.46***	1.51***	1.59***	1.65***	1.69***	1.42***	1.54***	1.56***
		(0.14)	(0.13)	(0.10)	(0.13)	(0.13)	(0.13)	(0.13)	(0.06)	(0.07)	(0.10)
	R^2	0.85	0.85	0.85	0.65	0.69	0.67	0.69	0.65	0.92	0.93
CZ	p_{eua}	0.82***	0.86***	0.81***	0.87***	0.85***	0.91***	0.89***	0.87***	0.79***	0.84***
		(0.08)	(0.07)	(0.09)	(0.04)	(0.04)	(0.03)	(0.03)	(0.04)	(0.11)	(0.11)
	p_{gas}	1.52***	1.55***	1.36***	1.51***	1.51***	1.54***	1.54***	1.33***	1.43***	1.45***
		(0.16)	(0.15)	(0.12)	(0.12)	(0.12)	(0.12)	(0.12)	(0.08)	(0.16)	(0.16)
	R^2	0.86	0.88	0.86	0.79	0.80	0.81	0.81	0.79	0.93	0.94
DE	p_{eua}	0.80***	0.77***	0.81***	0.82***	0.81***	0.80***	0.79***	0.83***	0.72***	0.69***
		(0.06)	(0.06)	(0.07)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.09)	(0.07)
	p_{gas}	1.47***	1.48***	1.31***	1.48***	1.47***	1.48***	1.47***	1.31***	1.40***	1.41***
		(0.17)	(0.17)	(0.13)	(0.12)	(0.12)	(0.12)	(0.12)	(0.08)	(0.16)	(0.14)
	R^2	0.89	0.90	0.89	0.84	0.84	0.84	0.84	0.83	0.94	0.94

Notes: Regression results of equation (4): Detailed information on the individual specifications is provided in Section 3.3. Heteroscedasticity-autocorrelation robust standard errors are shown in parentheses. *, **,***: Significant at the 10%, 5% and 1% levels, respectively.

TABLE B.5. Results sensitivity analyses (II)

		M01	M02	M03	M04	M05	M06	M07	M08	M09	M10
DK	p_{eua}	0.53***	0.45***	0.53***	0.50***	0.52***	0.43***	0.46***	0.50***	0.57***	0.50***
		(0.06)	(0.07)	(0.06)	(0.03)	(0.03)	(0.03)	(0.04)	(0.03)	(0.07)	(0.09)
	p_{gas}	1.19***	1.29***	1.19***	1.21***	1.20***	1.32***	1.29***	1.20***	1.09***	1.17***
		(0.16)	(0.17)	(0.09)	(0.14)	(0.15)	(0.14)	(0.15)	(0.08)	(0.19)	(0.20)
	R^2	0.81	0.82	0.81	0.72	0.73	0.73	0.74	0.72	0.89	0.90
EE	p_{eua}	0.86***	0.84***	0.86***	0.95***	0.85***	0.90***	0.82***	0.96***	0.86***	0.86***
		(0.13)	(0.11)	(0.13)	(0.06)	(0.06)	(0.06)	(0.06)	(0.06)	(0.17)	(0.14)
	p_{gas}	0.99***	1.04***	0.87***	0.95***	1.00***	1.04***	1.05***	0.79***	0.92***	0.93***
		(0.18)	(0.16)	(0.14)	(0.16)	(0.16)	(0.16)	(0.16)	(0.09)	(0.13)	(0.11)
	R^2	0.73	0.74	0.72	0.56	0.61	0.58	0.62	0.56	0.84	0.86
ES	p_{eua}	0.33***	0.33***	0.33***	0.32***	0.32***	0.31***	0.32***	0.32***	0.30***	0.30***
		(0.04)	(0.03)	(0.04)	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)	(0.06)	(0.05)
	p_{gas}	1.82***	1.83***	1.86***	1.80***	1.81***	1.81***	1.82***	1.88***	1.81***	1.82***
		(0.07)	(0.07)	(0.04)	(0.06)	(0.06)	(0.06)	(0.06)	(0.04)	(0.07)	(0.07)
	R^2	0.94	0.94	0.94	0.91	0.91	0.91	0.92	0.91	0.97	0.97
FI	p_{eua}	0.39***	0.22***	0.40***	0.40***	0.39***	0.21***	0.23***	0.41***	0.41***	0.30***
		(0.08)	(0.07)	(0.08)	(0.04)	(0.04)	(0.05)	(0.05)	(0.04)	(0.10)	(0.07)
	p_{gas}	1.15***	1.20***	0.92***	1.02***	1.10***	1.13***	1.16***	0.91***	1.16***	1.16***
		(0.25)	(0.21)	(0.19)	(0.17)	(0.17)	(0.16)	(0.17)	(0.09)	(0.22)	(0.17)
	R^2	0.63	0.67	0.62	0.50	0.53	0.55	0.57	0.50	0.75	0.78
FR	p_{eua}	0.80***	0.77***	0.79***	0.73***	0.76***	0.72***	0.73***	0.72***	0.79***	0.74***
		(0.09)	(0.09)	(0.09)	(0.04)	(0.04)	(0.04)	(0.04)	(0.03)	(0.13)	(0.14)
	p_{gas}	1.64***	1.65***	1.66***	1.67***	1.67***	1.68***	1.68***	1.75***	1.58***	1.60***
		(0.19)	(0.20)	(0.12)	(0.10)	(0.10)	(0.10)	(0.10)	(0.06)	(0.21)	(0.15)
	R^2	0.90	0.90	0.90	0.84	0.84	0.85	0.85	0.84	0.93	0.94

Notes: Regression results of equation (4): Detailed information on the individual specifications is provided in Section 3.3. Heteroscedasticity-autocorrelation robust standard errors are shown in parentheses. *, **,***: Significant at the 10%, 5% and 1% levels, respectively.

TABLE B.6. Results sensitivity analyses (III)

		M01	M02	M03	M04	M05	M06	M07	M08	M09	M10
GR	p_{eua}	0.56***	0.55***	0.56***	0.54***	0.56***	0.55***	0.56***	0.54***	0.56***	0.54***
		(0.07)	(0.06)	(0.07)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.12)	(0.11)
	p_{gas}	1.71***	1.74***	1.62***	1.73***	1.71***	1.75***	1.73***	1.62***	1.67***	1.71***
		(0.15)	(0.13)	(0.11)	(0.08)	(0.08)	(0.07)	(0.08)	(0.05)	(0.12)	(0.11)
	R^2	0.91	0.91	0.91	0.82	0.83	0.83	0.83	0.82	0.93	0.94
HR	p_{eua}	0.08	-0.04	-0.02	0.02	0.06	-0.14	-0.09	-0.04	0.12	0.08
		(0.14)	(0.15)	(0.12)	(0.08)	(0.08)	(0.09)	(0.09)	(0.07)	(0.11)	(0.10)
	p_{gas}	2.21***	2.23***	2.06***	2.16***	2.18***	2.25***	2.24***	2.06***	2.15***	2.04***
		(0.13)	(0.11)	(0.11)	(0.09)	(0.09)	(0.10)	(0.10)	(0.07)	(0.10)	(0.12)
	R^2	0.92	0.93	0.92	0.86	0.87	0.86	0.87	0.86	0.96	0.96
HU	p_{eua}	-0.12	-0.32**	-0.11	-0.48***	-0.19***	-0.70***	-0.34***	-0.46***	0.03	-0.20
		(0.15)	(0.15)	(0.15)	(0.04)	(0.04)	(0.04)	(0.05)	(0.04)	(0.21)	(0.24)
	p_{gas}	1.86***	2.00***	2.02***	1.97***	1.89***	2.14***	2.01***	2.16***	1.75***	1.88***
		(0.13)	(0.13)	(0.10)	(0.08)	(0.08)	(0.07)	(0.08)	(0.05)	(0.17)	(0.15)
	R^2	0.89	0.90	0.88	0.79	0.82	0.81	0.83	0.79	0.92	0.93
IE	p_{eua}	1.02***	0.92***	0.97***	1.29***	1.06***	1.30***	1.06***	1.27***	1.00***	0.89***
		(0.08)	(0.07)	(0.07)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.11)	(0.07)
	p_{gas}	1.47***	1.56***	1.92***	1.30***	1.49***	1.29***	1.46***	1.75***	1.54***	1.65***
		(0.19)	(0.17)	(0.12)	(0.08)	(0.08)	(0.08)	(0.08)	(0.05)	(0.19)	(0.14)
	R^2	0.88	0.89	0.88	0.69	0.74	0.70	0.75	0.69	0.94	0.95
IT	p_{eua}	0.18***	0.17***	0.19***	0.09***	0.15***	0.08***	0.14***	0.10***	0.19***	0.21***
		(0.04)	(0.04)	(0.04)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.05)	(0.05)
	p_{gas}	2.17***	2.22***	2.14***	2.25***	2.20***	2.26***	2.24***	2.21***	2.18***	2.21***
		(0.09)	(0.08)	(0.06)	(0.06)	(0.06)	(0.06)	(0.06)	(0.03)	(0.07)	(0.06)
	R^2	0.96	0.96	0.96	0.93	0.93	0.93	0.93	0.93	0.98	0.98

Notes: Regression results of equation (4): Detailed information on the individual specifications is provided in Section 3.3. Heteroscedasticity-autocorrelation robust standard errors are shown in parentheses. *, **,***: Significant at the 10%, 5% and 1% levels, respectively.

Table B.7. Results sensitivity analyses (IV)

		M01	M02	M03	M04	M05	M06	M07	M08	M09	M10
LT	p_{eua}	0.25*	0.23*	0.23*	0.32***	0.41***	0.30***	0.40***	0.32***	0.49**	0.48***
		(0.14)	(0.12)	(0.13)	(0.05)	(0.05)	(0.05)	(0.05)	(0.05)	(0.20)	(0.18)
	p_{gas}	1.46***	1.50***	1.27***	1.45***	1.42***	1.49***	1.45***	1.23***	1.31***	1.31***
		(0.16)	(0.14)	(0.15)	(0.15)	(0.15)	(0.15)	(0.15)	(0.09)	(0.14)	(0.10)
	R^2	0.73	0.74	0.72	0.59	0.61	0.60	0.63	0.58	0.84	0.86
LV	p_{eua}	0.34***	0.31***	0.37***	0.35***	0.38***	0.31***	0.35***	0.37***	0.36***	0.32***
		(0.06)	(0.06)	(0.07)	(0.03)	(0.03)	(0.03)	(0.03)	(0.04)	(0.06)	(0.06)
	p_{gas}	1.44***	1.55***	1.12***	1.47***	1.42***	1.62***	1.53***	1.13***	1.36***	1.43***
		(0.16)	(0.14)	(0.15)	(0.14)	(0.15)	(0.14)	(0.15)	(0.08)	(0.12)	(0.08)
	R^2	0.73	0.75	0.72	0.57	0.61	0.60	0.63	0.55	0.85	0.86
NL	p_{eua}	0.63***	0.63***	0.64***	0.67***	0.66***	0.67***	0.66***	0.67***	0.59***	0.58***
		(0.05)	(0.05)	(0.05)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.07)	(0.07)
	p_{gas}	1.77***	1.76***	1.66***	1.76***	1.77***	1.76***	1.76***	1.65***	1.73***	1.71***
		(0.13)	(0.13)	(0.10)	(0.07)	(0.08)	(0.08)	(0.08)	(0.05)	(0.13)	(0.11)
	R^2	0.93	0.93	0.93	0.85	0.86	0.85	0.86	0.85	0.96	0.96
NO	p_{eua}	0.59***	0.57***	0.58***	0.49***	0.49***	0.47***	0.47***	0.48***	0.78***	0.79***
		(0.09)	(0.08)	(0.08)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.17)	(0.16)
	p_{gas}	0.66***	0.65***	0.81***	0.67***	0.68***	0.66***	0.67***	0.83***	0.61***	0.61***
		(0.16)	(0.15)	(0.09)	(0.08)	(0.08)	(0.08)	(0.08)	(0.04)	(0.21)	(0.19)
	R^2	0.74	0.74	0.73	0.68	0.69	0.69	0.69	0.68	0.80	0.81
PL	p_{eua}	0.74***	0.68***	0.75***	0.72***	0.73***	0.67***	0.68***	0.73***	0.77***	0.69***
		(0.04)	(0.04)	(0.04)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.07)	(0.06)
	p_{gas}	0.81***	0.86***	0.64***	0.82***	0.82***	0.88***	0.88***	0.64***	0.76***	0.82***
		(0.16)	(0.15)	(0.12)	(0.11)	(0.11)	(0.11)	(0.11)	(0.06)	(0.15)	(0.13)
	R^2	0.86	0.87	0.85	0.73	0.74	0.75	0.76	0.73	0.92	0.93

Notes: Regression results of equation (4): Detailed information on the individual specifications is provided in Section 3.3. Heteroscedasticity-autocorrelation robust standard errors are shown in parentheses. *, **,***: Significant at the 10%, 5% and 1% levels, respectively.

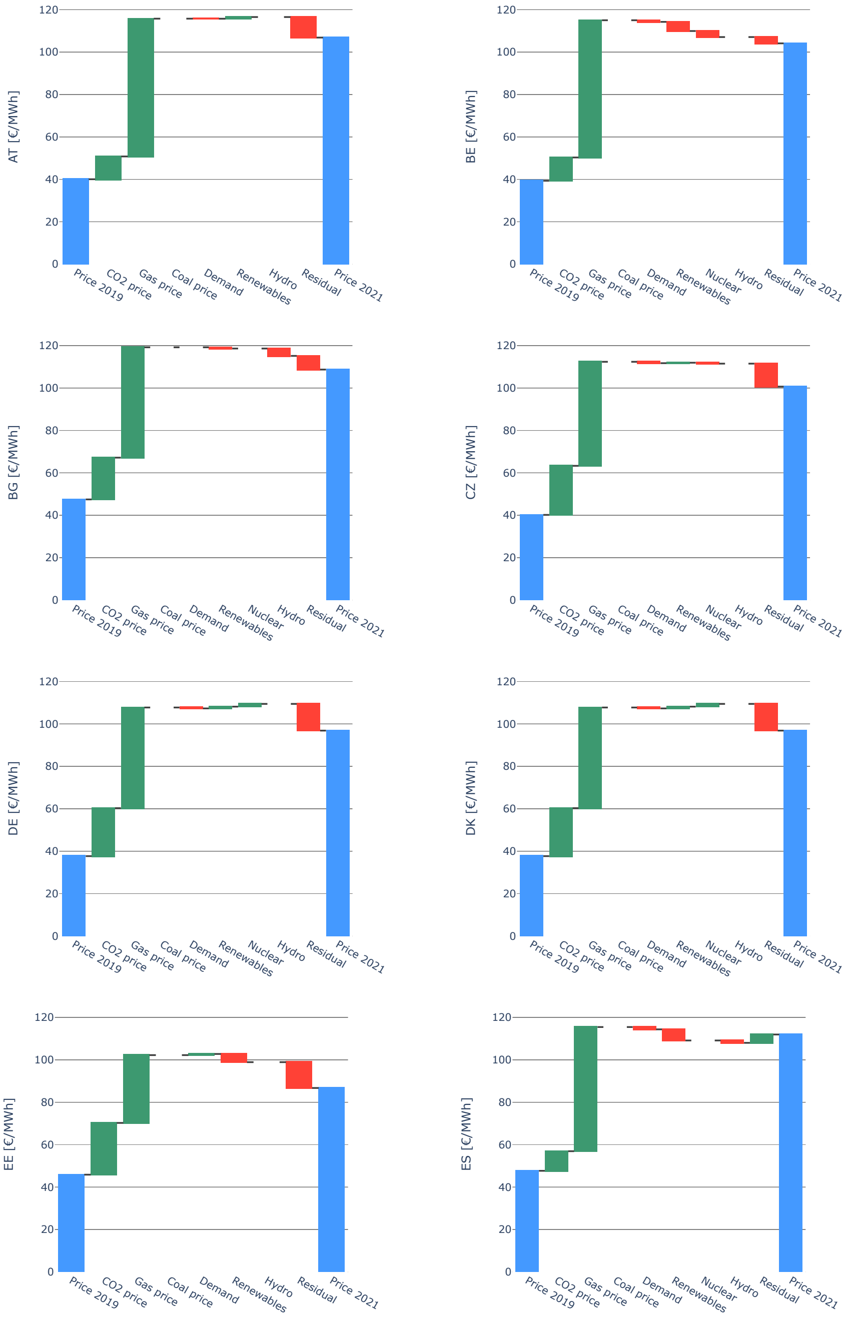
TABLE B.8. Results sensitivity analyses (V)

		M01	M02	M03	M04	M05	M06	M07	M08	M09	M10
PT	p_{eua}	0.24***	0.25***	0.24***	0.21***	0.21***	0.20***	0.20***	0.21***	0.24***	0.27***
		(0.04)	(0.04)	(0.04)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.05)	(0.04)
	p_{gas}	1.91***	1.87***	1.95***	1.86***	1.87***	1.84***	1.85***	1.98***	1.90***	1.85***
		(0.07)	(0.07)	(0.04)	(0.07)	(0.07)	(0.07)	(0.07)	(0.04)	(0.08)	(0.06)
	R^2	0.93	0.93	0.93	0.88	0.89	0.89	0.89	0.88	0.97	0.97
SE	p_{eua}	0.70***	0.69***	0.70***	0.66***	0.69***	0.72***	0.72***	0.66***	0.77***	0.72***
		(0.13)	(0.12)	(0.12)	(0.04)	(0.04)	(0.04)	(0.04)	(0.04)	(0.18)	(0.16)
	p_{gas}	0.33**	0.32**	0.44***	0.24**	0.30***	0.22**	0.27***	0.43***	0.34**	0.36***
		(0.16)	(0.15)	(0.11)	(0.10)	(0.10)	(0.09)	(0.09)	(0.05)	(0.16)	(0.13)
	R^2	0.62	0.63	0.61	0.54	0.56	0.57	0.58	0.53	0.70	0.72
SI	p_{eua}	0.55***	0.54***	0.55***	0.48***	0.50***	0.47***	0.49***	0.48***	0.55***	0.55***
		(0.07)	(0.06)	(0.07)	(0.03)	(0.03)	(0.03)	(0.02)	(0.03)	(0.10)	(0.08)
	p_{gas}	1.74***	1.77***	1.75***	1.80***	1.77***	1.84***	1.82***	1.82***	1.67***	1.67***
		(0.14)	(0.13)	(0.09)	(0.08)	(0.08)	(0.08)	(0.08)	(0.05)	(0.16)	(0.14)
	R^2	0.88	0.89	0.88	0.80	0.82	0.81	0.82	0.80	0.93	0.94
SK	p_{eua}	0.49***	0.49***	0.50***	0.39***	0.46***	0.41***	0.45***	0.40***	0.54***	0.53***
		(0.06)	(0.06)	(0.06)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.09)	(0.08)
	p_{gas}	1.62***	1.65***	1.53***	1.76***	1.67***	1.77***	1.71***	1.68***	1.49***	1.50***
		(0.17)	(0.17)	(0.12)	(0.11)	(0.11)	(0.11)	(0.11)	(0.07)	(0.20)	(0.18)
	R^2	0.83	0.83	0.82	0.71	0.75	0.73	0.76	0.71	0.92	0.93

*Notes:*Regression results of equation (4): Detailed information on the individual specifications is provided in Section 3.3. Heteroscedasticity-autocorrelation robust standard errors are shown in parentheses. *, **,***: Significant at the 10%, 5% and 1% levels, respectively.

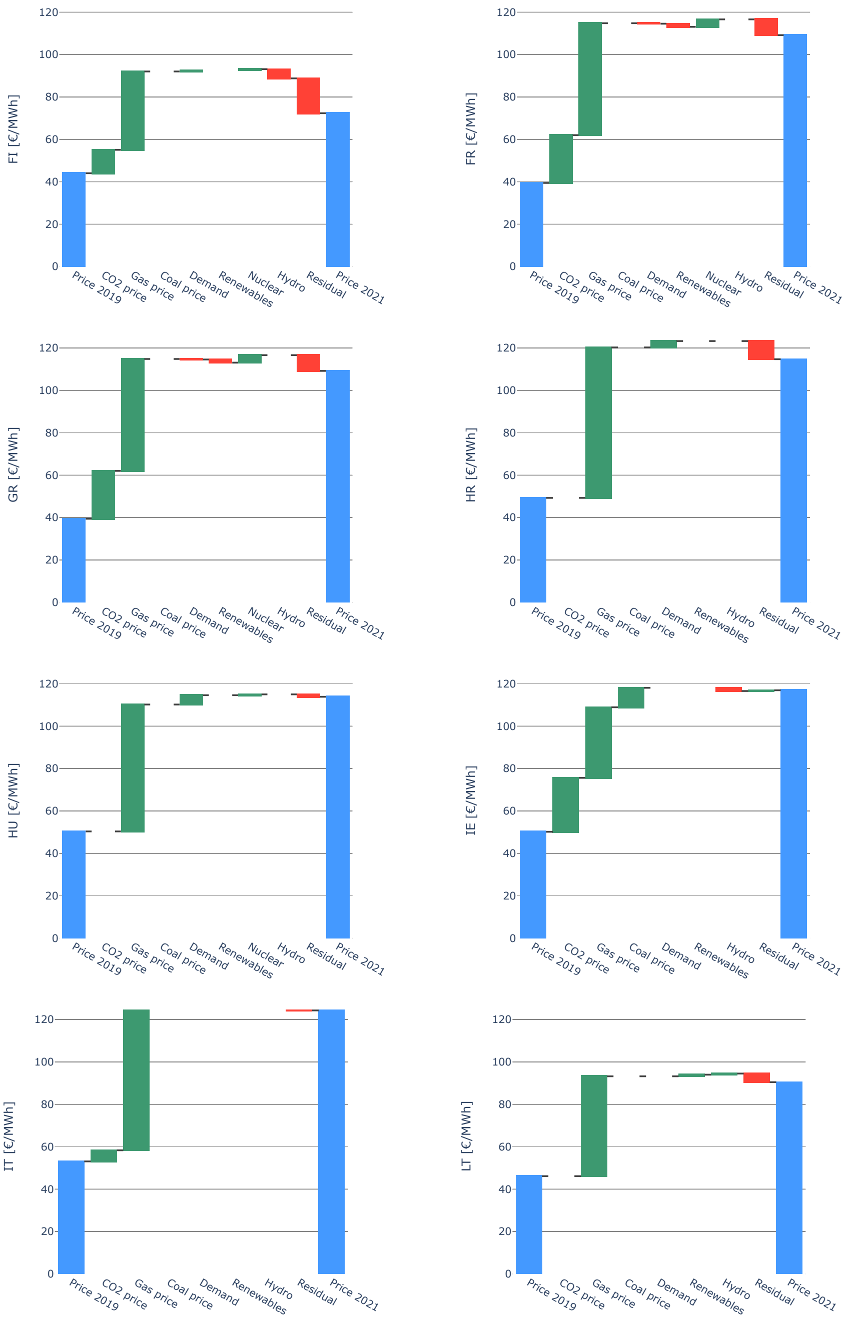
Appendix C. Decomposition of price impacts

Figure C.1. Decomposition of price impacts



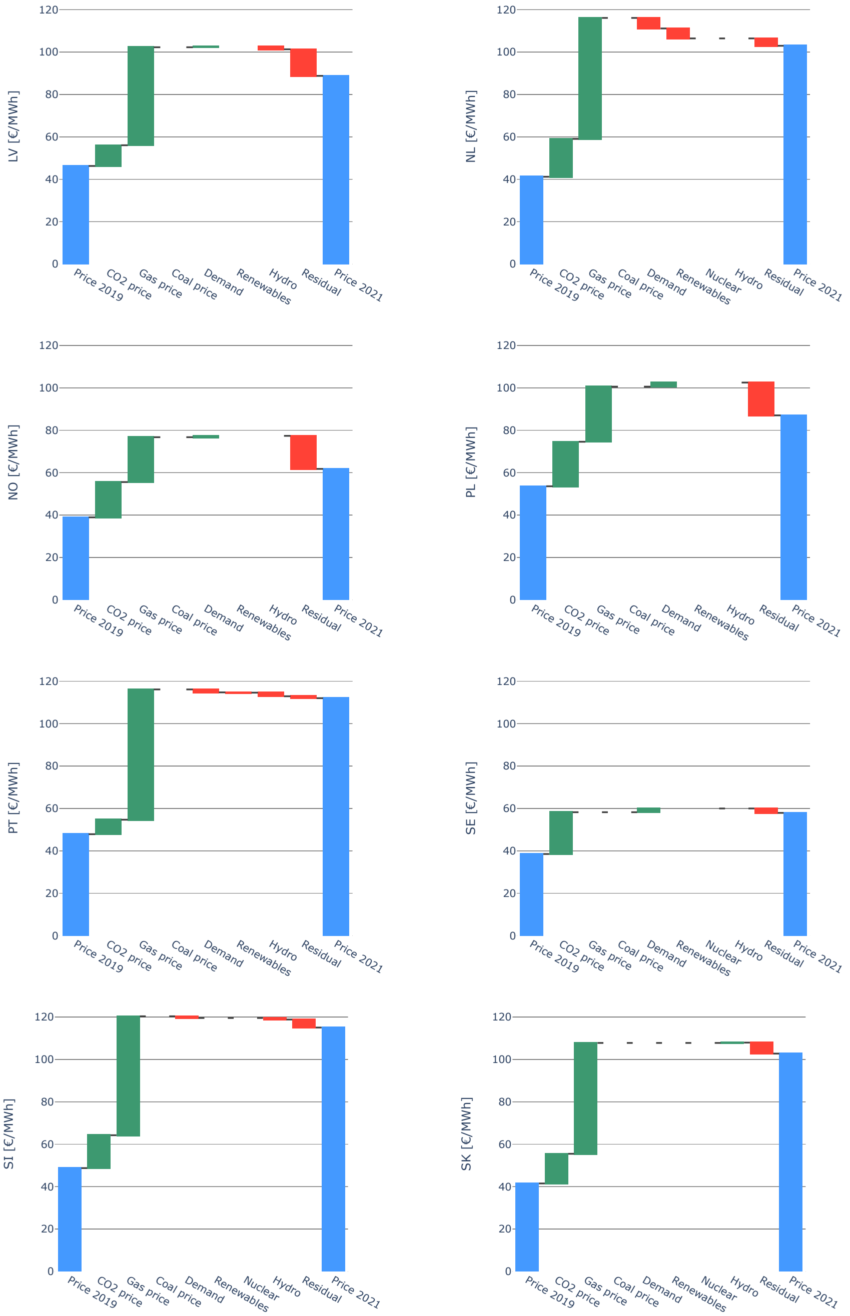
Notes: Decomposition of individual impacts that drive price difference between 2019 and 2021 as described by equation 5.

FIGURE C.2. Decomposition of price impacts



Notes: Decomposition of individual impacts that drive price difference between 2019 and 2021 as described by equation 5.

Figure C.3. Decomposition of price impacts



Notes: Decomposition of individual impacts that drive price difference between 2019 and 2021 as described by equation 5.