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Cross-country Spillovers of Renewable Energy Promotion – The Case of Germany

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Cross-country Spillovers of Renewable Energy Promotion - The Case of Germany

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Abstract

Electricity generation based on renewable energy (RE) sources such as wind and solar replace the most expensive generators that often rely on fossil fuels. In response to RE promotion, wholesale electricity prices and carbon emissions are therefore expected to decrease. In interconnected electricity systems, this so-called merit-order effect stimulates a change in electricity trade flows. Therefore, conventional generation and prices in neighboring countries are also likely to decrease. The impact of these trade reactions on carbon offsets is ambiguous and depends on installed generation and interconnector capacities. Moreover, the cross-border merit-order effect causes opposing effects on consumers and producers: Generators' profits decline, while consumers benefit from lower electricity costs and an increase in the consumer surplus. Using a rich data set of hourly technology-specific generation and wholesale market price data for ten central European countries, we estimate the domestic and cross-border impacts of German RE for the years 2015 to 2020. We find that German RE generation offset 79 to 113 $MtCO_2$ per year. The major emission effect took place in Germany (64 - 99 $MtCO_2$). The average cost of emission offset of 212 to 321 €/t were almost entirely borne by German market participants. Neighboring countries do not bear costs, but a significant shift from producer to consumer rents is observed.

Keywords: Renewable promotion, Electricity prices, Merit-order effect, Cross-border impacts, Carbon emissions
JEL: Q41, Q42, Q58

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1. Introduction

To combat climate change and limit global warming well below 2 degrees, a soon and drastic reduction of greenhouse gas emissions is needed. Decarbonizing the economy, the electricity sector is of particular importance as it is a major emitter of CO_2; and carbon mitigation strategies for mobility and heating largely rely on electrification, e.g., electro-mobility or heat pumps. Regulations to mitigate these emissions come in two major forms: Carbon pricing and renewable energy (RE) support (RES). In the European Union (EU), the European Emission Trading System (EU ETS) imposes a uniform price on carbon emissions of electricity generation. In contrast, RES policies are delegated to member states leading to different regulatory approaches and, in particular, subsidies for RE generation differing across countries and technologies. However, electricity generation does not occur in isolation as the European electricity grid is heavily interconnected.

These trade possibilities influence the impact of RES. Due to the low marginal cost structure of RE generation, domestic prices fall with the increase in RE generation (merit-order effect). In an interconnected electricity system this price decrease likely stimulates net-exports to neighboring countries leading to two major consequences: First, domestic renewable replace generation not only in the home but also in neighboring markets. RES therefore induces a cross-border abatement effect. Second, prices in neighboring countries are likely to decrease as well. This cross-border merit-order effect causes opposing effects on consumers and producers in neighboring countries. On the one hand, the price decrease leads to a decline of generators' profits. On the other hand, consumers benefit from decreasing prices through an increase in the consumer surplus. This implies that unilateral RES policies, which are usually paid for by the consumers within the country itself, also impact neighboring electricity markets.

In this article, we empirically study these effects for Germany and its neighbors. Relying on a rich data set of hourly technology-level generation, demand and prices for the period 2015 to 2020, we calculate the emission effects and distributional impacts of the large increase of German RE generation. Specifically, we pose three main questions: What was the impact of German RE generation on the offset of carbon emissions in Germany and its neighbors?[1] What were the average program cost per emission offset? What was the impact on electricity prices and how did it affect consumers' electricity cost and producers' profits in domestic and surrounding electricity markets?

We choose Germany as it is centrally located in Europe, well connected to its neighbors, and produces a high amount of RE. From 2010 to 2020, German wind and solar production increased from 38 to 131 TWh and 11 to 51 TWh, respectively (AG Energiebilanzen, 2021). Moreover, with a total transmission capacity of more than 20 GW, Germany (DE) is well connected to its neighbors. We analzye impacts on Austria (AT), Belgium (BE), Switzerland (CH), Czech Republic (CZ), Denmark (DK), France (FR), The Netherlands (NL), Poland (PL), and Sweden (SE).[2]

Our main findings are as follows: First, we find that German RE production offset on average 79 to 113 $MtCO_2$ per year in the period from 2015 to 2020. The major part (80-90%) occurred domestically. Around one third of German RE production is exported to neighboring countries, stimulating annual carbon offsets of 15 to 113 $MtCO_2$ in neighboring countries. This impact is rather divers across neighbors. The major part of foreign abatement took place in the Czech Republic and the Netherlands, where electricity markets are characterized by a large share of fossil generation. In the remaining countries the emission offset is relatively small as these countries are either largely characterized by carbon neutral generation assets (Austria, France and Sweden) or have very limited

[1] Due to the EU ETS the decrease of carbon emissions through RE generation is at least partly offset as the overall emission target is constant. Due to the Market Stability Reserve (MSR) at least part of the emission decrease in that period is translated into emission abatement, i.e., a decrease of the number of allowances under the EU ETS (Perino, 2018).

[2] ISO 3166-2 codes are used to abbreviate country names.

interconnector capacities to Germany (Poland and Belgium).

Second, these results of our core estimation are robust to a large set of alternative specifications. Only the re-sampling of our data set to weekly (instead of hourly) values leads to a substantially higher carbon offset. This can be explained by the behavior of hydro power plants: While at the hourly level RE replace a substantial amount of hydro generation, it is likely that in the case of reservoirs and pump-storage plants, this generation is shifted to another hour of the same week. This increase of hydro generation in other hours then replaces fossil generation and leads to an additional offset of carbon emissions. This effect cannot be observed at an hourly level, but is only accounted for when re-sampling the data to weekly values.

Third, RE generation decreased German electricity prices by 14 €/MWh on average. The cross-border merit-order effect of German RE is smaller, but nevertheless substantial for some countries: Prices in the Czech Republic and Denmark decrease around 10 €/MWh (23%), in all other countries except for Poland, prices decrease by 6 to 13%. Only in Poland, the price effect is with less than one percent very low - again this is due to very limited trade capacities.

Fourth, in surrounding countries German RES schemes leads to a decrease in conventional generators' profits and to an increase in the consumer surplus. The overall effect is rather modest. In net-importing countries, the increase in consumers' benefits exceeds the decrease in producers' profits, leading to a slight net benefit from German RE. In contrast, in net-exporting countries German RE induce a slight net loss.

Fifth, the average program costs add up to 212 to 321 €/tCO_2 and are almost entirely borne by German market participants. As these costs mainly consist of the refinancing surcharge of RE promotion, German consumers carry the major financial burden with about two third of total costs—although the costs of purchasing electricity on the wholesale market decrease. German producers, in contrast, bear about one third of total costs.

We contribute to the literature in three important ways. First, most studies concentrate either on the generation and emission or price impacts of RE generation. Combining both of these effects allows us to estimate the impact of RE generation on producers profits and consumers' cost of electricity not only in Germany but also in neighboring countries. We thus contribute to the literature by extending Abrell et al. (2019) to include cross-border effects of German RE promotion.

Second, We contribute to the literature on empirically estimating the environmental effectiveness of RE generation. Most of these studies (e.g. Cullen, 2013; Novan, 2015; Abrell et al., 2019; Gugler et al., 2021) concentrate on the domestic emission offset. In the US context, Callaway et al. (2018) estimate the spatial variation of marginal emission offsets of RE generation by region. Fell et al. (2021) and LaRiviere & Lu (2020) estimate the impact of grid congestion on the environmental effectiveness of wind power in Texas and the Midcontinent Independent Market Operator (MISO). Most similar to our work, Schnaars (2019) estimates the impact of German solar and wind power on domestic generation and export flows. Whereas Schnaars (2019) estimates the impact of RE generation on export flows, we directly estimate the impact of RE on generation by fuel source in neighboring countries. We contribute to this literature by providing an assessment of the total emission offset of German RE generation, i.e., the impact on emissions in Germany and its neighbors.

Third, we contribute to the literature estimating the decreasing price effect of RE promotion (merit-order effect). Most studies (e.g. Wuerzburg et al., 2013; Cludius et al., 2014; Abrell et al., 2019) concentrate on the domestic price effect of RE promotion. Phan & Roques (2015) and Haxhimusa (2018) analyze the cross-border merit-order effect for the case of German RE and French price levels. Likewise, Gugler & Haxhimusa (2019) look at price convergence between Germany and France. We complement the current literature providing the total merit-order effect of German RE, i.e., we estimate the domestic as well as cross-border price effect for Germany and its neighbors.

The remainder of this paper proceeds as follows. In the next section, we present some background on electricity markets in Germany and its neighbors, as well as data sources and construction. In Section 3 we present our estimation strategy. Sections 4, 5, and 6 show the results and Section 7 concludes.

2. Context and Data

In its *2020 climate & energy package*, the EU set a target to provide 20% of energy from renewables. The current target—specified in the *2030 climate & energy framework*—is to reach a share of 32% of RE by 2030. To increase their share of RE generation, all European countries have implemented RES schemes. While these schemes significantly differ in the type and magnitude of subsidies, they have induced substantial changes in many European electricity markets.

Next to the developments in the electriciy markets themselves, also the data availability has increased in recent years. Since 2015, the European Network of Transmission System Operators for Electricity (ENTSO-E) transparency platform[3] provides hourly data on electricity generation per technology and country, as well as wholesale market prices. Our analysis makes use of this rich set of data, which we complement with daily data on fuel and carbon prices as well as country-specific temperatures. In the following, we provide an overview of central European electricity markets, their interconnections, and how RE generation has recently developed.

Renewable energy generation—For central European countries, RE generation increased by about 60% between 2015 and 2020 (Table 1). In absolute terms, the largest increase is observed in Germany. In 2020, the country produced 176 TWh of wind and solar energy, which is more than all its neigbors together. Due to Germany's central location and the transmission infrastructure (see Figure 1), the large amount of German RE generation likely affects electricity trade and with that neighbors' electricity generation, carbon emissions, and prices.

Electricity trade—German RE impacts neighboring countries through a change in electricity flows. Germany has interconnectors to Austria (AT), Switzerland (CH), Czech Rebublic (CZ), Denmark (DK), France (FR), Netherlands (NL), Poland (PL) and Sweden (SE) (Figure 1).[4] We also include Belgium (BE) in our analysis, although no direct connection to Germany exists, but only

[3] https://transparency.entsoe.eu/

[4] In Spring 2021, *GreenLink* a direct current connection between Germany and Norway became operational.

Table 1. Wind and solar generation by country [TWh]

	DE	AT	BE	CZ	DK	FR	NL	PL	SE	total
2015	111.95	5.73	8.02	2.83	14.25	26.62	6.99	10.61	16.41	203.69
2016	110.26	6.25	7.48	2.62	12.64	27.51	4.43	11.61	15.60	198.79
2017	138.55	7.87	8.31	2.72	15.17	31.75	6.38	14.41	17.31	242.98
2018	149.80	7.82	9.82	2.94	14.91	36.52	6.53	12.33	16.30	257.38
2019	165.72	9.31	11.56	2.94	16.90	44.09	7.16	14.57	19.50	292.24
2020	175.79	8.49	15.20	2.85	17.66	50.75	7.53	16.98	26.87	324.61

Note: Annual generation of wind and solar generation by country is derived from hourly values obtained from (ENTSO-E, 2021).

Table 2. Annual net-imports from Germany [TWh]

	DE	AT	CZ	DK	FR	NL	PL	SE	total
2015	31.35	4.82	-3.65	-3.30	9.49	16.17	-0.70	-1.79	52.40
2016	27.97	7.89	-3.42	1.72	9.74	11.07	-0.65	-0.66	53.65
2017	31.79	8.55	-2.54	-2.37	13.73	9.58	-1.03	-1.91	55.81
2018	25.18	4.22	-2.18	-0.13	8.34	14.54	0.88	-0.85	50.00
2019	19.61	-0.59	1.94	1.92	2.45	4.02	2.33	-0.75	30.94
2020	18.47	-1.38	3.77	-6.94	1.61	-1.60	2.92	-2.14	14.70

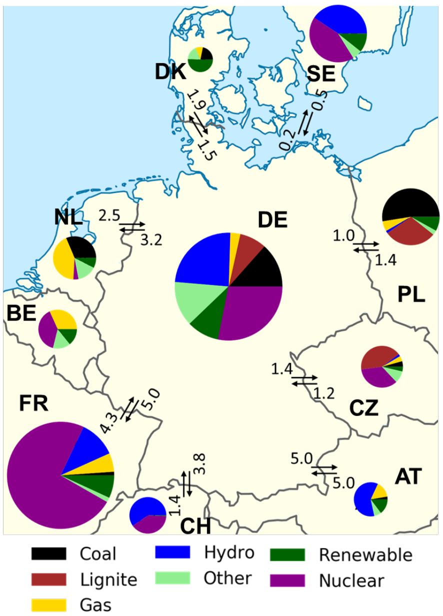
Note: Data are annual aggregates of hourly scheduled commerical exchanges (ENTSO-E, 2021). The total is interpreted as total commerical exchange of Germany with its neighbors in a given year, i.e., German net-exports to its neighbors. Belgium is not shown, as no electricity line between Germany and Belgium exists.

a 220kV line between Belgium and Luxembourg. The latter forms a common price zone with Germany, and is thus not included.

Table 2 shows the yearly net-imports of the neigboring countries from Germany. In 2015 Germany exported about 52 TWh and exports slightly increased until 2017. Although in later years one could expect further raising exports due to increasing RE generation, exports decreased after 2017. One likely explanation can be found in the reconfiguration of electricity price zones in central Europe (Bundesnetzagentur (BNetzA), 2019). Since October 1st 2018, Germany and Austria are separate electricity price zones and congestion pricing has been introduced at the German-Austrian border. Most neighbors are net-importers on an annual level. For Southern (Austria and Switzerland) and western (France and the Netherlands) neighbors, annual imports from Germany decreased in recent years. In contrast, Eastern neighbors (Czech Republic and Poland), turned from exporting to importing electricity from Germany. Finally, countries in the North (Sweden and Denmark), are net-exporters with increasing exports to Germany over time. Overall, the picture of net-imports from Germany is rather diverse as trade flows are impacted by several factors such as renewable generation, capacity and load developments, and the reconfiguration of price zones.

Market size and plant portfolio—How generation, emissions, and prices react to a trade change is determined by the generation portfolio and market size of the respective country (Table 3 and Figure 1). Within central Europe, Germany and France are the largest electricity markets with close to

FIGURE 1. German Electricity Trade Capacities [GW]



Notes: The figure shows the average hourly net transfer capacity (Bundesnetzagentur (BNetzA), 2019) and generation shares by technology (ENTSO-E, 2021) for the year 2018. The size of the pie charts is scaled to reflect total generation in the respective country. Mean hourly demand in Germany was about 58 GW. As Luxembourg and Germany form a common price zone, we do not show values for Luxembourg. No direct connection between Belgium and Germany exists but a 220kV line between Luxembourg and Belgium which is omitted in the graph.

500 TWh of annual demand. They are followed by Poland, Sweden and the Netherlands. Annual load in Belgium, the Czech Republic, Austria, Switzerland, and Denmark are below 100 TWh.

Countries are rather diverse in their production profiles and carbon intensity: Despite a high share of RE generation, Germany largely relies on carbon-intense lignite and coal as well as nuclear power plants. A similar pattern is observed in Denmark, although without nuclear. In the Netherlands gas and coal generation provide most of the electricity, in Belgium it's mostly nuclear and gas. Consequently, the carbon intensity of electricity generation in these four countries is neither very high nor very low. In contrast, very carbon intense generation is observed in Poland and the Czech Republic, which are characterized by large shares of coal and lignite generation and very low shares of RE. Finally, Sweden, France and Austria almost entirely rely on carbon free hydro and/or nuclear power; complemented by some gas plants in France and Austria to cover peak load.

ELECTRICITY PRICES—Figure 2 shows wholesale electricity market prices for Germany and its neighbors. We observe that prices generally develop very similarly across countries, especially in the last few years of our sample. An exception is Poland which in recent years had higher prices than the other countries.

Although—due to the near-zero marginal cost structure—the increase in RE generation exerts a decreasing impact on European electricity prices, most

TABLE 3. Mean of annual generation, demand and net-imports [TWh]

	DE	**AT**	**BE**	**CZ**	**DK**	**FR**	**NL**	**PL**	**SE**
Gas	36.87	8.78	22.26	3.74	2.94	33.66	36.39	7.81	-
Coal	63.55	1.29	0.49	3.54	6.10	5.69	22.17	77.21	-
Lignite	117.80	-	0.00	31.78	-	-	-	43.28	-
Hydro	16.57	32.62	-0.17	1.54	-	54.70	0.00	2.45	66.36
Nuclear	73.28	-	34.65	26.65	-	379.65	3.67	-	59.11
Other	69.16	3.67	9.78	7.52	4.30	6.68	13.44	3.87	7.76
Renewable	142.01	7.58	10.07	2.81	15.26	36.21	6.50	14.89	-
Load	471.48	74.36	77.85	72.06	28.26	500.12	92.98	149.98	151.16
Net-import	-5.33	1.11	0.24	-0.61	-0.02	-1.59	1.18	0.25	-0.07

Note: Shown is the the mean of annual generation by technology over the years 2015 to 2020. *Other* is a technology aggregate mostly containing biomass generation. Annual values are derived from houry data provided by (ENTSO-E, 2021), load is calculated as the sum of total generation and net-imports. Generation data for Switzerland are known to be incomplete and thus not used in our analysis.

countries show a slightly increasing trend until 2019 and a decline afterwards. This can be explained by developments of fuel and carbon prices (Figure 2, lower panel). They determine generation cost, and are thus another main driver of electricity prices together with load and RE generation. We observe that coal prices are rather constant over our sample period from 2015 to 2020, but gas prices are volatile with a peak in 2018 followed by a large decline. Moreover, carbon prices started to increase in mid 2017 from a level of 5 to over 30€/tCO_2 in 2020.

SUMMARY AND OUTLOOK—Summarizing, we observe an increasing trend of RE generation in all central European countries. By far Germany had the largest increase in absolute terms. As electricity generation and prices do not only depend on renewable generation the descriptive evidences of a cross-country impact of German RE on neighboring countries are rather weak. In the next section we thus introduce our econometric approach to estimate the impact of German RE while controlling for changes in fuel prices and load conditions.

3. Empirical Framework

3.1. Empirical Specification

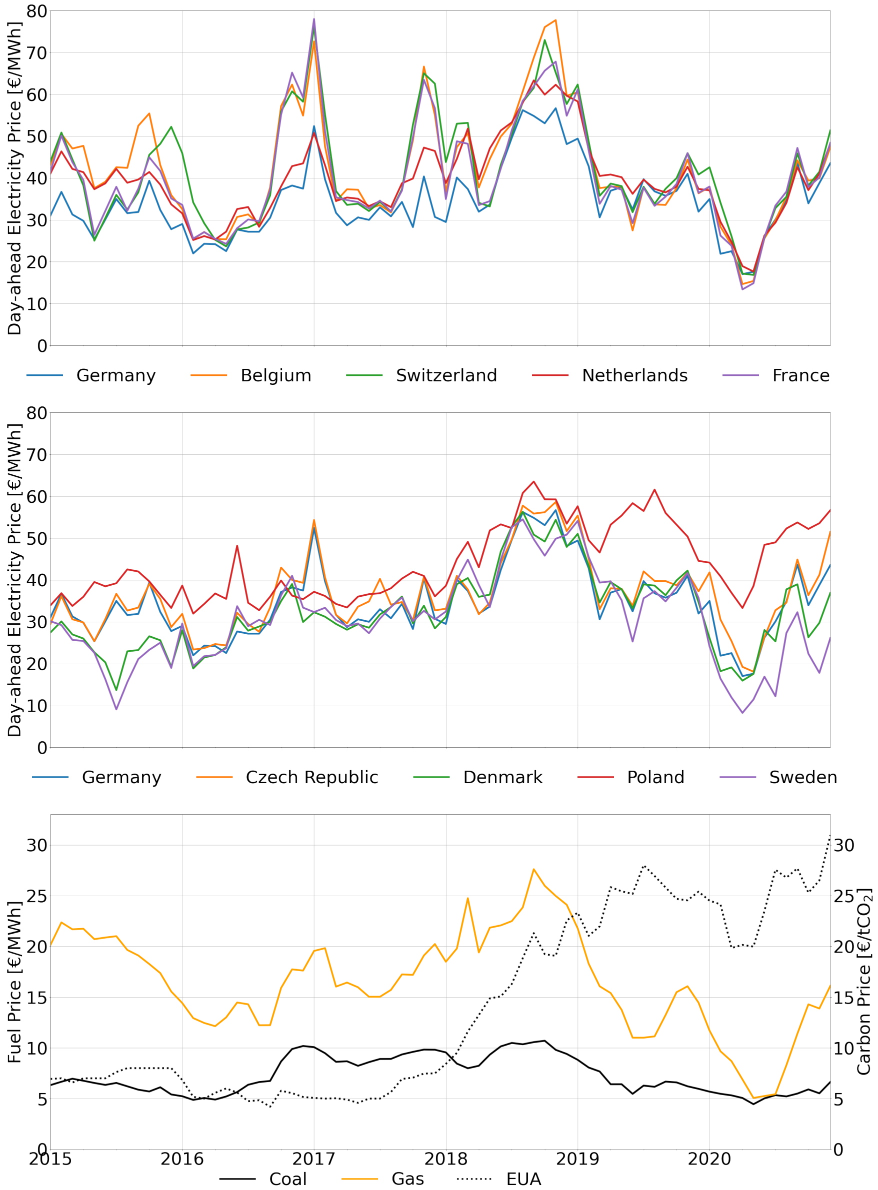
To disentangle the effect to German RE on generation in central Europe, our basic regression specification takes the following form:[5]

$$\begin{aligned} q_{itr} = \alpha_r + \beta_{ir} r_{t(DE)} + \gamma_{1ir} r_{tr} + \gamma_{2ir} d_{tr} + \gamma_{3ir} d_{t(DE)} \\ + \gamma_{4ir} \phi_t^{ctg} + \gamma_{5ir} \phi_t^{ltg} + \gamma_{6ir} t_{tr} + \boldsymbol{F}_t \boldsymbol{\delta}_{ir} + \epsilon_{itr} \,. \end{aligned} \tag{1}$$

We regress hourly generation of technology i in hour t and country r, q_{itr}, on German RE generation, $r_{t(DE)}$. To account for electricity demand in the respective country and Germany, we include load of both countries, d_{tr} and

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

Figure 2. Electricity, fuel and carbon prices



Notes: Upper two panels show monthly means of hourly day-ahead electricity prices obtained from (ENTSO-E, 2021). For Poland, ENTSO-E (2021) prices are incomplete and we thus used dayhead prices from EIKON (2017). The lower panel shows monthly average of daily fuel prices (measured on the left axis) and the EU Allowance (EUA) forward price (ICE, 2021).

$d_{t(DE)}$, as well as RE generation in the respective country, r_{tr}.[6] The output of technology i depends on its marginal cost relative to the marginal cost of all other generators in the market. We therefore include the coal-to-gas price ratio, ϕ_{tr}^{ctg}, and the lignite-to-gas price ratio, ϕ_{tr}^{ltg}, to control for changes in relative marginal cost. Both of these price ratios are carbon price inclusive, i.e. include the EU Emissions Allowance (EUA) price.[7] Further, we control for ambient temperatures (t_{tr}) as they affect the efficiency of power plants and capacity of the transmission lines. Since we observe available capacities by technology only at the annual level, they are omitted from the estimation due to missing variation. We also do not observe the net-transfer capacities at the hourly level. To control for changes in these variables, we include month-of-sample ($month \times year$) fixed effects ($\boldsymbol{F}$). Finally, to control for the impact of seasonal and daily cycles, we additionally include month-of-year ($month$) and hour-of-day ($hour$) time fixed effects. All variables and fixed effects are described in Table 4.

TABLE 4. Estimation variables

Variable	Description
p_{tr}^{ele}	Hourly electricity price in country r [€/MWh]
t_{tr}	Hourly RE production in country r [GWh]
t_{tr}	Daily mean temperature in country r [°C]
d_{tr}	Hourly system demand in country r [GWh]
p_t^{coal}	Daily coal price [€/MWh$_{th}$]
p_t^{gas}	Daily gas price [€/MWh$_{th}$]
p_t^{EUA}	Daily price of European Emissions Allowances [€/tCO$_2$]
ϕ_t^{ctg}	Daily carbon price inclusive coal-to-gas price ratio
ϕ_t^{ltg}	Daily carbon price inclusive lignite-to-gas price ratio
$month \times year$	Month-of-sample fixed effects
$month$	Month-of-year fixed effects
$hour$	Hour-of-day fixed effects

Notes: See Section 2 for detailed description of source data. Daily mean temperatures taken from ECAD (2020). MWh$_{th}$ refers to thermal energy.

To determine the effect of German RE on electricity prices in central Europe, we regress the electricity price on German RE and a similar set of controls:

$$\begin{aligned} p_{tr}^{ele} = \alpha_r + \beta_r r_{t(DE)} + \gamma_{1r} r_{tr} + \gamma_{2r} d_{tr} + \gamma_{3r} d_{t(DE)} \\ + \gamma_{4r} p_t^{coal} + \gamma_{5r} p_t^{gas} + \gamma_{6r} p_t^{EUA} + \gamma_{7r} t_{tr} + \boldsymbol{F}_t \boldsymbol{\delta}_r + \epsilon_{tr} \, . \end{aligned} \quad (2)$$

In a competitive electricity market, prices are equal to the generation cost of the marginal supplier. These cost depend on the level of fuel and carbon prices rather than on relative prices. We thus include absolute fuel prices, p_t^{coal} and

[6]For the case of Germany ($r = DE$), we include renewable generation and demand of all countries within our sample.

[7]$\phi_t^{ctg} := \frac{p_t^{coal} + \theta^{coal} p_t^{EUA}}{p_t^{gas} + \theta^{gas} p_t^{EUA}}$ and $\phi_t^{ltg} := \frac{p_t^{lignite} + \theta^{lignite} p_t^{EUA}}{p_t^{gas} + \theta^{gas} p_t^{EUA}}$. p_t^{coal}, p_t^{gas}, and $p_t^{lignite}$ are respective fuel prices and p_t^{EUA} the carbon price. θ is the fuel specific carbon content. For gas we use 0.2, for coal 0.34, and for lignite 0.39 tCO$_2$/MWh$_{th}$ (IPCC, 2006). Lignite extraction is mostly integrated with power generation and therefore not obtained on the international market. In the calculation of the lignite-to-gas price ratio, we therefore use a constant price level of 1.5 € /MWh as proxy for extraction cost (UBA, 2017).

p_t^{gas}, and the carbon price, p_t^{EUA}, to control for changes in generation cost.

In the quantity regression our main coefficients of interests are β_{ir}, i.e., the impact of German RE on generation of technology i. Likewise, in the price regression we are interested in β_r, the impact of German RE on electricity prices in region r. The identification of these coefficients relies on two crucial assumptions. First, we assume that RE generation is exogenous. This assumption can be justified as the marginal cost of RE are near zero. Thus, once the capacity is installed, RE generation is driven by natural conditions such as wind speed and solar radiation. Second, we assume demand to be inelastic. This assumption is justified by our time horizon as we investigate hourly electricity markets.

3.2. Alternative Specifications

To test the robustness of our results, we provide sensitivity analyses in four dimensions: (i) different sets of time fixed effects, (ii) a congestion dummy to account for congested interconnectors, (iii) different functional forms to account for non-linear effects, and (iv) changes in temporal resoultion by re-sampling to daily and weekly data.[8]

FUNCTIONAL FORM— Our core specifications rely on linear functional forms. However, the reaction of conventional generation and electricity prices to changes in RE generation might be non-linear. We thus estimate alternative semi-parametric specifications allowing coefficients to flexibly adjust depending on the level of load and renewable production:

$$\begin{aligned} q_{itr} = \sum_b Bin_b \big[&\alpha_{br} + \beta_{bir} r_{t(DE)} + \gamma_{b1ir} r_{tr} + \gamma_{b2ir} d_{tr} + \gamma_{b3ir} d_{t(DE)} \\ &+ \gamma_{b4ir}\phi_t^{ctg} + \gamma_{b5ir}\phi_t^{ltg} + \gamma_{b6ir} t_{tr}\big] + \boldsymbol{F}_t \boldsymbol{\delta}_{ir} + \epsilon_{itr}, \end{aligned} \tag{3}$$

$$\begin{aligned} p_{tr}^{ele} = \sum_b Bin_b \big[&\alpha_{br} + \beta_{br} r_{t(DE)} + \gamma_{b1r} r_{tr} + \gamma_{b2r} d_{tr} + \gamma_{b3r} d_{t(DE)} \\ &+ \gamma_{b4r} p_t^{coal} + \gamma_{b5r} p_t^{gas} + \gamma_{b6r} p_t^{EUA} + \gamma_{b7r} t_{tr}\big] + \boldsymbol{F}_t \boldsymbol{\delta}_r + \epsilon_{tr}\,. \end{aligned} \tag{4}$$

Bin_b represents an indicator for the b^{th} decile of a variable. We estimate equations (3) and (4) in two different versions: First, Bin_b representing the load deciles of the respective country; second, Bin_b representing the deciles of German RE generation.

CONGESTION—As shown by Fell et al. (2021) and LaRiviere & Lu (2020), congestion might affect the impact of RE on generation and prices. As congestion is not observed, we construct a measure of congestion of cross-country interconnectors: We define the interconnection between country r and r' as congested ($C_{trr'} = 1$) if the relative price difference exceeds two percent in hour t:

$$C_{trr'} = \begin{cases} 0 \text{ if } \left|\frac{p_{tr}^{ele} - p_{tr'}^{ele}}{p_{tr}^{ele}}\right| < 0.02 \\ 1 \text{ if } \left|\frac{p_{tr}^{ele} - p_{tr'}^{ele}}{p_{tr}^{ele}}\right| \geq 0.02\,. \end{cases}$$

Interacting the congestion dummy with German RE, we test the impact on

[8] In case of the price estimation (2), we only test robustness with resepct to different time fixed effects and functional forms.

our coefficient of interest, i.e., we alternatively estimate:

$$q_{itr} = \alpha_r + \beta_{1ir} r_{t(DE)} + \beta_{2ir} C_{tr(DE)} r_{t(DE)} + \gamma_{1ir} r_{tr} + \gamma_{2ir} d_{tr} + \quad (5)$$

$$+ \gamma_{3ir} d_{t(DE)} + \gamma_{4ir} \phi_t^{ctg} + \gamma_{5ir} \phi_t^{ltg} + \gamma_{6ir} t_{tr} + \boldsymbol{F}_t \boldsymbol{\delta}_{ir} + \epsilon_{itr} \quad (6)$$

The average marginal impacts are then calculated as:

$$\beta_i = \beta_{1ir} + \beta_{2ir} \overline{C}_{tr(DE)},$$

where $\overline{C}_{tr(DE)}$ is the share of congested hours between country r and Germany. We find the highest share of congested hours for Poland (91.7%), followed by Switzerland, Sweden and the Czech Republic (83.5, 80.6, and 78.7%). Lower congestion shares are observed for Denmark, France and the Netherlands (58.7, 54.9, and 48.8%). Since Austria was in the same price zone as Germany for most of our sample period and Belgium does not have a direct interconnector to Germany, we do not report congestion for these two countries.

TEMPORAL RESOLUTION— German RE might offset hydro generation in some hours. In the case of hydro storage, this generation is merely shifted to another hour, i.e., it might decrease fossil generation and emissions in another hour. Depending on the type of storage, this effect might occur on a daily or a larger cycle. We thus perform additional regressions by re-sampling our hourly data set to average daily and weekly data. This reduces the impact of very short-run impacts of RE generation as it accounts for the shift of hydro generation to another hour of the same day or week.

3.3. Annual Impacts and Emission Offsets

We calculate annual effects by evaluating estimated marginal effects at the annual average of German RE over our sample period 2015 to 2020:

$$\Delta p_r := \beta_r \overline{r}_{DE}, \quad (7)$$

$$\Delta q_{ir} := \beta_{ir} \overline{r}_{DE}, \quad (8)$$

where β_{ir} and βr refer to the coefficient in equations (1) and (2), and $\overline{R}_{DE}$ is mean annual RE production in Germany.

Multiplying the average annual generation change with the technology-specific emission coefficient e_i, we obtain the average annual emission offset:[9]

$$\Delta E_{ir} : = \Delta q_{ir} e_i. \quad (9)$$

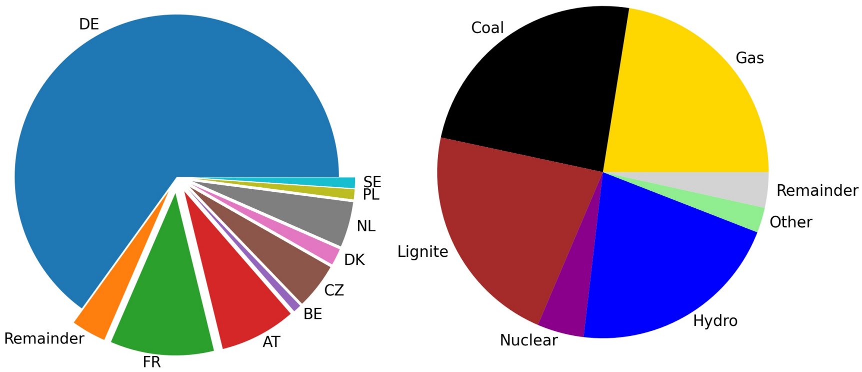
4. Replacement and Emission Impact of German RE

4.1. Marginal Impacts on Generation

What is the impact of an additional MWh of German RE generation on conventional generation in the domestic and neighboring markets? Table 5 and Figure 3 show the average marginal replacement effect of German RE by country technology and country.

[9] We use average emission coefficients of 1.17/0.95/0.37 tCO_2/MWh for lignite/coal/gas.

Figure 3. Share of replacement impacts by country and technology



Notes: Figures are based on total values in Table 5.

An additional MWh of German RE reduces German generation by 0.65 MWh, while 0.32 MWh are exported to neighboring markets. With 0.10 and 0.08 MWh the largest foreign replacement effect is observed in France and Austria as they have the largest interconnectors (see Figure 1). Around 0.05 MWh of conventional generation are replaced in the Czech Republic and the Netherlands, respectively. Generation in Belgium, Denmark, Poland, and Sweden only shows a minor reaction.

At the technology level, one MWh of German RE replaced on average 0.69 MWh of fossil generation inducing an offset of carbon emissions. Coal generation (0.24 MWh) is affected most, followed by gas (0.23 MWh) and lignite (0.22 MWh). Furthermore, we find an impact of 0.21 MWh on hydro generation, and a minor impact of 0.05 MWh on nuclear and 0.03 MWh on other generation. As expected, generation impacts follow a merit-order logic. The impact on fossil generators with high marginal costs is larger than the impact on generators with low marginal costs such as nuclear. However, concerning hydro power, a closer analysis is needed. As hydro generation includes both, non-dispatchable run-of-river generation with low marginal cost and dispatchable generation from reservoirs and pump-storage plants with high opportunity cost, indirect impacts of shifting generation in time can be expected. In the next section, we address this issue with two alternative specifications using different temporal resolutions of our data set.

At the country level, the replacement effects mirror the respective generation portfolio: In Austria, France and Sweden mostly hydro power is affected, in Belgium and the Netherlands mostly gas generation is replaced and in the Czech Republic and Poland, lignite producers show the largest reaction.

Under our assumption of inelastic demand, one MWh of German RE should replace one MWh of generation. With 0.97 MWh (per MWh of RE generation) the total replacement is therefore close to one. The remaining deviation is likely to be explained by three main reasons: First, Germany also trades electricity with Switzerland. Due to missing generation data, we are unfortunately not able to estimate this impact. As Swiss electricity generation is based on carbon-neutral hydro and nuclear power, this does not affect our estimate of the emission offset. Second, it is possible that German RE stimulate additional re-exports,

TABLE 5. Average marginal replacement effect of German RE [MWh/MWh]

	DE	AT	BE	CZ	DK	FR	NL	PL	SE	total
Gas	-0.109	-0.006	-0.012	-0.011	-0.005	-0.031	-0.051	-0.001	-	-0.225
	(0.004)	(0.001)	(0.001)	(0.000)	(0.000)	(0.002)	(0.002)	(0.000)	-	(0.005)
Coal	-0.212	-0.003	-0.000	-0.004	-0.007	-0.002	-0.010	-0.004	-	-0.242
	(0.007)	(0.000)	(0.000)	(0.000)	(0.001)	(0.001)	(0.001)	(0.001)	-	(0.007)
Lignite	-0.189	-	-	-0.024	-	-	-	-0.007	-	-0.219
	(0.006)	-	-	(0.001)	-	-	-	(0.001)	-	(0.006)
Hydro	-0.081	-0.066	0.002	-0.007	-	-0.042	0.000	0.002	-0.017	-0.210
	(0.003)	(0.002)	(0.000)	(0.000)	-	(0.002)	(0.000)	(0.000)	(0.002)	(0.004)
Nuclear	-0.027	-	0.002	0.000	-	-0.029	0.001	-	0.008	-0.046
	(0.003)	-	(0.001)	(0.000)	-	(0.005)	(0.000)	-	(0.001)	(0.006)
Other	-0.033	-0.001	0.000	-0.000	-0.004	0.000	0.014	0.000	-0.001	-0.025
	(0.004)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.004)
Total	-0.650	-0.076	-0.008	-0.046	-0.017	-0.103	-0.045	-0.010	-0.011	-0.965
	(0.011)	(0.002)	(0.001)	(0.001)	(0.001)	(0.006)	(0.002)	(0.001)	(0.002)	(0.029)

Notes: Numbers correspond to the coefficients β_{ir} of equation (1). Heteroscedasticity robust standard errors in parentheses.

e.g. via Austria to Italy. Some replacement will therefore realized outside our country scope. Third, the ENTSO-E data underlying our estimation only report generation of units with an installed capacity above 100 MW, and we therefore miss some generation impacts.

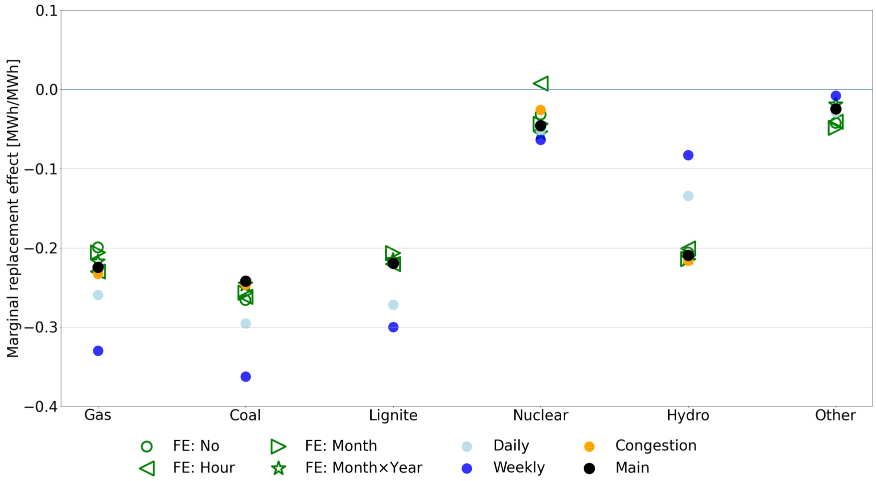
4.2. Robustness Checks

As described in Section 3.2, we provide four types of robustness checks: (i) different fixed effects, (ii) a congestion dummy to account for congested transfer capacities, (iii) changes in the functional form to account for non-linear effects, and (iv) changes in temporal resolution by re-sampling to daily and weekly data. The estimation results per technology and country are provided by Tables A.2 to A.6 in the Appendix. Figure 4 provides an overview of robustness results by technology.

FIXED EFFECTS AND CONGESTION—We find that our results are generally very stable to various specifications: The marginal replacement effects do not react substantially to the inclusion of different sets of time fixed effects. Also the impact of congestion is relatively low, i.e., there is no substantial change in results when including a dummy that accounts for hours when transfer lines between two countries are congested.

TEMPORAL RESOLUTION—The blue dots in Figure 4 show the results of our specifications with daily and weekly temporal resolution. It becomes visible, that the impact on hydro generation decreases while the impact on fossil technologies (gas, coal and lignite) increases compared to estimates based on hourly data. As hydro generation includes dispatchable generation from reservoirs and pump-storage plants, we expect hydro plants to shift generation from hours with high RE production and, thus, low prices to hours with low RE production and correspondingly higher electricity prices. Therefore, on the hourly level, German RE leads to a decrease of hydro generation. As this decrease likely leads to an increase of hydro generation in other hours, the impact on hydro decreases when evaluated at daily or weekly levels. In contrast, the impact on gas, coal and lignite generation increases, as hydro power is likely to replace fossil generation. As the shift of hydro generation in time likely leads

FIGURE 4. Marginal Replacement Effect by Model Specification



Notes: Shown are marginal replacement effect for different model specification. *FE* are specification with different fixed effects. *Congestion* includes the congestion dummy. *Weekly* and *Daily* are estimates based on resampled data. *Main* denotes aour core estimate.

to an additional emission offset, we also report the emission offset based on the sample with weekly resolution to provide an upper bound on the emission offset.

FUNCTIONAL FORM—Figures A.1 to A.3 in the Appendix show how the impact of German RE on conventional generation depends on (i) the demand level in each country, and (ii) the level of RE generation in Germany. We make three main observations. First, our core estimate mostly lies within the range of our semi-parametric results, indicating that a more flexible functional form that accounts for non-linear effects does not substantially alter our results. Only in the case of hydro power in Germany and Austria, there is no overlap between the core and the semi-parametric estimate, but the latter suggest a larger impact of German RE on hydro power. Second, we find that the impact on gas and coal increases in demand while the impact on lignite and nuclear decreases in demand. This agrees with our expectation as in high demand hours the more expensive technologies, i. e., gas or coal are marginal, while in low demand hours lignite and nuclear are the marginal technologies. Third, regarding the impacts of different levels of German RE, we find that values are often significantly different for the first decile. However, as RE generation values in this decile only go up to 3.5 GWh (compared to maximum values of more than 60 GWh in the highest decile), it is likely that these very low values lead to a distortion of marginal impacts.

4.3. Impacts on Emissions

Table 6 shows the average impact of German RE on annual carbon emissions over the period. We distinguish between two cases: The first two rows show the results for our core specification using hourly data. The second two rows provide the results for an alternative specification using weekly data and thus taking into account inter-temporal impacts of hydro power generation. This can be interpreted as an upper bound of the total emissions impact.

Table 6. Annual emission offset of German RE by technology and country [$MtCO_2$]

	DE	**AT**	**BE**	**CZ**	**DK**	**FR**	**NL**	**PL**	**Total**
Hourly sample	63.84 (1.34)	0.65 (0.05)	0.65 (0.06)	4.93 (0.16)	1.22 (0.07)	1.83 (0.16)	3.84 (0.20)	1.67 (0.18)	78.62 (2.00)
Weekly sample	99.10 (9.87)	1.19 (0.27)	-	6.45 (0.67)	1.23 (0.46)	1.89 (0.63)	2.81 (0.60)	0.15 (0.07)	112.83 (11.35)

Notes: The average annual offsets correspond to ΔE_{ir} as defined in equation (9). Sweden has no fossil generation and is thus not shown here. Heteroscedasticity robust standard errors in parentheses.

In our core specification, German RE induced an average annual emission offset of 78 million tons of CO_2 in the years form 2015 to 2020, i.e., around one ton of carbon per German inhabitant. The emissions impact was highest in Germany, where more than 80 % of the total offset took place. The cross-border emission impact is the largest in countries with high coal and lignite capacities, i.e., the Czech Republic and the Netherlands. Although the Polish generation mix is rather emission intense, the cross-border impact is limited due to the limited interconnector capacity. In France we observe a relatively large impact on gas generation leading to a moderate emission impact. In Denmark and Belgium the impact of German RE on conventional generation is generally low. Finally, in Austria mostly hydro power is replaced, leading to a small emissions impact.

Alternatively using the weekly resolution of our sample, the total emission impact increases to an average offset of 112 million tons of CO_2 per year. The increase is mostly caused by an increase of the offset in Germany followed by the Czech republic and Austria. For Denmark and France altering the sample resolution does not affect the emission impact. For the remaining countries the emission impact even decreases. One should however note that in these countries hydro capacities are rather limit (see Table 3).

5. The Merit-Order Effect: Impact of RE on Electricity Prices

5.1. Marginal and Total Impacts

What was the impact of German RE on domestic and neighbourings electricity prices? Table 7 presents the marginal impacts, i. e., the impact of one GWh of German RE, as well as total impacts on hourly wholesale market prices (see equation 7). To put them into perspective, we also show the relative price impacts compared to a hypothetical situation without German RE. These price effects have a close connection to the replacement effects presented in the preceding section. First, price impacts are naturally increasing in the absolute and relative amount of generation replaced. Second, as the merit-order curve usually has a convex shape, the price impact becomes larger in countries where fossil generation is replaced.

As the replacement effect mostly affects German generation, we observe the highest impacts on domestic electricity prices, which decrease by 14€/MWh. In the surrounding countries, the highest cross-border merit-order effect takes place in the Czech Republic (11€/MWh) followed by Denmark (10€/MWh). In both

Table 7. Price impacts of German RE

	DE	CH	BE	CZ	DK	FR	NL	PL	SE
β_r [€/MWh per GWh]	-0.88	-0.39	-0.18	-0.70	-0.62	-0.28	-0.34	-0.03	-0.24
	(0.02)	(0.01)	(0.03)	(0.02)	(0.02)	(0.02)	(0.01)	(0.01)	(0.01)
Δp_r [€/MWh]	-13.92	-6.11	-2.88	-10.98	-9.78	-4.35	-5.32	-0.46	-3.76
	(0.38)	(0.24)	(0.41)	(0.28)	(0.32)	(0.25)	(0.23)	(0.20)	(0.20)
$\Delta p_r^{\%}$ [%]	-40.18	-12.75	-6.42	-23.03	-23.21	-9.74	-11.85	-1.02	-10.90

Notes: β_r refers to the coefficients of equation (2). Δp_r is given by equation (7). The relative impact is definded as $\Delta p_r^{\%} := \frac{\Delta p_r}{\overline{p}_r - \Delta p_r}$, where $\overline{p}_r$ are annual means of observed prices.

countries, we observe—relative to their market size—a substantial replacement of fossil generation, inducing a large price impact.[10]

Somewhat smaller but still substantial impacts are observed in all other countries except for Poland: In the Netherlands and France, the price decreases by 5 and 4€/MWh, respectively. Although the total replacement effect in these countries is similar or even higher compared to the Czech Republic, it is smaller relative to the market size. This can explain the lower price impact. The price impacts in Sweden (4€/MWh) and Belgium (3€/MWh) are also lower. Relying and hydro and nuclear power, Swedish wholesale market prices are generally low. Belgium is not directly connected to Germany, leading to a low replacement and, thus, low price impact. For Switzerland, we observe an impact of 6€/MWh per GWh. As we do not observe Swiss electricity generation, we have no information about the replacement effect. However, Swiss electricity prices are usually determined by its neighbors. This explains the price impact, which is between the impact on German and French prices.

Finally, the impact on the Polish price is very low (less than 1€/MWh). This is consistent with the very low replacement effects due to limited interconnector capacities. In addition, Poland is one of the largest electricity markets, and Polish electricity prices seem to develop independently of other central European countries (see Figure 2).

Also in relativ terms we find the highest impact on Germany itself: Without RE generation, the average electricity price would have been around 40% lower. Again, Germany is followed by Denmark and the Czech Republic (23%). For Switzerland, Belgium, France, the Netherlands, and Sweden, the impact of German RE lies between 6 and 13%. For Poland it is with around 1% negligible.

5.2. Robustness Checks

We provide two types of robustness checks: different fixed effects, and changes in the functional form to account for non-linear effects.

Fixed effects—Table A.7 in the Appendix shows the results for alternative specifications using different sets of fixed effects. We would like to point out three issues: First, our results seem rather stable to the inclusion of different time fixed effects. Second, compared to the specifications without fixed effects, month-of-sample (month x year) fixed effects have the biggest impact

[10]Although the absolute replacement effect in Denmark is very low, this can have a substantial impact on the price, as the Danish electricity market is comparably very small.

on the results. As we include them them to control for unobserved variables such as installed capacities as well as reconfiguration of the Austrian-German price zone, the impact on the results is expected. Third, for Poland we observe positive impacts on the price for different specifications. The Polish impact is small in all cases and varies around zero. We therefor conclude, that there is no robust impact of German RE on Polish wholesale market prices.

FUNCTIONAL FORM—Figure A.4 shows the results of the semi-parametric estimations for all countries. The results are generally close to our core estimates. As in the case of the replacement effect, the coefficients on German RE become very volatile in the lowest decile for German RE. In this decile, RE generation is very low and even near zero, which likely distorts the coefficient.

6. German Renewable Support and the Cost of Offseting Carbon Emissions

6.1. Measuring Consumer and Producer Impacts

An increase in German RE generation leads to a decrease of electricity prices and conventional generation in Germany and its surrounding countries. Moreover, German consumers are affected by a surcharge on electricity consumption to refinance the cost of RE subsidies.[11] To determine the impact of German RE on the rents of consumers and producers, and to provide an estimate of the average cost of carbon offsets, we calculate the different cost components.

We define the change in consumer rents, $\Delta\pi^C$ as the decrease in annual costs of purchasing electricity, which is calculated by evaluating the estimated merit-order effect at the average annual electricity demand. In the case of Germany, we add the refinancing cost paid by consumers, R:

$$\Delta\pi_r^C := \Delta p_r \overline{d}_r \, [+R]_{\text{if } r=\text{DE}} \ ,$$

where $\overline{d}_r$ is the average of annual load over the period 2015 to 2020. Again, we rely on the assumption of inelastic short-term electricity demand. Annual payments of German consumers to refinance RE subsidies, R, are provided by Netz-Transparenz (2021).[12]

Changes in producers' profits are determined by both, decreasing prices and generation. As the generation decrease also leads to an unobserved decrease in generation cost, we follow Abrell et al. (2019) approximating profit losses with a lower and an upper bound:

$$\Delta\pi_r^P := \begin{cases} \text{Lower bound:} & \sum_i \Delta p_r^{ele} \overline{q}_{ir} \\ \text{Upper bound:} & \sum_i \Delta p_r^{ele} \left(\overline{q}_{ir} + \Delta q_{ir}\right) \end{cases} ,$$

where $\overline{q}_{ir}$ is the observed mean annual generation of technology i over the year 2015 to 2020. The lower bound assumes that producers are only affected by the decreasing wholesale price, Δp_r. In contrast, the upper bound of profit losses includes additional losses due to the reduction of output ($\Delta q_{ir} < 0$).

[11] These cost are known as differential cost and defined as the cost of RE subsidies net of the income obtained from selling RE to the market.

[12] At the time of writing, data for 2020 are not available. We therefore use data from the

Table 8. Cost of German RE Promotion [Billion €]

		DE	CH	BE	CZ	DK	FR	NL	PL	SE	Total
Consumers	Cost	-6.56	-0.3	-0.22	-0.79	-0.28	-2.18	-0.49	-0.07	-0.57	-11.46
	Refinancing	23.3	-	-	-	-	-	-	-	-	23.3
	Total	16.74	-0.3	-0.22	-0.79	-0.28	-2.18	-0.49	-0.07	-0.57	11.84
Producers	Lower	7.22	-	0.22	0.85	0.28	2.24	0.44	0.07	0.57	11.89
	Upper	8.47	-	0.22	0.92	0.3	2.3	0.47	0.07	0.58	13.33
Total	Lower bound	23.96	-0.3	0	0.06	0	0.06	-0.05	0	0	23.73
	Upper bound	25.21	-0.3	0	0.13	0.02	0.12	-0.02	0	0.01	25.17

Notes: The table provides estimates of the average annual cost of German renewable energy support over the period 2015 to 2020. For consumers, we provide decreases in the cost of electricity purchases together with payed surcharges to refinance RE subsidies. For producers, we show profit losses.

6.2. The Impact of German RE on Consumers and Producers

Table 8 provides our estimates of the average annual cost of German RE support on consumers and producers in Germany and its neighbors over the period 2015 to 2020. Total costs are the sum of changes in consumer and producer rents. In total, German RES caused annual costs of about 23.7 to 25.2 billion €. These costs are roughly equally split between consumers and conventional producers. Producers incurred losses between 11.9 up to 13.3 billion €. Consumers cost of electricity decrease by 11.5 billion €, but due to the annual refinancing charge of 23.3 billion € payed by German consumers, consumers incurred an overall average cost of 11.84 billion € per year.

With domestic costs of 24 to 25.5 billion € per year, Germany carries almost the entire cost. Looking at the distribution between producers and consumers, we find that—although the cost of purchasing electricity at the wholesale market decreases—German consumers carry the major financial burden with about two third of the total cost as they are paying the refinancing surcharge.

In contrast, the total cost impact of German RE on surrounding countries is negligible. As changes in consumer and producer rents are almost equally high, total costs are close to zero for most countries. For net-importing countries (see Table 3), the increase in consumers' benefits exceeds the decrease in producers' profits, leading to a net benefit. This can be observed in the case of the Netherlands. In contrast, in net-exporting countries, the decrease in producers' profits exceeds the increase in consumers' benefits from German RE, inducing a net loss for the country's electricity sector. This result can be observed in the Czech Republic and France.

While the total cost impacts in neighboring countries are very low, the shift of rents between consumers and producers is substantial. In total, the cross-border merit-order effect induces a consumer surplus of 4.9 billion € by reducing the cost of purchasing electricity, but this effect is offset by a decrease of profits of about the same size.

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income side of the so called EEG account provided by the same source.

Table 9. Average Cost of Emission Offset by German RE support [€/t CO_2]

	Hourly Sample	Weekly Sample
Lower bound	304.76	212.35
Upper bound	320.66	223.43

Notes: Annual average abatement cost are derived as the ration of the total cost of German RE and the estiamted average annual emission offset.

6.3. Average Cost of Emission Offset

Provided the annual emission offset (Table 6) and the cost of German RES (Table 8), we derive the average annual cost of emission offset with German RES as the ratio of the two. In our estimate, we ignore the beneficial effect of carbon reduction as well as other positive effect of RE deployment such as learning effects.

Table 9 shows our estimates. We provide values for the upper and lower bound of the cost impacts as well as for the case of the hourly and the weekly sample used to approximate the effect of shifting hydro power generation in time.

For our core specification, we estimate average abatement cost of German RES of between 305 and 321 €/tCO_2. Approximating the intertemporal effect of hydro power, the average annual emission offset increases from 79 to 112 MtCO_2 per year. Thus, average offset cost decrease to range from 212 to 223 €/tCO_2.

Our cost estimates fit well into the existing literature. Depending on the assumption on the carbon offset by hydro generation, Abrell et al. (2019) estimate a range of 105 to 276 €/tCO_2 and 638 to 973 €/tCO_2 for wind and solar, respectively, for the sample period from 2010 to 2015. Gugler et al. (2021) rely on a sample ranging from beginning 2017 to mid 2018. They find average cost of 182 to 206 and 744 to 978 €/tCO_2 for wind and solar power, respectively. Given that during our sample period German solar power accounted for one quarter to one third of total German RE production, and that we estimate the combined effect of wind and solar power, our estimate is naturally at the lower end compared to the existing literature.

7. Conclusions

Climate policies have induced a large increase in renewable energy generation across Europe, and in particular in Germany. Whereas the program cost of renewable energy support policies were borne by the country itself, the raise in German RE generation also affected neighboring electricity markets: Renewable energy (RE) sources such as wind and solar replace the most expensive generators that often rely on fossil fuels and thus at the same time induce a decrease in electricity sector emissions and wholesale market prices. In interconnected electricity systems this so-called merit-order effect stimulates an increase in net-exports. Thus conventional generation and prices in neighboring countries are also likely to decrease. The impact of these trade effects depend on installed generation and interconnector capacities.

To estimate these impacts, this paper makes use of hourly data on technology-specific generation and wholesale market prices for ten central European countries. Using a variety of econometric specifications, we come to the following three main conclusions. First, German RE induced a yearly CO_2 emission offset of around one ton per inhabitant of Germany, at an average cost of 212 to 321 €/t. In total, German RE offsets on average 79 to 113 $MtCO_2$ per year.

Second, the major part of emission offsets was realized in Germany itself. 80 to 90% (64 to 99 $MtCO_2$) of the total annual emission offset took place in Germany itself, the rest (14 to 15 $MtCO_2$) was offset in neighboring countries.

Third, German consumers bear the largest cost share of RE promotion followed by German producers. Surrounding electricity markets were mainly affected by decreasing wholesale market prices due to cheaper imports from Germany. This (cross-border) merit-order effect caused a significant shift of economic rents from producers to consumers: generators' profits declined, while consumers could benefit from lower costs for electricity. These effects nearly balance, but net-importing countries have a tendency to realize a slight economic benefit from German RE as the cost of imports are decreasing.

References

Abrell, J., Kosch, M., & Rausch, S. (2019). Carbon abatement with renewables: Evaluating wind and solar subsidies in germany and spain. *Journal of Public Economics*, *169*, 172–202.

AG Energiebilanzen (2021). Stromerzeugung nach Energietraegern 1990 - 2020 (Stand February 2021).

Bundesnetzagentur (BNetzA) (2019). *Monitoringbericht 2019*. Technical Report.

Callaway, D. S., Fowlie, M., & McCormick, G. (2018). Location, location, location: The variable value of renewable energy and demand-side efficiency resources. *Journal of the Association of Environmental and Resource Economists*, *5*, 39–75.

Cludius, J., Hermann, H., Matthes, F. C., & Graichen, V. (2014). The merit order effect of wind and photovoltaic electricity generation in germany 2008-2016: Estimation and distributional implications. *Energy Economics*, *44*, 302 – 313.

Cullen, J. (2013). Measuring the environmental benefit of wind-generated electricity. *American Economic Journal: Economic Policy*, *5(4)*, 107–133.

ECAD (2020). European Climate Assessment & Data.

EIKON (2017). Thomson reuters EIKON database.

ENTSO-E (2021). Transparency platform.

Fell, Harrison, D., Kaffine, K., & Novan (2021). Emissions, transmission, and the environmental value of renewable energy. *American Economic Journal: Economic Policy*, *13*, 241–72.

Gugler, K., & Haxhimusa, A. (2019). Market integration and technology mix: Evidence from the german and french electricity markets. *Energy policy*, *126*, 30–46.

Gugler, K., Haxhimusa, A., & Liebensteiner, M. (2021). Effectiveness of climate policies: Carbon pricing vs. subsidizing renewables. *Journal of Environmental Economics and Management*, *106*, 102405.

Haxhimusa, A. (2018). *The Effects of German Wind and Solar Electricity on French Spot Price Volatility: An Empirical Investigation*. Department of Economics Working Papers wuwp258 Vienna University of Economics and Business, Department of Economics.

ICE (2021). ICE EUA Futures.

IPCC (2006). *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*. IPCC.

LaRiviere, J., & Lu, X. (2020). Transmission constraints, intermittent renewables and welfare.

Netz-Transparenz (2021). www.netztransparenz.de/eeg/jahresabrechnungen.

Novan, K. (2015). Valuing the wind: renewable energy policies and air pollution avoided. *American Economic Journal: Economic Policy*, *7*, 291–326.

Perino, G. (2018). New EU ETS Phase 4 rules temporarily puncture waterbed. *Nature Climate Change*, *8*, 262–264.

Phan, S., & Roques, F. (2015). Is the depressive effect of renewables on power prices contagious? a cross border econometric analysis. *Cambridge Working Papers in Economics*, .

Schnaars, P. (2019). The real substitution effect of renewable electricity: An empirical analysis for germany. In *Available at SSRN*.

UBA (2017). Daten und Fakten zu Braun- und Steinkohle.

Wuerzburg, K., Labandeira, X., & Linares, P. (2013). Renewable generation and electricity prices: Taking stock and new evidence for Germany and Austria. *Energy Economics*, *40*, S159–S171.

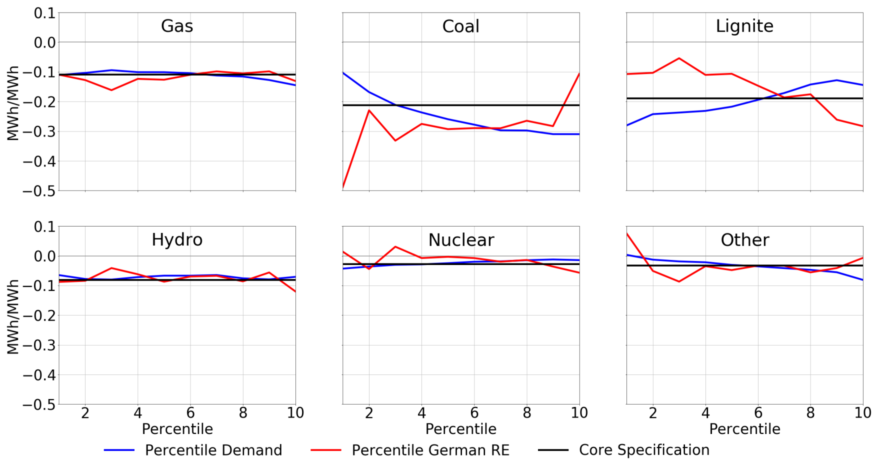
Appendix A. Robustness Checks

Table A.1. Robustness checks for marginal gas replacement effects [MWh/MWh]

DE	AT	BE	CZ	DK	FR	NL	PL	SE	total	FE	R.	C.
-0.109	-0.006	-0.013	-0.011	-0.005	-0.032	-0.056	-0.001	-	-0.233	all	H	yes
(0.004)	(0.001)	(0.002)	(0.001)	(0.000)	(0.003)	(0.002)	(0.001)	-	(0.005)			
-0.109	-0.006	-0.012	-0.011	-0.005	-0.031	-0.051	-0.001	-	-0.225	all	H	no
(0.004)	(0.001)	(0.001)	(0.000)	(0.000)	(0.002)	(0.002)	(0.000)	-	(0.005)			
-0.092	0.000	-0.015	-0.010	-0.007	-0.035	-0.041	0.001	-	-0.200	none	H	no
(0.006)	(0.000)	(0.002)	(0.001)	(0.000)	(0.003)	(0.002)	(0.000)	-	(0.007)			
-0.103	-0.000	-0.016	-0.010	-0.008	-0.035	-0.061	0.003	-	-0.230	h	H	no
(0.005)	(0.000)	(0.002)	(0.000)	(0.000)	(0.003)	(0.002)	(0.001)	-	(0.007)			
-0.095	-0.003	-0.013	-0.010	-0.006	-0.029	-0.051	0.001	-	-0.206	m	H	no
(0.005)	(0.001)	(0.001)	(0.000)	(0.000)	(0.003)	(0.001)	(0.000)	-	(0.006)			
-0.109	-0.005	-0.011	-0.011	-0.003	-0.030	-0.048	-0.002	-	-0.218	m×y	H	no
(0.004)	(0.001)	(0.001)	(0.000)	(0.000)	(0.002)	(0.001)	(0.000)	-	(0.005)			
-0.145	-0.008	-0.011	-0.012	-0.004	-0.030	-0.048	-0.002	-	-0.259	all	D	no
(0.013)	(0.002)	(0.002)	(0.001)	(0.001)	(0.005)	(0.005)	(0.001)	-	(0.015)			
-0.213	-0.008	0.000	-0.011	-0.003	-0.037	-0.055	-0.003	-	-0.330	all	W	no
(0.042)	(0.004)	(0.000)	(0.002)	(0.001)	(0.012)	(0.012)	(0.001)	-	(0.046)			

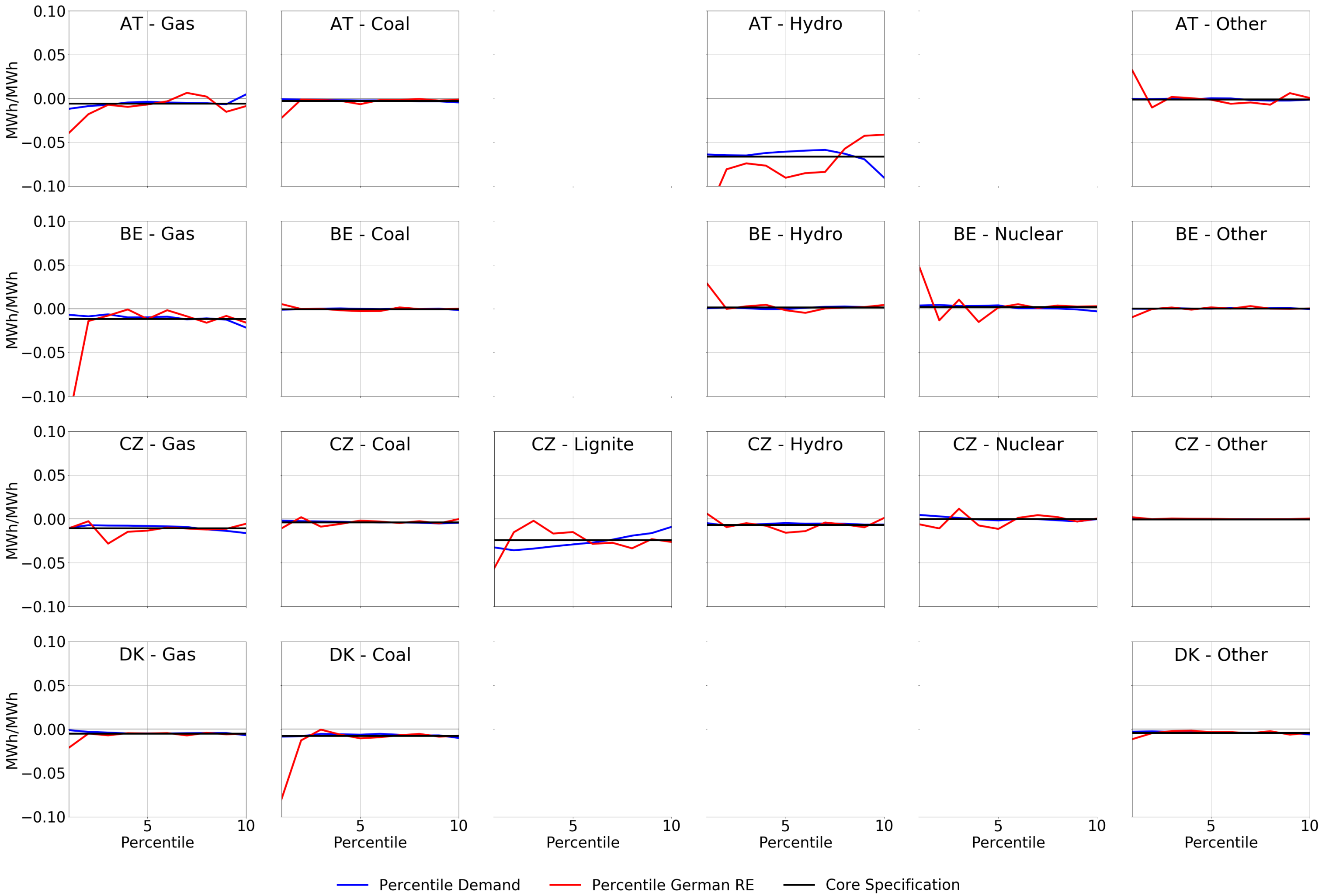
Notes: Numbers correspond to the coefficients β_{ir} of equation (1). **FE** denotes fixed effects; the main specification inlcudes all fixed effects, $m{\times}y/m/h$ refers to month-of-sample/month-of-year/hour-of-day fixed effects. **R.** denotes the temporal resolution of the input data; H refers to hourly, D to daily and W to weekly. **C.** denotes whether or not we control for congestion. Heteroscedasticity robust standard errors in parentheses.

Figure A.1. Results semi-parametric estimation replacement effect Germany [MWh/MWh]



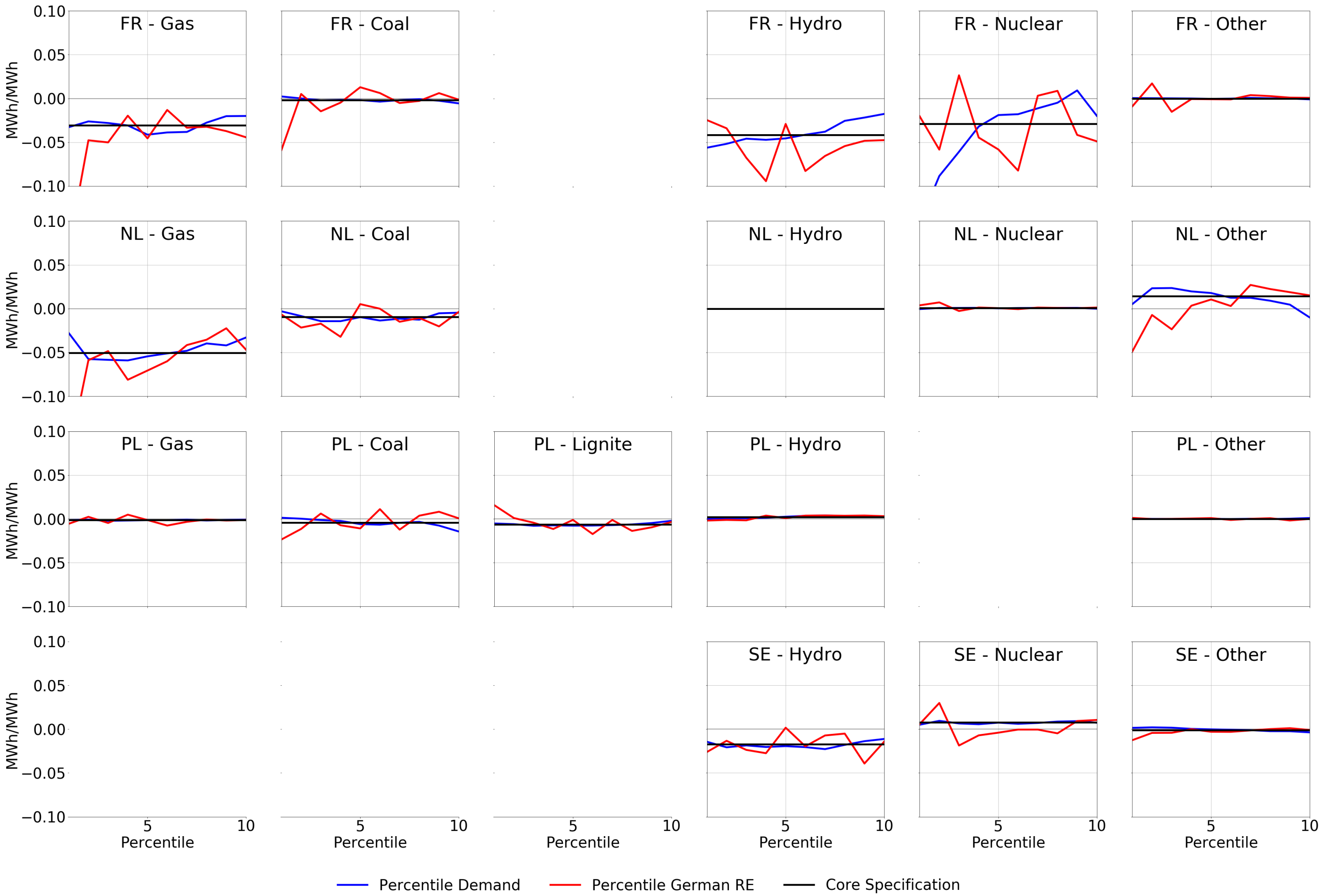
Notes: Figures depict the coefficients β_{bir} of equation (3).

Figure A.2. Results semi-parametric estimation replacement effect [MWh/MWh]



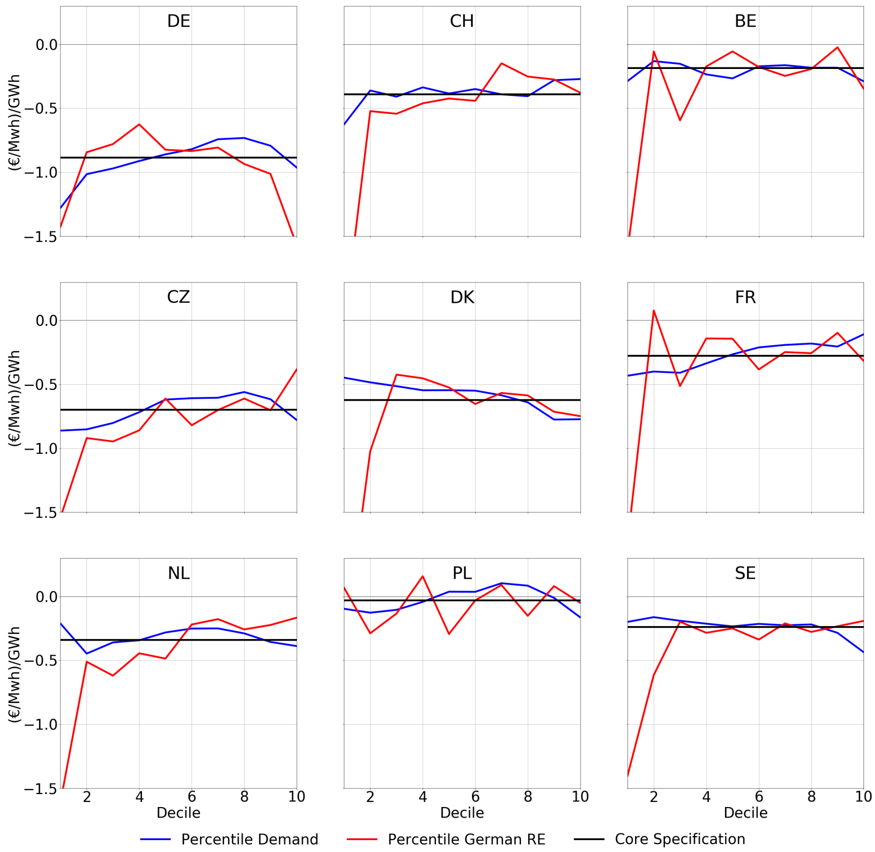
Notes: Figures depict the coefficients β_{bir} of equation (3).

Figure A.3. Results semi-parametric estimation replacement effect [MWh/MWh]



Notes: Figures depict the coefficients β_{bir} of equation (3).

FIGURE A.4. Results semi-parametric estimation prices [€/MWh per GWh]



Notes: Figures depict the coefficients β_{br} of equation (4).

Table A.2. Robustness checks for marginal coal replacement effects [MWh/MWh]

DE	**AT**	**BE**	**CZ**	**DK**	**FR**	**NL**	**PL**	**SE**	**total**	**FE**	**R.**	**Cong.**
-0.212	-0.003	-0.001	-0.004	-0.007	-0.004	-0.011	-0.005	-	-0.247	all	H	yes
(0.007)	(0.000)	(0.000)	(0.000)	(0.001)	(0.001)	(0.002)	(0.002)	-	(0.008)			
-0.212	-0.003	-0.000	-0.004	-0.007	-0.002	-0.010	-0.004	-	-0.242	all	H	no
(0.007)	(0.000)	(0.000)	(0.000)	(0.001)	(0.001)	(0.001)	(0.001)	-	(0.007)			
-0.224	-0.003	-0.002	-0.005	-0.012	-0.007	-0.004	-0.010	-	-0.266	none	H	no
(0.007)	(0.000)	(0.000)	(0.000)	(0.001)	(0.001)	(0.001)	(0.001)	-	(0.007)			
-0.229	-0.003	-0.001	-0.005	-0.012	-0.008	0.000	-0.005	-	-0.262	h	H	no
(0.007)	(0.000)	(0.000)	(0.000)	(0.001)	(0.001)	(0.000)	(0.001)	-	(0.007)			
-0.223	-0.003	-0.002	-0.006	-0.011	-0.004	-0.000	-0.009	-	-0.257	m	H	no
(0.007)	(0.000)	(0.000)	(0.000)	(0.001)	(0.001)	(0.000)	(0.001)	-	(0.007)			
-0.213	-0.003	-0.000	-0.004	-0.006	-0.002	-0.010	-0.009	-	-0.247	m×y	H	no
(0.007)	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.001)	(0.001)	-	(0.007)			
-0.271	-0.003	0.000	-0.004	-0.007	0.000	-0.010	0.000	-	-0.296	all	D	no
(0.020)	(0.001)	(0.000)	(0.001)	(0.001)	(0.000)	(0.004)	(0.000)	-	(0.021)			
-0.342	-0.006	0.000	-0.007	-0.008	0.000	0.000	0.000	-	-0.362	all	W	no
(0.052)	(0.001)	(0.000)	(0.002)	(0.003)	(0.000)	(0.000)	(0.000)	-	(0.053)			

Notes: Numbers correspond to the coefficients β_{ir} of equation (1). **FE** denotes fixed effects; the main specification inlcudes all fixed effects, $m{\times}y/m/h$ refers to month-of-sample/month-of-year/hour-of-day fixed effects. **R.** denotes the temporal resolution of the input data; H refers to hourly, D to daily and W to weekly. **C.** denotes whether or not we control for congestion. Heteroscedasticity robust standard errors in parentheses.

Table A.3. Robustness checks for marginal lignite replacement effects [MWh/MWh]

DE	**AT**	**BE**	**CZ**	**DK**	**FR**	**NL**	**PL**	**SE**	**total**	**FE**	**R.**	**C.**
-0.189	-	-	-0.024	-	-	-	-0.006	-	-0.219	all	H	yes
(0.006)	-	-	(0.001)	-	-	-	(0.002)	-	(0.006)			
-0.189	-	-	-0.024	-	-	-	-0.007	-	-0.219	all	H	no
(0.006)	-	-	(0.001)	-	-	-	(0.001)	-	(0.006)			
-0.197	-	-	-0.015	-	-	-	-0.006	-	-0.218	none	H	no
(0.007)	-	-	(0.001)	-	-	-	(0.001)	-	(0.007)			
-0.192	-	-	-0.017	-	-	-	-0.011	-	-0.221	h	H	no
(0.007)	-	-	(0.001)	-	-	-	(0.001)	-	(0.007)			
-0.181	-	-	-0.020	-	-	-	-0.006	-	-0.207	m	H	no
(0.007)	-	-	(0.001)	-	-	-	(0.001)	-	(0.007)			
-0.189	-	-	-0.024	-	-	-	-0.003	-	-0.216	m×y	H	no
(0.006)	-	-	(0.001)	-	-	-	(0.001)	-	(0.006)			
-0.237	-	-	-0.027	-	-	-	-0.007	-	-0.272	all	D	no
(0.018)	-	-	(0.002)	-	-	-	(0.002)	-	(0.019)			
-0.269	-	-	-0.031	-	-	-	-0.000	-	-0.300	all	W	no
(0.042)	-	-	(0.004)	-	-	-	(0.000)	-	(0.042)			

Notes: Numbers correspond to the coefficients β_{ir} of equation (1). **FE** denotes fixed effects; the main specification inlcudes all fixed effects, $m{\times}y/m/h$ refers to month-of-sample/month-of-year/hour-of-day fixed effects. **R.** denotes the temporal resolution of the input data; H refers to hourly, D to daily and W to weekly. **C.** denotes whether or not we control for congestion. Heteroscedasticity robust standard errors in parentheses.

Table A.4. Robustness checks for marginal hydro replacement effects [MWh/MWh]

DE	**AT**	**BE**	**CZ**	**DK**	**FR**	**NL**	**PL**	**SE**	**total**	**FE**	**R.**	**C.**
-0.081	-0.071	0.001	-0.007	-	-0.044	0.000	0.002	-0.017	-0.217	all	H	yes
(0.003)	(0.002)	(0.000)	(0.001)	-	(0.004)	(0.000)	(0.000)	(0.002)	(0.005)			
-0.081	-0.066	0.002	-0.007	-	-0.042	0.000	0.002	-0.017	-0.210	all	H	no
(0.003)	(0.002)	(0.000)	(0.000)	-	(0.002)	(0.000)	(0.000)	(0.002)	(0.004)			
-0.085	-0.062	0.000	-0.011	-	-0.039	0.000	0.002	-0.011	-0.206	none	H	no
(0.004)	(0.002)	(0.000)	(0.000)	-	(0.004)	(0.000)	(0.000)	(0.002)	(0.007)			
-0.081	-0.060	-0.000	-0.007	-	-0.035	0.000	0.002	-0.020	-0.201	h	H	no
(0.003)	(0.002)	(0.000)	(0.000)	-	(0.004)	(0.000)	(0.000)	(0.002)	(0.006)			
-0.085	-0.064	-0.001	-0.008	-	-0.045	0.000	0.001	-0.011	-0.214	m	H	no
(0.004)	(0.002)	(0.000)	(0.001)	-	(0.004)	(0.000)	(0.000)	(0.002)	(0.006)			
-0.079	-0.075	0.001	-0.008	-	-0.043	0.000	0.001	-0.010	-0.213	m×y	H	no
(0.004)	(0.001)	(0.000)	(0.001)	-	(0.003)	(0.000)	(0.000)	(0.001)	(0.005)			
-0.030	-0.051	0.000	-0.004	-	-0.033	0.000	0.002	-0.019	-0.135	all	D	no
(0.003)	(0.003)	(0.000)	(0.000)	-	(0.005)	(0.000)	(0.000)	(0.005)	(0.008)			
0.000	-0.026	0.000	-0.001	-	-0.036	0.000	0.000	-0.019	-0.083	all	W	no
(0.000)	(0.005)	(0.000)	(0.001)	-	(0.014)	(0.000)	(0.000)	(0.007)	(0.016)			

Notes: Numbers correspond to the coefficients β_{ir} of equation (1). **FE** denotes fixed effects; the main specification inlcudes all fixed effects, $m \times y/m/h$ refers to month-of-sample/month-of-year/hour-of-day fixed effects. **R.** denotes the temporal resolution of the input data; *H* refers to hourly, *D* to daily and *W* to weekly. **C.** denotes whether or not we control for congestion. Heteroscedasticity robust standard errors in parentheses.

Table A.5. Robustness checks for marginal nuclear replacement effects [MWh/MWh]

DE	**AT**	**BE**	**CZ**	**DK**	**FR**	**NL**	**PL**	**SE**	**total**	**FE**	**R.**	**C.**
-0.027	-	0.003	0.000	-	-0.010	0.001	-	0.008	-0.026	all	H	yes
(0.003)	-	(0.001)	(0.000)	-	(0.001)	(0.000)	-	(0.001)	(0.004)			
-0.027	-	0.002	0.000	-	-0.029	0.001	-	0.008	-0.046	all	H	no
(0.003)	-	(0.001)	(0.000)	-	(0.005)	(0.000)	-	(0.001)	(0.006)			
-0.048	-	0.000	0.006	-	0.000	-0.003	-	0.014	-0.032	none	H	no
(0.005)	-	(0.000)	(0.001)	-	(0.000)	(0.000)	-	(0.002)	(0.005)			
-0.040	-	-0.000	0.003	-	0.023	-0.002	-	0.024	0.007	h	H	no
(0.005)	-	(0.000)	(0.001)	-	(0.008)	(0.000)	-	(0.002)	(0.009)			
-0.035	-	0.000	0.004	-	-0.022	-0.001	-	0.010	-0.044	m	H	no
(0.004)	-	(0.000)	(0.001)	-	(0.006)	(0.000)	-	(0.002)	(0.008)			
-0.027	-	0.000	0.000	-	-0.034	0.000	-	0.005	-0.056	m×y	H	no
(0.003)	-	(0.000)	(0.000)	-	(0.004)	(0.000)	-	(0.001)	(0.005)			
-0.037	-	0.000	0.000	-	-0.025	0.000	-	0.010	-0.052	all	D	no
(0.007)	-	(0.000)	(0.000)	-	(0.010)	(0.000)	-	(0.003)	(0.013)			
-0.070	-	0.000	0.000	-	0.000	0.006	-	0.000	-0.064	all	W	no
(0.027)	-	(0.000)	(0.000)	-	(0.000)	(0.003)	-	(0.000)	(0.027)			

Notes: Numbers correspond to the coefficients β_{ir} of equation (1). **FE** denotes fixed effects; the main specification inlcudes all fixed effects, $m \times y/m/h$ refers to month-of-sample/month-of-year/hour-of-day fixed effects. **R.** denotes the temporal resolution of the input data; *H* refers to hourly, *D* to daily and *W* to weekly. **C.** denotes whether or not we control for congestion. Heteroscedasticity robust standard errors in parentheses.

Table A.6. Robustness checks for marginal replacement effects of *other* technologies [MWh/MWh]

DE	AT	BE	CZ	DK	FR	NL	PL	SE	total	FE	R.	C.
-0.033	-0.002	0.001	-0.000	-0.004	-0.001	0.015	0.000	-0.001	-0.025	all	H	yes
(0.004)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.005)			
-0.033	-0.001	0.000	-0.000	-0.004	0.000	0.014	0.000	-0.001	-0.025	all	H	no
(0.004)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.004)			
-0.063	-0.006	0.000	0.000	0.000	-0.001	0.027	0.000	0.000	-0.042	none	H	no
(0.006)	(0.001)	(0.000)	(0.000)	(0.000)	(0.001)	(0.001)	(0.000)	(0.000)	(0.007)			
-0.056	-0.004	0.001	0.000	0.002	-0.001	0.017	0.000	-0.000	-0.041	h	H	no
(0.006)	(0.001)	(0.000)	(0.000)	(0.001)	(0.001)	(0.001)	(0.000)	(0.000)	(0.006)			
-0.065	-0.003	0.001	-0.001	-0.000	-0.000	0.019	0.000	-0.000	-0.049	m	H	no
(0.006)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.006)			
-0.031	-0.002	0.001	-0.000	-0.004	-0.000	0.017	-0.000	-0.000	-0.019	m×y	H	no
(0.004)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.004)			
-0.023	0.000	0.000	0.000	-0.004	0.000	0.000	0.000	-0.002	-0.029	all	D	no
(0.010)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.010)			
0.000	0.000	0.000	0.000	-0.004	0.000	0.000	0.000	-0.004	-0.008	all	W	no
(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.000)	(0.001)	(0.002)			

Notes: Numbers correspond to the coefficients β_{ir} of equation (1). **FE** denotes fixed effects; the main specification inlcudes all fixed effects, $m{\times}y/m/h$ refers to month-of-sample/month-of-year/hour-of-day fixed effects. **R.** denotes the temporal resolution of the input data; H refers to hourly, D to daily and W to weekly. **C.** denotes whether or not we control for congestion. Heteroscedasticity robust standard errors in parentheses.

Table A.7. Marginal price impact per GWh of German RE [€/MWh per GWh]

FE	DE	CH	BE	CZ	DK	FR	NL	PL	SE
all	-0.88	-0.39	-0.18	-0.70	-0.62	-0.28	-0.34	-0.03	-0.24
	(0.02)	(0.01)	(0.03)	(0.02)	(0.02)	(0.02)	(0.01)	(0.01)	(0.01)
none	-0.91	-0.46	-0.31	-0.81	-0.49	-0.37	-0.30	0.08	-0.26
	(0.03)	(0.02)	(0.03)	(0.02)	(0.02)	(0.02)	(0.01)	(0.01)	(0.02)
h	-0.96	-0.47	-0.33	-0.75	-0.65	-0.39	-0.39	-0.04	-0.31
	(0.03)	(0.02)	(0.03)	(0.02)	(0.02)	(0.02)	(0.02)	(0.01)	(0.02)
m	-0.95	-0.47	-0.28	-0.73	-0.63	-0.31	-0.40	0.04	-0.26
	(0.03)	(0.02)	(0.03)	(0.02)	(0.02)	(0.02)	(0.01)	(0.01)	(0.02)
m × y	-0.89	-0.42	-0.19	-0.70	-0.60	-0.29	-0.35	0.05	-0.21
	(0.02)	(0.01)	(0.03)	(0.02)	(0.02)	(0.02)	(0.01)	(0.01)	(0.01)

Notes: Numbers correspond to the coefficients β_r of equation (2). **FE** denotes fixed effects; the main specification inlcudes all fixed effects, $m{\times}y/m/h$ refers to month-of-sample/month-of-year/hour-of-day fixed effects. Heteroskedasticity robust standard errors in parentheses.

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