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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 in the market, and thus induce a decrease in wholesale electricity prices. This so-called merit-order effect stimulates an increase in net-exports. Consequently, prices in neighboring countries are also likely to decrease. This cross-border merit-order effect causes opposing effects on consumers and producers: Generators' profits decline, while consumers benefit from decreasing prices and an increase in the consumer surplus. This implies that unilateral RE promotion, which is usually paid for by the consumers within the country itself, impact neighboring electricity markets. We estimate the cross-border merit-effect for German RE using hourly data on electricity generation, demand and wholesale prices for the period from 2015 to 2018. We find that German RE decreased electricity prices in surrounding countries by up to 10€/MWh or 23%, and can thus have a significant impact on their consumer and producer rents.

Keywords: Renewable promotion, Electricity prices, Merit-order effect, Cross-border impacts

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. With its climate and energy package 2020, the European Union (EU) made a first step in this direction. The legislation contains three main targets for the year 2020 (2030): A reduction of 20 (40)% in carbon dioxide (CO₂) emissions relative to 1990; a share of 20 (32)% renewable energy (RE) generation; and a 20 (32.5)% increase in energy efficiency relative to a business as usual scenario. To reach this and further targets, the electricity sector is especially relevant as it is a major emitter of CO₂ and carbon mitigation strategies for mobility and heating largely rely on electrification, e.g., electro-mobility or heat pumps. Regulation to mitigate these emissions come in two major forms: Carbon pricing and renewable energy (RE) support (RES). Within the European Emission Trading System (EU ETS) carbon price is harmonized across electricity generators and

member states of the EU. In contrast, RES is determined at the Member State level. As the European electricity grid is however highly interconnected, RES in one country affects consumers and producers in the neighbor countries through changes in electricity trade and prices.

RE production leads to a decrease of conventional generation by replacing the most expensive generators in the market, which leads to a decrease of the wholesale electricity price. This so-called merit-order effect stimulates an increase in electricity exports or, likewise, a decrease in imports. Consequently, prices in neighboring countries are also likely to decrease. 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, consumers, and producers.

The size of this cross-border merit order effect crucially depends on the amount of RE generation and trade possibility between countries. If sufficient cross-border interconnections exist, we expect prices to converge and be equal across countries. RE generation in one country would, therefore, affect prices in all countries by the same amount. In the case of congestion, however, the limitation of trade capacities leads to a price effect asymmetric across countries.

The German electricity market has both, a high amount of RE and a good connection to its neighboring countries through its location in the center of Europe. From 2010 to 2019, German wind and solar production increased from 38 to 125 TWh and 11 to 46 TWh, respectively ([AG Energiebilanzen, 2019](#)). Also, Germany is currently connected to most of its neighboring countries (Austria (AT), Switzerland (CH), Czech Republic (CZ), Denmark (DK), France (FR), The Netherlands (NL), Poland (PL), and Sweden (SE)) with a hourly export capacity of more than 20 GW. Thus, the increase in near zero marginal cost and highly subsidized generation, likely induces a decrease in German electricity price which, through an increase in exports, also decreases prices in neighboring countries.

Against this background, this paper asks three main questions: What was the impact of RE generation in Germany and its neighbors on domestic wholesale electricity market prices (merit-order effect)? What was the impact of German RE generation on electricity prices of its neighbors (cross-border merit-order effect)—and how does it depend on congestion? What was the impact of German RE on producer and consumers rents in neighboring countries?

These questions are of high political interest. For example, Swiss hydro generators argue that due to a decrease in electricity prices—partly induced by German RE promotion—they are no longer profitable. As a consequence, the Swiss government grants subsidies to Swiss hydro generators. In contrast, Swiss consumers should benefit from lower prices. Yet, at the same time, German consumers suffer from higher end consumer electricity prices as RE promotion is financed by a tax on electricity consumption. Despite their political relevance, these effects have not yet been quantified.

This paper contributes to this ongoing debate estimating the domestic merit-order effect, as well as the impact of German RE on neighboring electricity prices (cross-border merit-order) within the period from 2015 to 2018 individually for each country. We use an empirical quantitative framework and hourly data on (exogenous) RE production, load and electricity prices, including further controls such as daily fuel and carbon prices, and weather data. Finally, we assess the impacts on producer and consumer rents.

Our main findings are as follows. First, we find that the domestic merit-order effects vary significantly across countries. For Germany itself it is relatively low with -1.1 €/MWh per GWh of RE generation; for Poland it is highest with -3.7 €/MWh . In the case of Switzerland and the Czech Republic, we do not observe a (statistically significant) merit-order effect.

Second, the impact of German RE on foreign electricity prices is smaller than the effect on the German price as well as the domestic merit-order effect of the respective country. German RE has the largest impact on prices in the Czech Republic (-0.7 €/MWh per GWh of German RE generation), and the smallest on Polish prices.

Third, considering average instead of marginal price effects, German RE has an impact on foreign prices similar to the effect of RE installed in these countries. This is due to the high amount of German RE compared to neighboring countries' RE. German RE generation lead to a decrease in neighboring electricity prices of up to 10 €/MWh (about 23 % decrease).

Fourth, as a consequence the cross-border merit-order effect induces significant shifts from producer to consumer rents. Lower prices decrease the capacity rents of producers but at the same time electricity cost for consumers also decline.

Fifth, the size of these effects crucially depends on the import and export possibilities of the different electricity markets: Higher export possibilities reduce the domestic merit-order effects. Higher import possibilities (from Germany) increase the cross-border merit-order impact of German RE generation.

Existing literature has analyzed the merit-order effect within Germany and some other countries (Abrell et al., 2019; Cludius et al., 2014; Wuerzburg et al., 2013), and—on an aggregated level—the impact of German RE on exports (Abrell et al., 2019). So far, the literature on merit-order effects concentrated on within country effects but largely ignored price effects across border. As notable exception, Mulder & Scholtens (2016) look at the impact of German RE on Danish generation and prices, and find an elasticity of -3% of Danish prices. Phan & Roques (2015) and Haxhimusa (2018) analyze the impacts of German RE on French price levels and volatility. Gugler & Haxhimusa (2019) look at price convergence and congestion between Germany and France. This paper contributes in three ways: First, we provide estimates of the domestic merit-order effect for a larger set of countries. Second, we analyze the cross-border merit-order effects for all neighbors of Germany. As we use the same data source and estimation model for all countries, the results become comparable and provide insights to the drivers of the impacts. Third, we assess to what extent German RE promotion lead to a shift from producer to consumer rents

in neighboring countries, which—to the best of our knowledge—has not yet been analyzed.

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

2. Context and Data

To increase their share of RE generation, all European countries have implemented RES schemes. These schemes, however, significantly differ in size. Within central Europe, Germany has implemented the most extensive RES scheme by far, resulting in a very large share of RE generation. As Germany lies in the center of Europe and is highly integrated in international power trade (see Figure 1), its RE generation is likely to affect neighboring countries.

2.1. Renewable energy promotion and its impacts on prices and trade

RE GENERATION—Over the years 2015 to 2019, the average hourly generation amounted to 12.4 GWh for wind, and 4.7 GWh for solar (see Table 1). Together, this corresponds to around 25% of total generation. In absolute terms, German RE generation is around four times larger compared to France, the biggest neighboring country with a RE generation of 4.2 GWh per hour. In relative terms, only Denmark has a higher share of RE generation (43%).

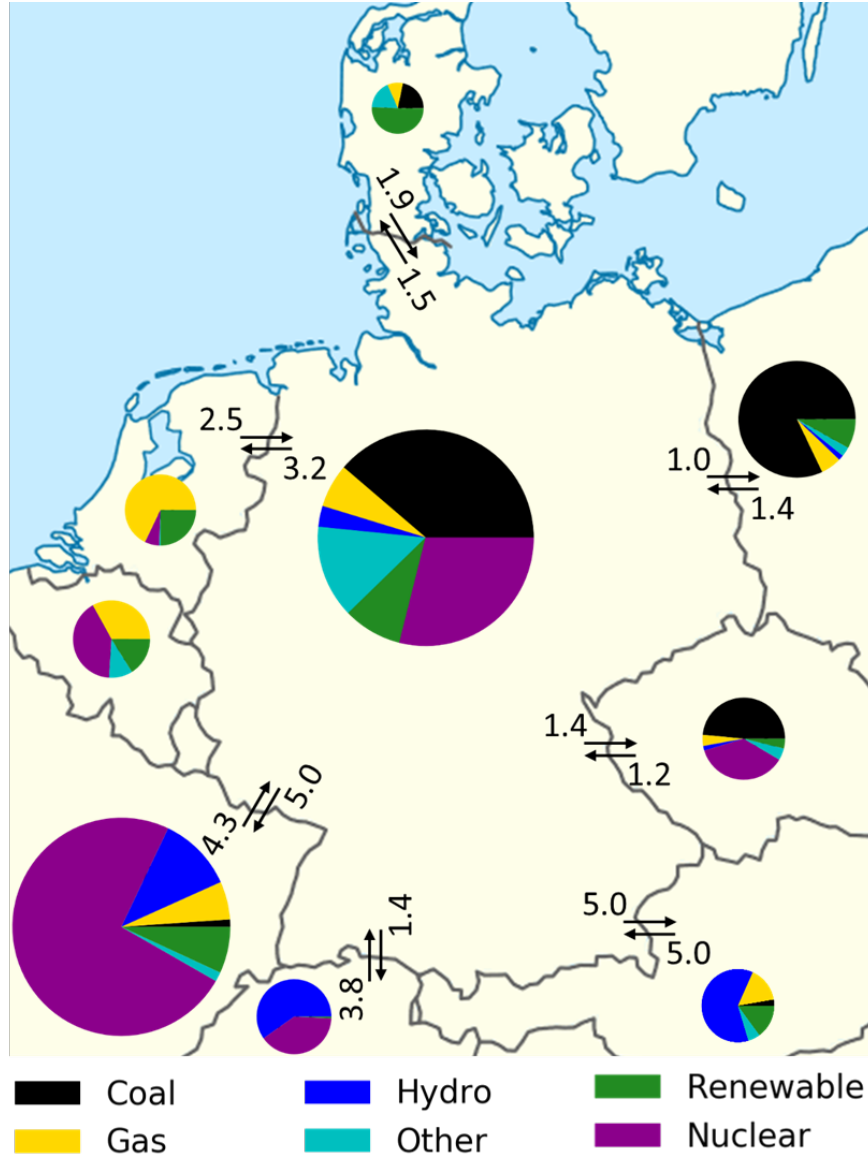
PRICE IMPACTS OF RE GENERATION—RE generation with near zero marginal cost replaces more expensive, mostly fossil-based, generation. This has three implications. First, domestic electricity prices decrease due to the merit-order effect. Figure A.6 in the Appendix shows that there is a negative correlation between RE generation and electricity prices in each country. Second, a decrease in domestic prices incentivizes exports. Germany lies in the center of Europe and is highly interconnected with its neighbors, as can be seen by the net transfer capacities (NTC) shown in Figure 1. Looking at the relation between German RE generation and net exports to surrounding countries in Figure 2, we indeed find a positive correlation for all countries, indicating a positive impact of RE on exports. Third, this increase in exports (or decrease in imports, respectively) lowers electricity prices in neighboring countries (cross-border merit-order effect). Yet, Figure A.7 in the Appendix shows, that the correlation between German RE and foreign electricity prices is not in all cases negative.

Obviously, there are many other factors influencing the electricity price. This paper thus contributes by estimating the merit order effect of Germany and its neighbors, and the cross-border merit-order impact of German RE.

2.2. Electricity markets: production, prices and trade

Historically, European electricity markets are very heterogeneous, and the impact of RE depends on these different market characteristics. In the following,

FIGURE 1. German Electricity Trade Capacities [GW]



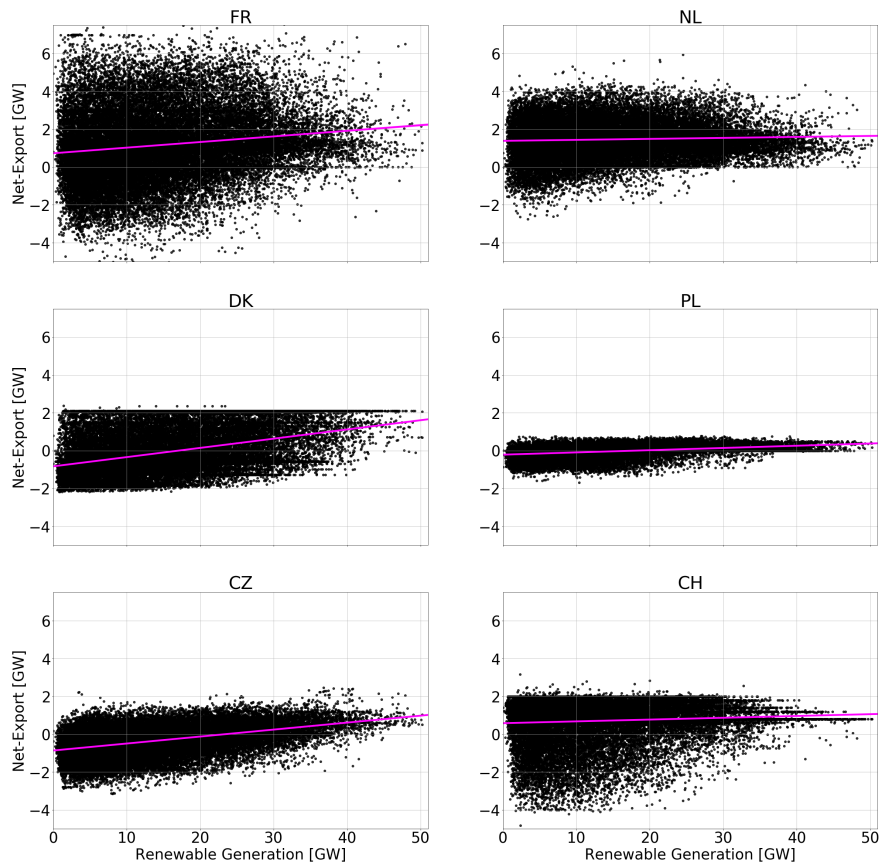
Notes: Figure shows the average hourly net transfer capacity (Bundesnetzagentur (BNetzA), 2019). Germany, France, and Netherlands are coupled in a flow-based system. No direct connection exists between Germany and Belgium. Load values are provided to put number into relation (ENTSOE, 2019).

TABLE 1. Installed Generation Capacity, Hourly Renewable Generation, and Load

	CH	CZ	DE	DK	FR	NL	PL
Generation Capacities (GW)							
Pump Storage	6.6	1.2	8.9	-	5.0	-	1.8
Hydro	5.9	1.1	5.3	0.0	19.8	0.0	0.6
Other	-	0.6	8.3	2.0	2.0	0.6	0.8
Nuclear	3.4	4.0	9.5	-	63.1	0.5	0.0
Lignite	-	8.5	21.3	-	-	-	8.6
Coal	-	1.2	25.0	3.7	4.0	4.6	20.1
Gas	-	1.2	31.4	1.8	11.8	18.4	2.1
Oil	-	-	4.3	1.0	6.3	-	0.4
Total	15.9	17.8	114.0	8.5	112.0	24.2	34.3
Average Hourly Renewable Generation (GWh)							
Wind Onshore	0.0	0.1	10.2	1.1	3.1	0.8	1.4
Wind Offshore	-	-	2.2	0.5	-	0.4	-
Solar	0.0	0.3	4.7	0.1	1.1	0.4	-
Total	0.0	0.3	17.1	1.7	4.2	1.6	1.4
Hourly Load (GWh)							
Average	6.7	7.6	58.1	3.8	53.8	13.1	19.5
Maximum	9.8	11.1	78.3	7.7	94.5	18.8	26.3
Average Electricity Price (2015-2018) (€/MWh)							
Average	44.1	36.5	34.9	32.0	42.6	41.0	41.0
Net Transfer Capacities from/to Germany							
Import from DE (GW)	1.4	1.4	-	1.5	5.0	3.2	1.0
% of average load	20.9	18.4	-	39.5	9.3	24.4	5.1
Export to DE (GW)	3.8	1.2	-	1.9	4.3	2.5	1.4
% of average load	56.7	15.8	-	50.0	8.0	19.1	7.2
Average congestion share							
(%)	90	82	-	72	62	56	92

Source: ENTSOE (2019).

FIGURE 2. German Renewable Generation and Net-Exports [GW]



Notes: Figure shows total hourly German RE generation of wind and solar power together with net-exports to neighboring countries (ENTSOE, 2019).

FIGURE 3. Electricity prices



Notes: Shown are monthly averages of hourly day-ahead prices (ENTSOE, 2019). The left (right) panel shows prices in south-west (north-east) neighboring countries together with German prices (dashed line).

we thus shortly describe the electricity markets of Germany and its neighbors in terms of size, conventional and renewable production portfolio, prices, and net transfer capacities (NTC) to Germany (see Table 1). Currently, our analysis does not include Belgium, which has no direct inter-connector line to Germany; and Austria, which for many years was in the same price zone as Germany.

MARKET SIZE—In terms of average hourly load, Germany and France are the largest electricity markets in our sample with 58 and 54 GWh, respectively. They are followed by Poland and the Netherlands. Average hourly load in the Czech Republic, Switzerland, and Denmark are below 10 GWh.

PLANT PORTFOLIO—The countries are characterized by different production profiles. In Germany itself, the predominant technologies were coal and nuclear power. In recent years, however, there was a drastic increase in RE generation, and the political decisions to phase-out coal and nuclear power. Denmark shows a similar pattern with large shares of coal and RE generation. Also Poland and the Czech Republic are characterized by large shares of coal and lignite generation, yet in both countries RE generation is still very small. A smaller share of coal generation can be observed in the Netherlands, where gas is the major electricity source. Finally, France and Switzerland are both characterized by large shares of nuclear. To cover their peak load hours, France relies on coal and gas plants, while Switzerland has large pump storage capacities.

PRICES—These differences in production portfolios lead to different electricity prices between countries. Figure 3 shows the development of electricity prices from 2015 to 2018. The left panel shows prices in south-west neighboring countries (CH, FR, NL). We observe three main points: First, most of the time, monthly average prices in Germany are lower than in the other countries. Second, during summer months, the prices of neighbors are relatively similar to Germany; while in winter months they are significantly higher. Third, dutch prices, seem to be somewhere in between.¹ Looking at the installed capacities,

¹The Netherlands have own natural gas resources. It is thus likely, that electricity producers can benefit from prices lower than international market prices for gas.

we find that all countries have very low shares of coal capacity. Thus peak prices in winter are likely to be defined by gas plants (or imports in the case of Switzerland). Thus, resulting electricity prices are higher compared to Germany. In contrast, for the north-eastern countries (DK, PL, CZ), which all have higher shares of coal and/or lignite, but lower shares of gas generation, we observe that prices are relatively close to German prices. In the case of Denmark, which has a large share of RE generation, they are most of the time slightly lower. In the case of Poland, with almost no RE generation, they are slightly higher. In summary, depending on the installed plant portfolio, prices have been following the coal or gas price respectively, and RE generation seemed to have a decreasing effect on the electricity price. As a result, yearly average electricity prices are lowest in Denmark, Germany and the Czech Republic; somewhere in between for Poland, the Netherlands, and France; and highest for Switzerland and Belgium.

TRADE—Figure 1 shows the average hourly net transfer capacities for Germany. For some countries, imports from Germany can account for a large share of average domestic generation. This is the case for the two smallest electricity markets, Switzerland and Denmark, where German exports can cover 57% and 39%, respectively, of average domestic generation. To what extent German RE generation impacts neighboring electricity markets crucially depends on the available export capacities and thus on whether or not the installed export lines are congested or not. The share of hours with congestion differs between countries (see Table 1). It is highest for Poland and Switzerland (more than 90%), somewhat lower for the Czech Republic (82%) and Denmark (72%), and lowest for France (62%) and the Netherlands (56%).²

2.3. Data Sources and Construction

We use hourly data on electricity demand (also called load), electricity prices, and renewable generation for each country from the ENTSO-E transparency platform (ENTSOE, 2019). They separately provide data on solar, wind onshore, and wind offshore generation, which we aggregate to total hourly RE generation.

Daily coal and natural gas prices are taken from EIKON (2017). We use daily forward contract for carbon prices (ICE, 2020) and daily mean temperature from ECAD (2020).

As we do not directly observe congestion, we construct a measure for congestion: We assume, that whenever prices between two countries differ by more

²As we do not observe congestion rates, we calculate them by exploiting the price difference between the countries as described in Section 2.3.

than 2%, the lines are congested.

$$C_{trr'} = 0 \quad \text{if} \quad \frac{p_{tr}^{ele} - p_{tr'}^{ele}}{p_{tr}^{ele}} < |0.02| \quad (1)$$

$$C_{trr'} = 1 \quad \text{if} \quad \frac{p_{tr}^{ele} - p_{tr'}^{ele}}{p_{tr}^{ele}} \geq |0.02| \quad (2)$$

3. Empirical Framework

3.1. Price Formation in Electricity Markets

In competitive electricity markets, the electricity price p in hour t and region r is equal to the marginal cost c of the most expensive, i. e., marginal, generator in the market:

$$p_{tr} = c_{tr}^* \quad (3)$$

The marginal generator, in turn, depends on residual demand, i. e., total load net of RE production, and the supply curve of conventional generation in a given hour. The latter is determined by marginal cost and available capacities of conventional producers. Thus, the electricity market price is a function of demand D , RE generation R , marginal cost c , and available capacities k of conventional power plants:

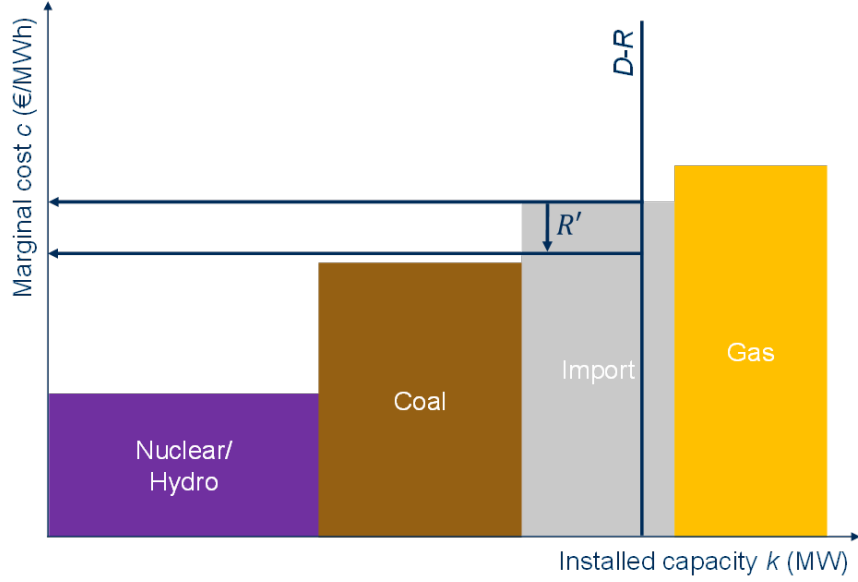
$$p_{tr} = f(D_{tr}, R_{tr}, c_{tr}, k_{tr}) + \epsilon_{tr} \quad (4)$$

Within our context, we observe hourly electricity demand (D) and RE generation (R) for each country. Marginal cost of conventional producers are not observed, however, we know that they are mainly determined by fuel and carbon prices, as well as heat efficiencies. While we observe coal, gas, and carbon prices ($p^{coal}, p^{gas}, p^{EUA}$), this is not the case for heat efficiencies. However, we can use observed daily mean temperature (T), which influences heat efficiencies of thermal power plants, as a proxy for heat efficiency. Finally, capacities are only observed at a yearly level. Thus, we use month-of-year fixed effects to account for changes in capacities. In a closed electricity market, we can thus estimate the hourly electricity price as a function of demand, RE generation, fuel and carbon prices, temperature, and time fixed effects F :

$$p_{tr}^{ele} = f(D_{tr}, R_{tr}, T_{tr}, p_{tr}^{coal}, p_{tr}^{gas}, p_{tr}^{EUA}, F_{tr}) \quad (5)$$

Given that electricity markets in Europe are highly connected with each other, also imports and exports can influence the domestic electricity prices. As illustrated by the stylized electricity market model in Figure 4, imports can be seen as additional generation technologies, where the available capacity corresponds to the net transfer capacity (NTC), and the marginal cost to the

FIGURE 4. Stylized electricity market model [GW]



Notes: $D-R$ denotes residual demand, i. e., demand net of RE generation. The arrow denoted by R' represents the decrease in import prices due to RE generation of the neighboring country.

electricity price in the neighboring country. Thus, if RE generation in Germany induce lower prices, the import cost decrease, leading to lower electricity prices in neighboring countries. To account for this effect, we can include RE generation of neighboring countries (R') as a control. Finally, as the impact of foreign RE generation on imports is limited by the NTC, we assume that the impact on neighboring electricity prices depends on the utilization of the inter-connector lines. To account for this effect, we include a dummy variable (C), indicating whether or not there is congestion between the two countries. This allows us to separately assess the impact of German RE generation on foreign prices for hours with and without congestion:

$$p_{tr}^{ele} = f(D_{tr}, R_{tr}, R'_{tr}, C_{trDE}, T_{tr}, p_{tr}^{coal}, p_{tr}^{gas}, p_{tr}^{EUA}, F_{tr}) + \epsilon_{tr} \quad (6)$$

Currently, we individually estimate the impact of German RE on each of its neighbors. This implies that we neglect the impact of other countries, and also the impact of neighboring markets on Germany. In a next step, we aim at jointly estimating the electricity prices of all countries, depending on exogeneously determined fuel and carbon prices, RE generation, and weather data.

3.2. Estimation model

Based on the consideration above, we define our model to estimate the impact of RE on the electricity price as follows:

TABLE 2. Estimation variables

Variable	Description
p_{tr}^{ele}	Hourly electricity price in country r (€/MWh)
R_{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)
p_t^{gas}	Daily gas price (€/MWh)
P_t^{EUA}	Daily price of European Emissions Allowances (EUA) (€/t)
$C_{trr'}$	Dummy indicating congestion between countries r and r'

$$\begin{aligned}
P_{tr}^{ele} = & \alpha_r + \beta_{r1}R_{tr} + \beta_{r2}R_{tDE} + \beta_{r3}C_{trDE}R_{tDE} \\
& + \gamma_{r1}D_{tr} + \gamma_{r2}D_{tr}^2 + \gamma_{r5}P_{tr}^{coal} + \gamma_{r6}P_{tr}^{gas} + \gamma_{r7}P_{tr}^{EUA} \quad (7) \\
& + \gamma_{r8}T_{tr} + \mathbf{F}_t\boldsymbol{\delta}_r + \epsilon_{tr},
\end{aligned}$$

where the vector \mathbf{F}_t denotes time fixed effects, e. g., for each month of the year or hour of the day. All estimation variables are described in Table 2.

The identification of our coefficients of interest relies on two crucial assumptions: First, we assume, that demand does not react to price changes, i. e., is inelastic, and thus exogenous. Second, we assume that also renewable generation (R), is exogenous, i. e., does only depend on the availability of the natural resource.

3.3. Alternative Specifications

To analyze the robustness of our results, we use different specifications of our model. First, we estimate the model without including any time fixed effects. Second, we estimate specifications including hourly and/or month-of-year fixed effects. Third, in some specifications we include the German load as a control variable.

4. Results

The detailed regression results for our main specification given by Equation (7) are presented in Table B.6 in the Appendix.

In the following, we present our results for the marginal domestic and cross-border merit-order effects for Germany and its neighbors. We then use marginal effects and average RE generation to calculate the average impacts on electricity prices. Finally, we set the absolute impacts in relation to average electricity prices, to assess to what extent lower electricity prices lead to a shift from producer to consumer rents.

TABLE 3. Merit-order effect (€/MWh per GWh)

	CH	CZ	DE	DK	FR	NL	PL
<i>MO</i>	-3.28	-0.48	-1.08***	-2.68***	-1.55***	-2.49***	-3.66***
	(3.44)	(0.48)	(0.03)	(0.14)	(0.13)	(0.16)	(0.21)

Notes: *, **, ***: Significant at the 10%, 5% and 1% levels, respectively.

4.1. Merit-order effect

The marginal merit-order effect, i. e., the impact of one GWh of RE generation on the domestic electricity price, is given by β_{r1} :

$$MO_r := \frac{\partial P_{tr}^{ele}}{\partial R_{tr}} = \beta_{r1} \quad (8)$$

Table 3 shows the merit-order effect for Germany and its neighbors. In all countries (except for Switzerland and the Czech Republic), we find a negative impact of RE generation on the electricity price. The impact is relatively low for Germany³ and France; higher for Denmark and the Netherlands; and highest for Poland.

In Switzerland and the Czech Republic we do not observe a significant impact of domestic RE generation on the electricity price. Out of our sample, these two countries have the lowest RE generation, both, in absolute and in relative terms. Also, especially the Swiss electricity market is characterized by a very high market integration, i. e., high export capacities to neighboring countries. Thus, it is more likely, that additional RE generation leads to more exports, but does not affect the domestic price.

The same argument is likely to hold for Germany and France, the two largest electricity markets in our sample. Both countries lie in the center of Europe with many inter-connectors to other countries. Also, as both markets have an average hourly load of more than 50 GWh, the impact of one additional GWh of RE generation is likely to be relatively small. In contrast, the electricity markets of Denmark, the Netherlands, and Poland are smaller and also lie more at the borders of Europe, i. e., do not have as many export possibilities. Thus, a one GWh increase of RE generation has a larger impact on the domestic electricity prices.

³The estimated German merit-order effect of -1.1€/MWh for the years 2015 to 2018 is very similar to the results in Abrell et al. (2019), who—for the years 2010 to 2015—find a merit-order effect of -1.2, and -0.7 €/MWh per GWh of wind and solar generation, respectively.

TABLE 4. Cross-border merit-order effect (€/MWh per GWh)

	CH	CZ	DK	FR	NL	PL
MO^{cross}	-0.29*** (0.00)	-0.73*** (0.00)	-0.29*** (0.00)	-0.13*** (0.00)	-0.26*** (0.00)	0.06*** (0.00)
no congestion ($C_{rDE} = 0$)	-0.30*** (0.03)	-0.79*** (0.03)	-0.29*** (0.02)	-0.15*** (0.03)	-0.40*** (0.02)	-0.03 (0.03)
congestion ($C_{rDE} = 1$)	-0.29*** (0.04)	-0.71*** (0.03)	-0.30*** (0.03)	-0.12*** (0.03)	-0.15*** (0.02)	0.07** (0.03)

Notes: *, **, ***: Significant at the 10%, 5% and 1% levels, respectively.

4.2. Cross-border merit-order effect

The average cross-border merit-order effect, i. e., the impact of one GWh of German RE generation on electricity prices in neighboring markets, is defined as:

$$MO_r^{cross} := \left. \frac{\partial P_{tr}^{ele}}{\partial R_{tDE}} \right|_{C_{trDE} = \bar{C}_{trDE}} = \beta_{r4} + \beta_{r5} \bar{C}_{trDE}, \quad (9)$$

where \bar{C}_{trDE} is the share of congested hours between country r and Germany. Thus, the cross-border merit-order effect during non-congested hours corresponds to β_{r4} , and to $\beta_{r4} + \beta_{r5}$ during hours with congestion. Table 4 shows the results.

We estimate the highest cross-border merit-order effect for the Czech Republic, followed by Switzerland, Denmark, and the Netherlands. In all four countries, the import capacity from Germany is high compared to the size of the electricity market, e. g., in Denmark 40% of the hourly average load can be covered by imports from Germany. Thus, changes in import prices are likely to have a significant impact on domestic electricity prices. In France, where imports from Germany can only account for up to 9% of the average hourly load, the cross-border merit-order effect is smaller. Finally, for Poland, we even find a positive impact on prices. However, this result is not very robust to different specifications, i. e., Table C.14 shows that for some specifications, no statistically significant effect of German RE on Polish electricity prices can be found.

We find that the cross-border merit-order effect differs between hours with and without congestion. It is generally higher in hours without congestion, and lower in congested hours, when an additional unit of German RE generation cannot increase exports and further decrease neighboring prices. However, the share of congested hours does not seem to have an impact on the average cross-border merit-order effect.

4.3. Sensitivity

Our estimations of domestic and cross-border merit-order effects seems to be robust for most of the countries. Yet, there are two exceptions. First, the Swiss domestic merit-order effect highly varies between specifications. A possible reason for this behavior is the high share of (pump) storage plants in Switzerland, which can flexibly react to a change in imports and prices. However, a more detailed analysis of the Swiss merit-order effect is needed. Second, the cross-border effect of German RE on Polish prices is—for some specifications—positive and for others not statistically significant, which is more likely. Here, a possible explanation are the high congestion rates between Germany and Poland of more than 90%. Yet again, a more detailed analysis of this result is needed.

4.4. Domestic versus cross-border merit-order effect

For all countries except for Switzerland and the Czech Republic, the cross-border merit-order effect is significantly lower than the within country merit-order effect (see left panel of Figure 5). This means, that electricity prices are more affected by one GWh of RE generation in the own country as compared to an additional GWh of RE generation in Germany.

Yet, not only the marginal, but also the total impacts of RE generation in the electricity prices are of interest. To calculate the average impact of RE generation on the electricity price, we thus multiply the marginal merit-order effect with the average hourly generation in country r or Germany, respectively:

$$\Delta P_r := MO_r \bar{R}_r \quad (10)$$

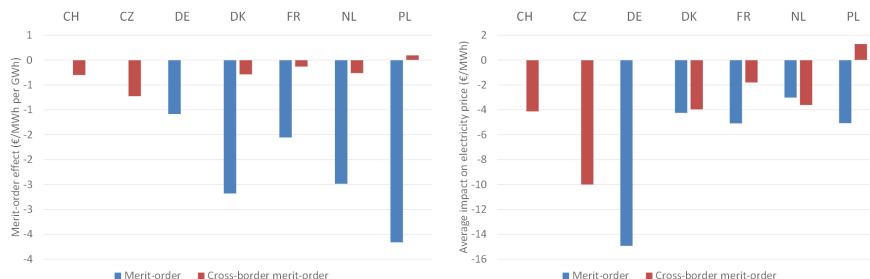
$$\Delta P_r^{cross} := MO_r^{cross} \bar{R}_{DE} \quad (11)$$

Figure 5 and Table B.7 shows that we find the highest impact of RE generation on electricity prices in Germany itself: Without RE generation, the average electricity price would be around 15 € higher. The impact of German RE on Czech prices is around 10 €. For all other countries (except for Poland), the impact of domestic and German RE on price lie between around 2 and 6 €. The main driver of these results is the average RE generation, which is significantly larger in Germany compared to all the other countries. As a consequence, the difference between domestic and cross-border *average* effects (right panel) is smaller than the difference between *marginal* effects (left panel).

4.5. Implications for consumer and producer rents

A higher share of RE generation in Germany impacts neighboring electricity markets in two ways. First, it increases exports from Germany, and thus leads to lower domestic generation neighboring countries. Second, as a result of the first, electricity prices decrease. Both effects impact producer rents by reducing quantities and revenues. We currently focus on the second effect, i. e., the impact of decreasing electricity prices on producer (and consequently also consumer) rents.

FIGURE 5. Merit-order effects and impact on electricity prices



Notes: These results include only coefficients significant at a 1% level. Data are given by Tables B.7 and 5.

TABLE 5. Average impact on electricity price (%)

CH	CZ	DE	DK	FR	NL	PL
0.0	0.0	-32.0	-13.3	-11.3	-7.5	-12.0
-9.1	-23.0	-	-12.6	-4.3	-8.9	3.6

Notes: The percentage impact on electricity prices is calculated using the average impacts on the electricity prices from Table B.7 and average electricity prices from Table 1.

Capacity rents of producers are defined as their revenue from selling electricity net of marginal costs. In Figure 4 they correspond to the area between the electricity price and the marginal cost. Lower electricity prices, induced by cheaper imports, thus lead to a decrease in revenues for domestic producers, while the cost remain the same. Consequently, capacity rents of producers decrease. In the long-run, this effect can lead to lower investments in domestic capacities. Consumers, on the other side, benefit from lower electricity prices, i. e., the consumer rent of electricity consumption increases.

Table 5 presents the impact of RE relative to average electricity prices. Our estimations show, that the domestic merit-order effect reduces average electricity prices by up to 32% for Germany itself, and values between 8 and 13% for the other countries. The impact of German RE on neighboring electricity prices goes from -4% in the case of France up to -23% in the case of the Czech Republic. This implies that German RE promotion induces a substantial shift from producer to consumer rents in neighboring electricity markets.

5. Conclusions

RE promotion has been implemented in many European countries as an instrument to increase the share of RE generation and decrease CO₂ emissions. Germany is the country with the most extensive RES scheme, inducing a RE

generation of up to 170 TWh. This RE generation at near zero marginal cost reduces more expensive (fossil) generators, leading to a decrease in electricity market prices (merit-order effect). Lower prices incentivize exports and lead to lower electricity market prices in neighboring countries (cross-border merit-order effect). As a consequence of German RES schemes, producer rents in neighboring countries decrease while consumer rents increase.

Using an empirical quantitative framework and hourly electricity market data, this paper contributes by quantifying these impacts for the period between 2015 and 2018. Our main findings are as follows. First, we find that the domestic merit-order effects vary significantly across countries. For Germany itself it is relatively low with -1.1 €/MWh per GWh of RE generation; for Poland it is highest with -3.7 €/MWh . In the case of Switzerland and the Czech Republic, we do not observe a (statistically significant) merit-order effect. Second, the impact of German RE on foreign electricity prices is smaller than the effect on the German price as well as the domestic merit-order effect of the respective country. German RE has the largest impact on prices in the Czech Republic (-0.7 €/MWh per GWh of German RE generation), and the smallest on Polish prices. Third, considering average instead of marginal price effects, German RE has an impact on foreign prices similar to the effect of RE installed in these countries. This is due to the high amount of German RE compared to neighboring countries' RE. German RE generation leads to a decrease in neighboring electricity prices of up to 10 €/MWh (about 23% decrease). Fourth, as a consequence the cross-border merit-order effect induces significant shifts from producer to consumer rents. Lower prices decrease the capacity rents of producers but at the same time electricity cost for consumers also declines. Fifth, the size of these effects crucially depends on the import and export possibilities of the different electricity markets: Higher export possibilities reduce the domestic merit-order effects. Higher import possibilities (from Germany) increase the cross-border merit-order impact of German RE generation.

In its current version, our analysis has several limitations, which we aim to address in the future. First, we only estimate the impact of German RE on neighboring prices. We neglect the impact of other neighbors, as well as the impact of other countries' RE generation on German prices. In a next step, we will estimate the impact of more than two countries at the same time. Our goal is to jointly estimate the impacts of RE schemes in different countries on their neighbors. Second, we currently focus only on the impact on prices. RE however also induces a decline of conventional generation. As a consequence, producer rents are also affected by decreasing quantities. Moreover, the decrease in conventional generation also affects carbon emissions. We are going to estimate the quantity effects of RE generation based on hourly plant-level panel data, and evaluate the total carbon impact of renewable promotion not only within but also across countries.

Notwithstanding these caveats, our preliminary findings indicate that there are cross-border impacts of national RES schemes. Our results imply that German RE promotion—financed by German electricity consumers—leads to a shift from producer to consumer rents in neighboring electricity markets. While from

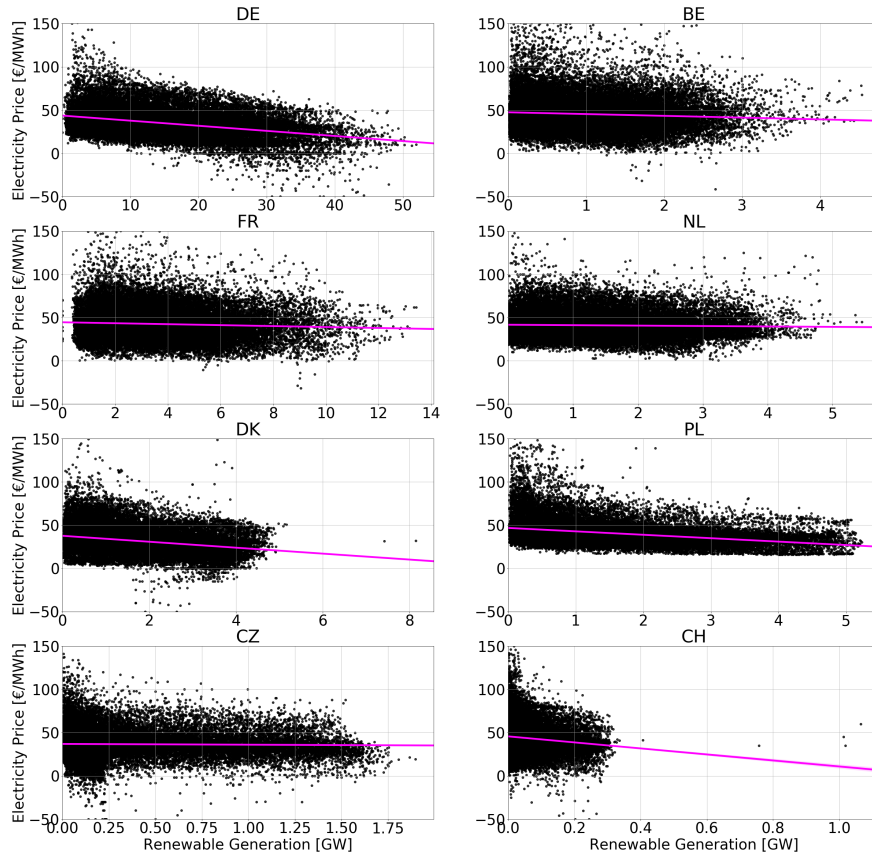
a consumer point of view, this effect is desirable, it has negative impacts on domestic producers. In the long-run, the decrease in capacity rents for conventional producers leads to lower capacity investments and a potential decrease in domestic capacity. If, as in the case of Swiss hydro power, policy makers want to prevent this impact, domestic capacity needs to be subsidized. It is very likely that these subsidies are financed by a tax on electricity demand, counteracting the decrease in electricity prices. Yet, the size of this impact depends on market characteristics and trade possibilities. Our results suggest, that for most countries, the price impacts of German RE are moderate.

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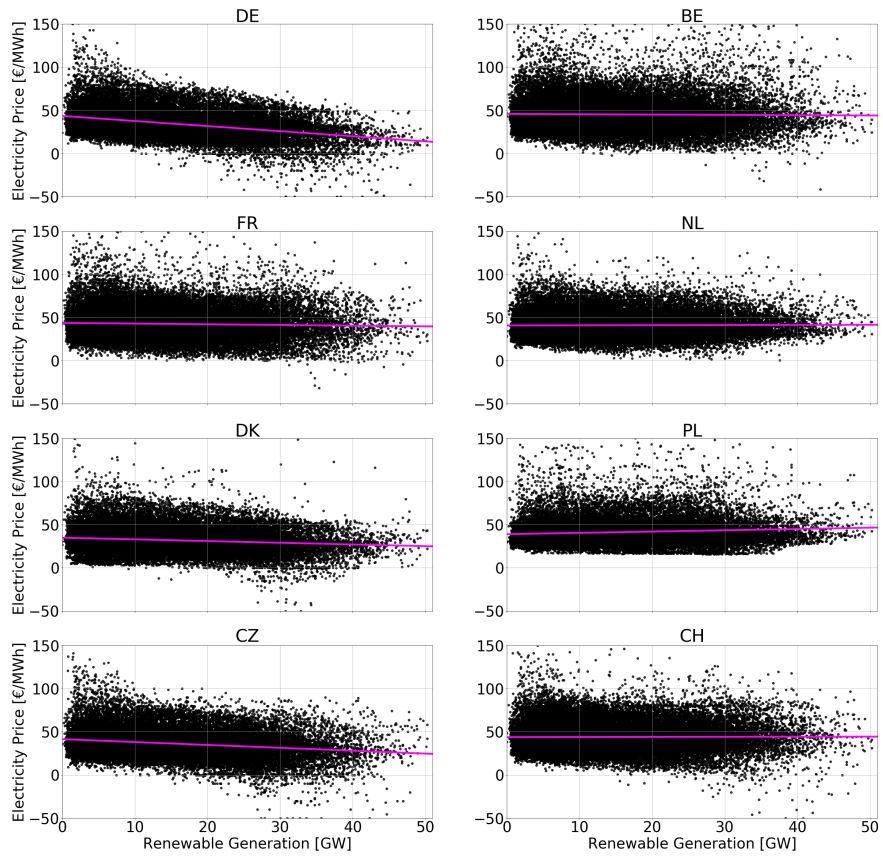
Appendix A. Additional Graphs

FIGURE A.6. Renewable Generation and Day-ahead Prices



Notes: Figure shows total hourly domestic RE generation of wind and solar power together with day-ahead electricity prices (ENTSOE, 2019).

FIGURE A.7. German Renewable Generation and Day-ahead Prices



Notes: Figure shows total hourly German RE generation of wind and solar power together with day-ahead electricity prices (ENTSOE, 2019).

Appendix B. Regression results and price impacts for main model

TABLE B.6. Detailed regression results - Main specification (M2)

	CH	CZ	DE	DK	FR	NL	PL
R_r	-3.28 (3.44)	-0.48 (0.48)	-1.08*** (0.03)	-2.68*** (0.14)	-1.55*** (0.13)	-2.49*** (0.16)	-3.66*** (0.21)
R_{DE}	-0.30*** (0.03)	-0.79*** (0.03)		-0.29*** (0.02)	-0.15*** (0.03)	-0.40*** (0.02)	-0.03 (0.03)
$C_{rDE}R_{DE}$	0.01 (0.02)	0.08*** (0.01)		-0.01 (0.01)	0.03** (0.01)	0.24*** (0.01)	0.10*** (0.01)
D_r	11.72*** (3.54)	5.50*** (1.79)	0.28* (0.16)	9.29*** (2.18)	0.47** (0.19)	3.34*** (0.61)	-2.14*** (0.54)
D_r^2	-0.32 (0.27)	0.35*** (0.12)	0.01*** (0.00)	0.04 (0.30)	0.01*** (0.00)	0.01 (0.03)	0.13*** (0.02)
p^{coal}	4.17*** (1.05)	0.19 (0.86)	0.53 (0.76)	-0.21 (0.63)	2.08** (0.85)	-0.31 (0.50)	0.46 (0.71)
p^{gas}	0.72*** (0.24)	-0.16 (0.20)	-0.04 (0.16)	-0.02 (0.13)	0.36 (0.22)	0.79*** (0.14)	-0.17 (0.17)
p^{EUA}	-0.32 (0.67)	2.26*** (0.54)	1.05** (0.49)	-0.77 (0.57)	0.60 (0.72)	0.60* (0.32)	0.45 (0.57)
$temp$	0.01 (0.07)	0.41*** (0.05)	0.14** (0.06)	-0.20** (0.08)	0.80*** (0.07)	0.04 (0.05)	0.30*** (0.06)
Month-Year FE	x	x	x	x	x	x	x
N	25312	24487	25431	25430	25350	23429	25332
R ²	0.72	0.76	0.77	0.66	0.69	0.70	0.47

Notes: *, **, ***: Significant at the 10%, 5% and 1% levels, respectively.

TABLE B.7. Impact on electricity price (€/MWh)

	CH	CZ	DE	DK	FR	NL	PL
ΔP^{ele}	0.0	0.0	-14.9	-4.3	-5.1	-3.0	-5.1
ΔP^{cross}	-4.1	-10.0	-	-4.0	-1.8	-3.6	1.3
no congestion	-4.1	-10.9	-	-4.0	-2.1	-5.5	0.0
congestion	-4.1	-9.8	-	-4.0	-1.6	-2.1	1.4

Notes: Results include only coefficients significant at a 1% level.

Appendix C. Robustness Checks

TABLE C.8. Robustness checks Switzerland

	M0	M1	M2	M3	M4	M5
<i>MO</i>	-5.52 (6.98)	-29.95*** (4.40)	-3.28 (3.44)	-12.59*** (3.32)	-33.20*** (2.62)	-15.68*** (2.40)
<i>MO^{cross}</i>	-0.27*** (0.00)	-0.30*** (0.00)	-0.29*** (0.00)	-0.31*** (0.00)	-0.37*** (0.00)	-0.34*** (0.00)
no congestion	-0.37*** (0.04)	-0.45*** (0.04)	-0.30*** (0.03)	-0.36*** (0.03)	-0.45*** (0.03)	-0.41*** (0.03)
congestion	-0.26*** (0.05)	-0.29*** (0.05)	-0.29*** (0.04)	-0.30*** (0.04)	-0.36*** (0.03)	-0.33*** (0.03)
Controls	x	x	x	x	x	x
<i>D^{DE}</i>					x	x
Hourly FE		x		x		x
Month-Year FE			x	x	x	x

Notes: *, **, ***: Significant at the 10%, 5% and 1% levels, respectively.

TABLE C.9. Robustness checks Czech Republic

	M0	M1	M2	M3	M4	M5
<i>MO</i>	1.75*** (0.47)	0.43 (0.76)	-0.48 (0.48)	-0.63 (0.67)	-0.60 (0.47)	-1.19* (0.62)
<i>MO^{cross}</i>	-0.80*** (0.00)	-0.81*** (0.00)	-0.73*** (0.00)	-0.73*** (0.00)	-0.81*** (0.00)	-0.81*** (0.00)
no congestion	-0.87*** (0.03)	-0.89*** (0.03)	-0.79*** (0.03)	-0.79*** (0.03)	-0.89*** (0.03)	-0.89*** (0.03)
congestion	-0.78*** (0.03)	-0.79*** (0.03)	-0.71*** (0.03)	-0.72*** (0.03)	-0.79*** (0.03)	-0.79*** (0.03)
Controls	x	x	x	x	x	x
<i>D^{DE}</i>					x	x
Hourly FE		x		x		x
Month-Year FE			x	x	x	x

Notes: *, **, ***: Significant at the 10%, 5% and 1% levels, respectively.

TABLE C.10. Robustness checks Germany

	M0	M1	M2	M3	M4	M5
<i>MO</i>	-1.10*** (0.03)	-1.13*** (0.03)	-1.08*** (0.03)	-1.12*** (0.03)	-1.08*** (0.03)	-1.13*** (0.03)
controls	x	x	x	x	x	x
<i>D^{DE}</i>					x	x
Hourly FE		x		x		x
Month-Year FE			x	x	x	x

Notes: *, **, ***: Significant at the 10%, 5% and 1% levels, respectively.

TABLE C.11. Robustness checks Denmark

	M0	M1	M2	M3	M4	M5
<i>MO</i>	-2.82*** (0.15)	-2.67*** (0.16)	-2.68*** (0.14)	-2.60*** (0.15)	-2.84*** (0.14)	-2.77*** (0.14)
<i>MO^{cross}</i>	-0.31*** (0.00)	-0.35*** (0.00)	-0.29*** (0.00)	-0.31*** (0.00)	-0.30*** (0.00)	-0.33*** (0.00)
no congestion	-0.31*** (0.03)	-0.35*** (0.03)	-0.29*** (0.02)	-0.30*** (0.03)	-0.30*** (0.02)	-0.33*** (0.03)
congestion	-0.31*** (0.03)	-0.35*** (0.04)	-0.30*** (0.03)	-0.31*** (0.03)	-0.31*** (0.03)	-0.33*** (0.03)
Controls	x	x	x	x	x	x
<i>D^{DE}</i>					x	x
Hourly FE		x		x		x
Month-Year FE			x	x	x	x

Notes: *, **, ***: Significant at the 10%, 5% and 1% levels, respectively.

TABLE C.12. Robustness checks France

	M0	M1	M2	M3	M4	M5
<i>MO</i>	-1.74*** (0.18)	-2.02*** (0.19)	-1.55*** (0.13)	-1.52*** (0.14)	-1.74*** (0.13)	-1.56*** (0.13)
<i>MO^{cross}</i>	-0.16*** (0.00)	-0.29*** (0.00)	-0.13*** (0.00)	-0.13*** (0.00)	-0.26*** (0.00)	-0.23*** (0.00)
no congestion	-0.29*** (0.04)	-0.45*** (0.04)	-0.15*** (0.03)	-0.19*** (0.03)	-0.33*** (0.03)	-0.29*** (0.03)
congestion	-0.07 (0.05)	-0.20*** (0.05)	-0.12*** (0.03)	-0.10** (0.04)	-0.22*** (0.03)	-0.19*** (0.03)
Controls	x	x	x	x	x	x
<i>D^{DE}</i>					x	x
Hourly FE		x		x		x
Month-Year FE			x	x	x	x

Notes: *, **, ***: Significant at the 10%, 5% and 1% levels, respectively.

TABLE C.13. Robustness checks Netherlands

	M0	M1	M2	M3	M4	M5
<i>MO</i>	-2.99*** (0.17)	-2.70*** (0.18)	-2.49*** (0.16)	-2.45*** (0.17)	-2.45*** (0.16)	-2.46*** (0.17)
<i>MO^{cross}</i>	-0.21*** (0.00)	-0.25*** (0.00)	-0.26*** (0.00)	-0.24*** (0.00)	-0.29*** (0.00)	-0.26*** (0.00)
no congestion	-0.34*** (0.02)	-0.38*** (0.02)	-0.40*** (0.02)	-0.38*** (0.02)	-0.43*** (0.02)	-0.40*** (0.02)
congestion	-0.10*** (0.02)	-0.14*** (0.03)	-0.15*** (0.02)	-0.13*** (0.02)	-0.18*** (0.02)	-0.15*** (0.03)
Controls	x	x	x	x	x	x
<i>D^{DE}</i>					x	x
Hourly FE		x		x		x
Month-Year FE			x	x	x	x

Notes: *, **, ***: Significant at the 10%, 5% and 1% levels, respectively.

TABLE C.14. Robustness checks Poland

	M0	M1	M2	M3	M4	M5
<i>MO</i>	-3.53*** (0.18)	-3.20*** (0.16)	-3.66*** (0.21)	-3.35*** (0.20)	-3.66*** (0.21)	-3.34*** (0.20)
<i>MO^{cross}</i>	0.03*** (0.00)	-0.04*** (0.00)	0.06*** (0.00)	-0.02*** (0.00)	0.05*** (0.00)	-0.04*** (0.00)
no congestion	-0.09*** (0.03)	-0.16*** (0.03)	-0.03 (0.03)	-0.11*** (0.03)	-0.04 (0.03)	-0.14*** (0.03)
congestion	0.04 (0.03)	-0.03 (0.03)	0.07** (0.03)	-0.01 (0.03)	0.06* (0.03)	-0.03 (0.04)
Controls	x	x	x	x	x	x
<i>D^{DE}</i>					x	x
Hourly FE		x		x		x
Month-Year FE			x	x	x	x

Notes: *, **, ***: Significant at the 10%, 5% and 1% levels, respectively.