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JEL-Codes: C21, F15, L94, Q41

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Radioinactive: Are nuclear power plant outages in France contagious to the German electricity price?

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Abstract

Are nuclear power plant outages in France contagious to the German electricity price? In the case of the extensive inspections from October 2016 to February 2017 in 12 French nuclear power plants: Yes. This capacity shock increased the French electricity spot market price by 14.15 Euros per MWh. The German-Austrian electricity spot market price was affected, with an increase of 1.72 Euros per MWh through cross-border trade. Hence, the current market integration between France and Germany to balance supply and demand in times of capacity shocks is limited. These results derive from a quasi-experimental approach based on coarsened exact matching. Thereby, the exogenous nature of the capacity shock is exploited as a random treatment in order to identify causal effects.

Keywords: electricity price, electricity trade, nuclear power, market integration
JEL: C21, F15, L94, Q41

1. Introduction

From October 2016 to February 2017 the French electricity market was subject to an exogenous shock. In October 2016, the French Nuclear Safety Authority announced that the mechanical strength of a certain type of steam generator channel head was in question. Steam generators are used in pressurized water reactors as part of the cooling scheme. Hence, they are essential to ensure a nuclear power plant's safety. Due to this security concern, 20% of the French nuclear power plant capacity was unavailable at short notice, and under extensive inspection until February 2017. Therefore, the French electricity market faced a capacity shock.

The research question in this paper regarding the extensive inspections in the French nuclear power plants is twofold: First, to identify the effect on prices on the French electricity market. Second, to investigate whether this exogenous shock was passed on to the German market through cross-border trade. Hence, this paper strives to estimate the causal effects of these inspections on the electricity spot market price in France and Germany.

Cross-border electricity trade is a possible mechanism to ensure the security of the supply at times of a demand or supply shock. The integration of national electricity markets in Europe is an ongoing process (Jamasb and Pollitt, 2005; Eberlein, 2008). Although the market integration is being continuously intensified, a "European supergrid" and a "law of one European electricity price" is far from a reality (Van Hertem and Ghandhari, 2010; Torriti, 2014; Bosco et al., 2010). In 2016, the average electricity day-ahead spot market price was 28.98 Euros per MWh in Germany and Austria and 36.75 Euros per MWh in France. Hence, the considerable difference in prices came to, on average, 7.77 Euros per MWh (ACER and CEER, 2017).

A quasi-experimental identification strategy is applied in this paper in order to estimate causal effects. Two elements are central for the definition of causality. First, that a function as a set of factors generates a set of possible outcomes. Second, that a change in one of these factors evokes a change (treatment) in the outcome. This idea manifests itself in the expression *ceteris paribus*. Although causality is compellingly clear in this definition, it is highly challenging to achieve empirically. To this end, the link between the treatment and counterfactuals is crucial (Heckman, 2005, 2008). To identify causal effects using non-randomized observational data, a thorough identification strategy is necessary (Rubin, 1974). In the present study, the treatment consists of the inspection in the affected French nuclear power plants. The exogenous nature of the inspection is exploited as a random treatment. Moreover, the counterfactuals, as a control group, are identified on the basis of coarsened exact matching, as suggested by Ho et al. (2007) and Iacus et al. (2011, 2012).

This paper contributes to the existing literature with insights into the economic effects of national capacity shocks in an integrated electricity market with limited transmission capacity. To the author's knowledge, it is the first study to investigate the price effect of the inspections from October 2016 to February 2017.

The structure of this paper is as follows. Section 2 gives information on the French and German electricity market. Section 3 discusses the economic effect of nuclear power capacity shocks. Section 4 presents the dataset and identification strategy. Section 5 contains the empirical application. Section 6 summarizes and concludes.

2. The French and German electricity markets

Despite their geographical proximity and close links in politics and economics, France and Germany vary enormously when it comes to electricity generation. In Germany, the majority of the population disapproves of nuclear electricity generation (Andor et al., 2015). In France, on the other hand, public opinion is much more supportive. Indeed, the majority of the French population approves nuclear electricity generation (Brouard et al., 2012; Hadjilambrinos, 2000).

These different public opinions are reflected in the countries respective energy policies. In Germany, a core element of the energy transition is the complete phase-out of the nuclear reactor fleet by 2022 (Bundestag, 2011). Due to the planned phase-out and the promotion of renewable electricity generation, the share of nuclear electricity generation in Germany is decreasing. From 1996 to 2016, the share of nuclear electricity generation in Germany sunk from 30.8% to 13.1% (AGEB, 2017). In France, the Energy Transition Law passed in 2014 sets a medium and long-term goal of increasing the share of renewables and lowering the share of nuclear energy generation. Thereby, the electricity mix will be diversified and the strong reliance on nuclear electricity reduced (Bizet and Lévêque, 2015). However, nuclear electricity generation is in the short-run still predominant, with a share of over 70% (RTE, 2016). All in all, differences concerning the generation of electricity across Europe are the rule rather than the exception (Abrell and Rausch, 2016; Csereklyei et al., 2017).

Article 194 of the Lisbon treaty of the functioning of the European Union stresses the intention to promote the interconnection of energy networks. Still, cross-border electricity trade can be prevented for two reasons. First, due to the absence of the physical infrastructure of transmission lines. Second, by individual strategic incentives for congested transmission lines. Thereby, competitors from neighboring markets can be excluded in order to exercise market power. Hence, the allocation of transmission rights is essential to induce welfare gains from cross-border trade (Borenstein et al., 1997;

Oren, 1997; Joskow and Tirole, 2000; Neuhoff et al., 2013; Gebhardt and Höffler, 2013).

The German-Austrian and the French electricity markets are the biggest electricity markets in Europe and connected institutionally as well as physically. For these reasons, these markets are very suitable for the analysis of cross-border electricity trade in times of an exogenous shock. Institutionally, the markets are very well connected by the European Power Exchange (EPEX). For the day-ahead and intraday market, electricity is sold and bought using an auction mechanism. Market coupling is applied to process the cross-border trade by an implicit auction of transmission capacities. Hence, market participants do not bid separately for electricity and transmission capacity. Instead, EPEX allocates the available cross-border transmission capacity to minimize the price difference between two or more market areas (EPEX, 2018). The physical connection is between the grids of the French Transmission System Operator (TSO) Réseau de Transport d'Électricité (RTE) and the German TSOs Amprion and TransnetBW.

The cross-border trade of electricity differs from the trade of other goods and services. As Antweiler (2016) points out, electricity imports and exports between two markets vary over the course of the year and day. This applies to the cross-border electricity trade between Germany and France as well. On average, more electricity is exported from France to Germany than vice versa. The effects of exports and imports between the German and French market have already been the subject of some papers. The majority of these papers focuses on the effect caused by German renewable electricity generation on neighboring markets (Schaber et al., 2012; Spiecker et al., 2013; Böckers et al., 2013; DNVGL, 2014; Phan and Roques, 2015; Rintamäki et al., 2017; Keppler et al., 2017; Haxhimusa, 2018). Hence, the present study contributes to the existing literature through insights on the cross-border effect of outages in nuclear power plants.

3. The economic effect of outages in French nuclear power plants

On April 7, 2015, the French Nuclear Safety Authority (ASN) issued a statement about the discovery of an anomaly concerning the reactor vessel of the pressurized water reactor Flamanville 3[1]. Further investigation revealed

[1] The Flamanville 3 reactor was still in the building process.

this anomaly to be a high carbon concentration which may affect the vessel's mechanical properties. On June 28, 2016, the ASN reported that a similar anomaly was found in certain steam generator heads and named 18 nuclear power plants as liable to be affected. On October 18, 2016, the ASN requested additional inspections of 12[2] of these reactors over a three-month period. On February 24, 2017, the ASN authorized restarting the last of the respective reactors after the inspections (ASN, 2016, 2017a).

Plant components, such as the reactor vessel heads or the steam generator heads, have to meet high safety standards. For this reason, manufacturing and replacing such components in a nuclear power plant takes at least seven years. Therefore, in the short run, concerns regarding a mechanical problem can only be addressed by careful monitoring and thorough inspections (ASN, 2017b).

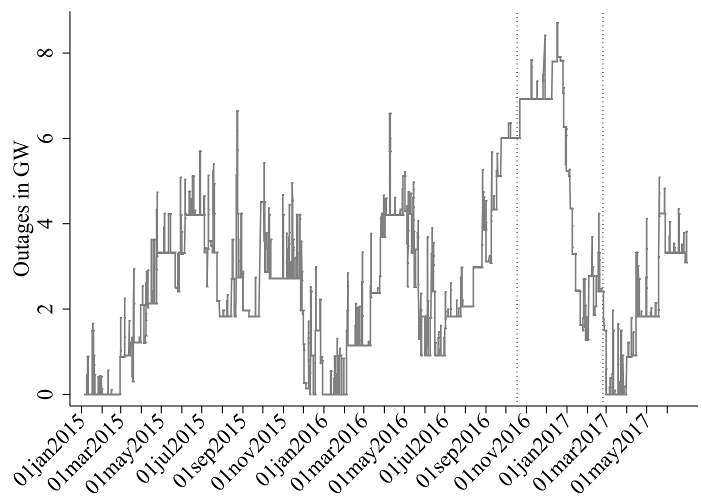


Figure 1: *Outages in the 12 affected nuclear power plants from 01.01.2015 to 30.06.2017. Doted lines indicate the inspection period.*

These inspections consequently led to an accumulation of outages in the French power plant fleet, as shown in Figure 1. In 2016, the French nuclear power plant fleet consisted of 58 reactors. Hence, 20% of the French nuclear

[2] Bugey NPP, reactor 4, Civaux NPP, reactors 1 and 2; Dampierre NPP, reactor 3, Fessenheim NPP, reactor 1, Gravelines NPP, reactors 2 and 4, Saint-Laurent-des-Eaux NPP, reactor B1, Tricastin NPP, reactors 1, 3 and 4

power plant fleet was affected by the inspections between October 2016 and February 2017[3]. Outages in these nuclear power plants occurred before and after the inspection period. Due to maintenance, planned outages occur on a regular basis and so are not exogenous. Moreover, unplanned outages usually affect only one power plant for a short period of time. Hence, the outages during the inspection period are special, since they were unexpected and affected simultaneously several power plants for months.

Since a considerable number of nuclear power plants were affected over a long period, significant economic consequences were very likely. In order to meet the electricity demand in France, alternative supply sources had to be used. The affected nuclear power plants are part of the first best solution to supply electricity. Thereby, their use is assumed to be cost effective. Hence, every alternative in supply has to involve higher costs.

Some lessons on the economic impact of a sudden capacity loss of nuclear power plants can be learned from previous events. One example is the nuclear moratorium in Germany as a reaction to the Fukushima nuclear disaster in 2011. For this reason, the German nuclear power plants were subject to inspections and unavailable at short notice.

Grossi et al. (2017) estimate an average price increase of 8.7% (3.72 Euros per MWh) on the German-Austrian spot market caused by the moratorium. Moreover, they argue that Germany was in a fortunate situation, since high solar electricity generation coincides with periods of high electricity demand. Hence, countries with a less diverse electricity mix are likely to be more affected by a capacity loss in nuclear electricity generation. Betzer et al. (2013) analyze the sudden policy change from the perspective of the shareholder. Using stock market data, they find a strong impact of the policy decision for the nuclear and conventional energy companies in Germany. Ferstl et al. (2012) identify in their event study significant negative cumulative abnormal returns for nuclear energy companies as well. Joskow and Parsons (2012) argue that significant changes in reaction to the accident at Fukushima as in Germany are rather an exception. On a global level, they expect an adoption of improvements in safety criteria or no change at all.

Davis and Hausman (2016) examine the effects of the sudden closure of the San Onofre Nuclear Generating Station (SONGS) in California in February 2012. They estimate that 25% of the generation loss of SONGS was

[3] A complete list of all French nuclear power plants is in Table A.8 in the Appendix

replaced by electricity imports. Accounting for the increase in generation costs, they find a total net increase of 351 $ million for the first year after the shutdown. However, the interpretation of this number is not straightforward. The decision to not maintain the plant was affected by the uncertainty whether the plant could return to service or not. All in all, the study of Davis and Hausman illustrates the strong economic impact of decisions about the operating life of nuclear power plants.

The research question in the present study focuses on the direct economic effects of the capacity shock on the French electricity spot market and the indirect effect on the neighboring German market. Figure 2 shows the movement of the French day-ahead electricity price from January 2015 to June 2017. The price spikes from November 2016 to February 2017 indicate a causal relation between the decreased capacity and the electricity price. Hence, the first hypothesis can be formulated as follows:

H_1 : *The inspection period increased the French electricity spot market price.*

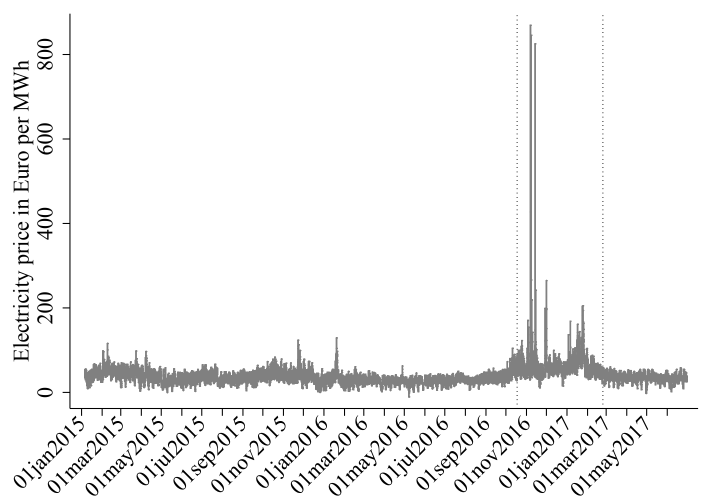


Figure 2: *French day-ahead electricity spot market price from 01.01.2015 to 30.06.2017. Doted lines indicate the inspection period.*

To balance supply and demand in times of low nuclear power plant capacities, two options exist. First, the electricity generation of other resources in France can be increased. Second, electricity from neighboring electricity markets can be imported. Therefore, the question arises whether supply shortages in the French electricity market have an economic effect on other electricity markets through cross-border trade.

Figure 3 shows the movement of the German day-ahead electricity price from January 2015 to June 2017. Indeed, high prices in the period from November 2016 to February 2017 are also visible for the German-Austrian market. Hence, the second hypothesis to be tested is:

H_2 : *The inspection period increased the German-Austrian electricity spot market price through the cross-border trade with France.*

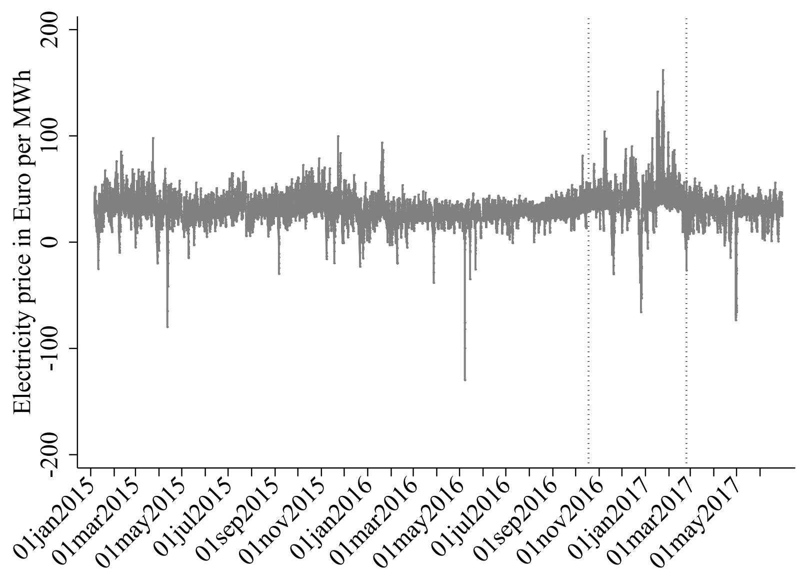


Figure 3: *German-Austrian day-ahead electricity spot market price from 01.01.2015 to 30.06.2017. Doted lines indicate the inspection period.*

Nevertheless, these price spikes are of a lower intensity compared to the French market. Due to the physically limited transmission capacities, the economic effect on the German-Austrian market is limited. Moreover, imports from other neighboring countries, such as Belgium, the United Kingdom, Spain, Italy, and Switzerland, were possible. Therefore, a potential economic effect on the German market has to be smaller than on the French market. To shed light on these preliminary indications from the price movements on both markets, a thorough identification strategy is necessary.

4. Method

The gold standard for identifying causal effects in empirical economics is a randomized and controlled experiment with an exogenous treatment (Splawa-Neyman et al., 1990; Fisher, 1935; Cox, 1958). Thereby, researchers face perfect conditions in the sense that they are able to control all relevant influences on the variable of interest.

Recently, several experimental field studies in energy economics have contributed to the understanding of households' energy consumption behavior, such as Allcott (2011), Allcott and Rogers (2014) and Jessoe and Rapson (2014). Applied to the causal impact of the outages in the nuclear power plants in France, field experiments would require a rather complex setting. The researcher need to be able to create outages in nuclear power plants on a random basis. Moreover, the electricity demand in France and Germany as well as the renewable electricity generation would have to be chosen by the researchers conducting the experiment. Obviously, this is a field experiment not likely to be approved, for many reasons.

Still, insights into the causal relation between the outages in the French nuclear power plants and the French and German-Austrian electricity price can be gained from a quasi-experimental approach. Thereby, observational data is used instead of data created through an experiment. Arguably, the discovery of the carbon anomaly in the steam generator heads is of an exogenous nature. By using a quasi-experimental approach, the observations from a dataset can be divided into "treated" and "untreated". Nevertheless, the treatment and control group have yet to be determined. For this reason, the challenge is to identify the counterfactual situation. Hence, the answer to the following question needs to be found: "If there were no inspection, what would have been the electricity prices during that period?" With an answer to that, the price effect of the inspection is simply the price difference between the treated observations within the inspection period and their untreated doppelgänger. In order to find a lid (untreated observation) for every pot (treated observation), coarsened exact matching is used in this analysis.

This quasi-experimental approach differs from the widely used time series models. Sophisticated time series models are very popular for forecasting "ill-behaved" price series which are characterized by heteroscedasticity, outliers, and seasonal effects (Conejo et al., 2005; Uniejewski et al., 2017). Since forecasting the electricity price is not the aim of this study, autoregressive models are not used in the empirical application. Instead, the focus lies on the effect of the exogenous treatment in the form of the extensive inspections. Therefore, the identification of a counterfactual control group is the core element in this analysis. Nevertheless, the variation in the electricity demand and supply due to seasonal changes, heteroscedasticity, nonlinearity, and outliers, is addressed within the identification strategy.

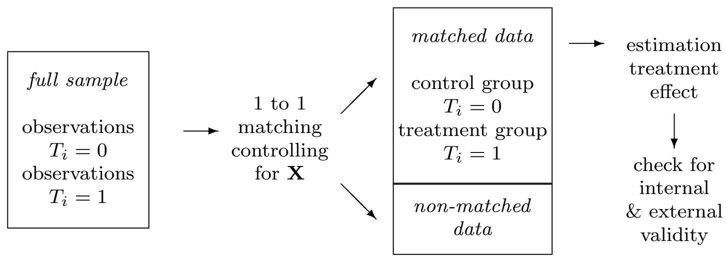


Figure 4: *Identification strategy*

The identification strategy for this study is illustrated in Figure 4. In the first step, the observations are categorized as treated and untreated. Next, a one to one matching process is applied in order create the treatment and control group. The matching process is explained in detail in Section 4.2. To be successful, the matching process needs to eliminate the differences between the treatment and control group (internal validity). At the same time, the treatment group needs to be a representative subsample of all the treated observations (external validity). The last step is then the estimation of the treatment effect for the French and German-Austrian electricity prices (Section 5.1), and robustness checks (Section 5.2).

4.1. Dataset

The dataset for the French and German-Austrian electricity markets used in the analysis covers the period 01.01.2015–30.09.2017. The day-ahead hourly equilibrium prices have been derived from the EPEX Spot Website. The data on outages, the overall day-ahead load, and the cross-border trade, originates from ENTSO-E. Information about the expected German solar and wind electricity generation are provided online by the four Transmission System Operators (TSOs). Daily prices for CO_2-emission allowances, gas, and coal are provided by Thomson Reuters EIKON. In order to convert and level the prices in 2015 Euros, the daily exchange rates and monthly deflators have been obtained from the German Central Bank's website. With the exception of the commodity prices, all the data is publicly available.

The descriptive statistics are displayed in Table 1. The upper part of the table contains the electricity prices as the dependent variables. The variables related to the treatment are displayed in the middle section. The control variables are in the lower part of the table. In the full sample with all observations, the French electricity spot market price is on average 38.82 Euros per MWh. In the inspection period, the price is on average 64.28 Euros per MWh. The average hourly equilibrium price for the German-Austrian market is 31.29 Euros per MWh. In the inspection period, this price is, at 42.14 Euros per MWh, also higher. Hence, the electricity prices for both markets are considerably higher in the inspection period.

Moreover, the average cross-border electricity trade between Germany and France computed on the basis of all observations also differs from that for the inspection period. In the sample with all observations, the electricity exports from Germany to France are on average 0.172 GWh. In the inspection period, the electricity exports amount to on average 0.426 GWh. The opposite holds for the electricity imports to Germany from France. Considering all observations, on average 1.034 GWh are transferred to Germany from France. Within the inspection period, on average only 0.588 GWh are transferred. This is another indication that the inspections in the French nuclear power plants might have affected the German electricity market through the cross-border trade.

Still, the price difference, of around 25 Euros and 10 Euros per MWh in the French and German-Austrian markets, can not be attributed directly to the extensive inspections in the affected nuclear power plants. For all observations, the load as the hourly equilibrium quantity for the French market is on average 54.684 GWh and in the inspection period 66.656 GWh. The higher electricity demand during winter in France increases the electricity price and coincides with the inspection period. Neither is the price difference in the German-Austrian market monocausal. During winter, less solar electricity is generated in Germany due to the lessened daylight. With marginal costs close to zero, renewable electricity decreases the price of electricity (Würzburg et al., 2013). Moreover, the average prices for CO_2-emission allowances, gas, and coal for the inspection period differ from those for all observations. Therefore, commodity prices are included as controls in the estimation model. Although for both markets the average price differences between the full sample with all observations and the inspection period are quite high, a thorough identification strategy is necessary to disentangle the various simultaneous influences on the electricity prices.

Variables	**full sample** all observations	inspection period	**without outliers †** all observations †	inspection period †
Number of observations	21,387	2,995	21,260	2,917
Electricity price France in € per MWh	38.821 (20.156)	64.281 (34.376)	38.461 (16.493)	61.893 (19.094)
Electricity price Germany in € per MWh	31.290 (13.857)	42.135 (19.794)	31.314 (12.493)	41.320 (16.161)
Outages in affected plants in GW	2.747 (1.964)	5.226 (2.277)	2.742 (1.961)	5.257 (2.259)
Exports from Germany to France in GWh	0.172 (0.398)	0.426 (0.633)	0.170 (0.396)	0.427 (0.635)
Imports to Germany from France in GWh	1.034 (0.991)	0.588 (0.741)	1.037 (0.992)	0.591 (0.745)
Load France in GWh	54.684 (11.802)	66.656 (10.072)	54.620 (11.718)	66.372 (9.807)
Load Germany in GWh	54.591 (9.531)	58.270 (9.513)	54.579 (9.500)	58.128 (9.364)
Solar and wind Germany in GWh	3.945 (4.985)	1.640 (2.035)	3.942 (4.977)	1.649 (2.049)
CO_2 price in € per ton	6.195 (1.379)	5.334 (0.564)	6.200 (1.380)	5.334 (0.563)
Coal price in € per ton	51.195 (6.477)	59.189 (2.589)	51.159 (6.457)	59.141 (2.283)
Gas price in € per MWh	16.980 (3.203)	18.289 (1.437)	16.973 (3.206)	18.267 (1.435)

Table 1: *Descriptive statistics before the matching*

All prices in 2015 Euros. Standard errors in parentheses. The dataset with all observations covers the period 01.01.2015–30.06.2017. The inspection period was from 18.10.2016 to 24.02.2017. † Without prices $>$ 167.41 (101.52) or $<$ -38.85 (-17.25) Euros per MWh on the French (German-Austrian) market.

As can be seen in Figures 2 and 3, as well in the standard errors in Table 1, the electricity prices are subject to price spikes. This underlines the relevance of examining the economic effects of the inspections in the affected nuclear power plants. Nevertheless, a few extreme events are not representative of the whole inspection period. Moreover, average estimators are sensitive to these extreme values. Since the aim of the present study is to estimate the average effect of the whole inspection period, outliers need to be addressed. However, it is important not to throw out the baby with the bathwater. If the threshold for outliers is chosen to be too restrictive, too much data is excluded and the estimators would be biased as well.

The strategy to address outliers in this analysis is twofold. First, a sub-sample is created by the matching algorithm. Outliers with a rare combination in terms of the control variables are less likely to be matched. Second, an adjusted dataset without outliers is also used in the analysis, as a robustness check.

A common method to identify outliers is the 3σ-rule. That is, observations which deviate from the mean by more than three standard deviations are classified as outliers (Pukelsheim, 1994). In this case, electricity prices greater (less) than 167.41 (-38.85) Euros per MWh on the French market or greater (less) than 101.52 (-17.25) Euros per MWh on the German-Austrian market are excluded, as outliers. As presented in the last columns of Table 1, thereby 127 observations are excluded (78 of them within the inspection period). Consequently, the French electricity price is, on average, 61.89 Euros per MWh lower and its variation greatly reduced. The average German-Austrian electricity price is reduced to 41.32 Euros per MWh. The other variables are hardly affected by excluding these very high and very low prices.

4.2. Coarsened exact matching

Matching is a nonparametric method to control for the influence of the control variables. The aim is to prune the observational dataset with treated and untreated observations to a treatment and a control group. Hence, the dissimilarities in the empirical distribution of the covariates between the treated and untreated observations are reduced (Iacus et al., 2012).

To identify causal effects, coarsened exact matching is applied, as suggested by Ho et al. (2007) and Iacus et al. (2011, 2012). Thereby, continuous variables are "coarsened" into categories. Then, by matching each observations with control variables within the same categories, a subsample is created. In previous studies in energy and environmental economics, coarsened exact matching has been successfully applied to estimate the spill-over effects from municipal green-building procurement rules (Simcoe and Toffel, 2014), the effect of installations of solar energy systems on residential properties (Qiu et al., 2017), and the effect of incentives and information on residential electricity consumption (Alberini and Towe, 2015).

Coarsened exact matching is preferable to other matching methods, such as propensity score matching, on several grounds, of which the most important is that coarsened exact matching is nonparametric and considers the higher moments of the control variables, and thus does not rely only on the means. Moreover, the counterfactuals are not extrapolated beyond the scope of the actual observational data (Iacus et al., 2012). Therefore, it is very suitable for the analysis of hourly electricity prices.

In general, coarsened exact matching with a pre-defined treatment and one to one matching can described as follows:

Let T_i inform about the assignment to the treatment:

$$T_i = \begin{cases} 0 & \text{for treated observations} \\ 1 & \text{for untreated observations} \end{cases} , \tag{1}$$

and let a sample of size n be drawn from a population N with $n \leq N$. Each observation belongs either to group 1, $Y_i(1)$, or to group 0, $Y_i(0)$, thus

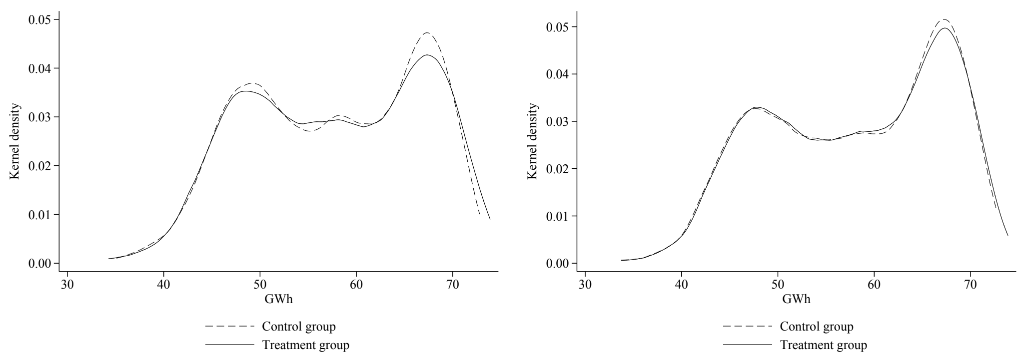
$$Y_i = T_i Y_i(1) + (1 - T_i) Y_i(0) \ . \tag{2}$$

In addition to the dependent variable Y and the treatment variable T, the k-dimensional matrix $\boldsymbol{X}$ holds any remaining controls. The k continuous variables are partitioned into j categories. In order to be identified as a "match," two observations in the dataset have to be in the same category for each and every variable of the matrix $\mathbf{X}$.

$$\mathbf{X} = \begin{bmatrix} X_{11} & X_{12} & X_{13} & \dots & X_{1j} \\ X_{21} & X_{22} & X_{23} & \dots & X_{2j} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ X_{k1} & X_{k2} & X_{k3} & \dots & X_{kj} \end{bmatrix}$$

Depending on the defined exogenous treatment, the matched observations are assigned to the treatment and control group. Thereby, each observation in the matched dataset has a "partner" with very similar characteristics with the exception of the treatment.

In the case of the affected French nuclear power plants, the treatment consists of the inspection period from 18.10.2016 to 24.02.2017 ($T_i = 1$). Hence, all observations outside this inspection period are classified as untreated ($T_i = 0$). The dependent variable Y is the hourly French and German-Austrian electricity spot market price. The k-dimensional matrix $\boldsymbol{X}$ includes the total load for the French and the German-Austrian market. Moreover, it includes the generation of solar and wind electricity in Germany. Hence, a treated observation is matched to an untreated observation if the untreated observation shares the same categories with the treated observation in regard to the load in France and Germany and the generation of solar and wind electricity in Germany. Since the electricity supply and demand curves differ over the course of a day, the matching process is done individually for each hour. Hence, for every match, the hour of the day is identical as well.



(a) *10 categories with* $1,798$ *matches*

(b) *15 categories with* $1,183$ *matches*

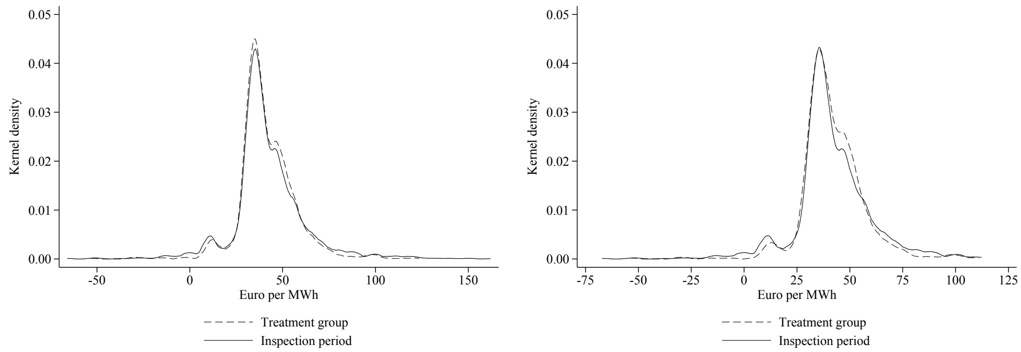
Figure 5: *Comparison of the distribution of the load in GWh for the German market in the control and treatment groups*

	Matching algorithm		
Number of categories j	10	15	20
Number of matches	$1,798$	$1,183$	727
Dissimilarities between the control & treatment group?	Yes	No	No
Dissimilarities between the treatment group & treated observations?	No	No	Yes

Table 2: *Variation of the matching algorithm.*

The chance of finding a match depends on the number of control variables and the number of categories for the control variables. Having more categories increases the similarity for the matched observations regarding the controls. Thereby, dissimilarities between the control and treatment group regarding the control variables are reduced. At the same time, this decreases the number of matches. Hence, with too few matches, dissimilarities between the treatment group and the treated observations might occur. In that case, the treatment group is not representative of all treated observations. Therefore, the number of categories for the matching algorithm is linked to a trade-off between the similarity of the control group with the treatment group and the similarity of the treatment group with all treated observations.

As shown in Table 2, with 10 categories, the algorithm is able to match $1,798$ observations out of the total of $2,995$ observations from the inspection period. With 15 or 20 categories, the number of matches is reduced to $1,183$ and 727. Figure 5 shows the distribution of the load in Germany after



(a) *15 categories with* 1,183 *matches* **(b)** *20 categories with* 727 *matches*

Figure 6: *Comparison of the distribution of the electricity price in Euros per MWh in Germany in the treatment group and inspection period*

the matching with 10 and 15 categories. When only using 10 categories, dissimilarities between the treatment and control group are visible. With 15 categories, the dissimilarities are reduced.

Figure 6 compares the distribution of the German-Austrian electricity price before and after the matching. With 15 categories and 1,183 matches, the distribution of the matched treated observations in the treatment group and all treated observations in the inspection period are very similar. With 20 categories and only 727 matches, dissimilarities between the treatment group and the inspection period become visible. Therefore, the matching algorithm with 15 categories has been used for the analysis. The tests for differences for all variables will be explained in detail in Section 5.2.

Variables	**full sample** control group	treatment group	**without outliers †** control group †	treatment group †
Number of observations	1,183	1,183	1,172	1,172
Electricity price France in € per MWh	41.876 (14.243)	62.607 (37.646)	42.001 (14.160)	61.151 (19.289)
Electricity price Germany in € per MWh	35.468 (12.575)	41.491 (15.280)	35.578 (12.304)	41.372 (13.645)
Outages in affected plants in GW	1.342 (1.452)	5.870 (2.043)	1.327 (1.425)	5.893 (2.025)
Exports from Germany to France in GWh	0.106 (0.285)	0.400 (0.574)	0.099 (0.275)	0.404 (0.570)
Imports to Germany from France in GWh	1.179 (0.995)	0.524 (0.703)	1.195 (1.001)	0.521 (0.708)
Load France in GWh	63.468 (9.174)	63.511 (9.153)	63.433 (9.137)	63.442 (9.092)
Load Germany in GWh	58.039 (9.083)	58.136 (9.101)	58.036 (9.068)	58.129 (9.081)
Solar and wind Germany in GWh	1.658 (2.129)	1.622 (2.143)	1.665 (2.143)	1.630 (2.152)
CO_2 price in € per ton	6.709 (1.381)	5.403 (0.561)	6.741 (1.373)	5.405 (0.566)
Coal price in € per ton	48.289 (6.839)	58.919 (2.516)	48.267 (6.843)	58.924 (2.554)
Gas price in € per MWh	16.940 (3.331)	17.948 (1.347)	17.019 (3.357)	17.939 (1.350)

Table 3: *Descriptive statistics after the matching*

All prices in 2015 Euros. Standard errors in parentheses. † Without prices $>$ 167.41 (101.52) or $<$ -38.85 (-17.25) Euros per MWh on the French (German-Austrian) market.

Table 3 displays the descriptive statistics after the matching. After the matching, the price differences between the control and treatment groups are smaller than the differences between the treated and untreated observations. Hence, as suspected, the load as well as the generation of solar and wind electricity influence the electricity price as well. After the matching, the load in France and Germany along with the generation of solar and wind electricity in Germany are on average almost identical in the control and treatment group. Moreover, the commodity prices are included as controls in the estimation model to take into account their influence. Hence, it can be assumed that the remaining price differences between the control and treatment groups are caused by the treatment in the form of the inspection period.

5. Results

After the matching process, the causal effects of the outages on the electricity price are estimated using a multivariate linear regression model. Due to the quasi-experimental identification strategy, the first model is rather simple:

$$\text{electricity price} = \beta_0 + \beta_1 \times T_i + \delta \times \boldsymbol{X} + \epsilon \ . \qquad \text{(model 1)}$$

The average treatment effect is captured by β_1, the matrix $\boldsymbol{X}$ includes the control variables. The effects of the controls are estimated in the vector δ while ϵ is an error term. The standard errors are clustered at the hour of the observation.

The second model connects the inspections to the actual cross-border trade between Germany and France:

$$\text{electricity price} = \gamma_0 + \gamma_1 \times T_i \times Ex + \gamma_2 \times T_i \times Im + \delta \times \boldsymbol{X} + \epsilon \ . \quad \text{(model 2)}$$

The average treatment effect of electricity exports from Germany to France (Ex) is captured by γ_1. The average treatment effect of electricity imports to Germany from France (Im) is captured by γ_2. Again, the matrix $\boldsymbol{X}$ includes the control variables and the vector δ their effect. The standard errors ϵ are also clustered at the hour of the observation.

5.1. Effects on French and German-Austrian electricity prices

Table 4 reports the estimation results for the French market. In the first model (1) the average treatment effect of the inspection period is estimated. To this end, the French electricity price in the treatment group is, compared to the control group, on average 14.15 Euros per MWh higher. With a standard error of 1.213, this estimator is statistically significant at the 0.1% level. With an average treatment effect of 13.79 Euros per MWh for the adjusted sample without outliers, the estimator is significant at the 0.1% level as well. Hence, the analysis of the full sample suggests that the average electricity in the counterfactual scenario to the inspection period would have been on average 50.14 Euros per MWh instead of 64.28 Euros per MWh. For the adjusted dataset without outliers the average electricity price in the counterfactual scenario amounts to 48.11 Euros per MWh instead of on average 61.89 Euros per MWh.

	Estimation model	
	full sample	**without outliers †**
	(1)	(1†)
# of observations	2,366	2,344
Electricity price France in € per MWh		
Inspection period		
$T_i = 1$	14.146***	13.786***
	(1.213)	(1.119)
Load France in GWh	×	×
Load Germany in GWh	×	×
Solar and wind Germany in GWh	×	×
CO_2 price in € per ton	×	×
Coal price € per ton	×	×
Gas price in € per MWh	×	×
Hour	×	×

Table 4: *Price effects of the inspections in affected nuclear power plants on the French electricity price*

All prices in 2015 Euros. Standard errors in parentheses clustered at the level of the hour. ***, **, * indicate statistical significance at the 0.1%, 1%, 5% levels. Model includes hour fixed effects. Full report of all coefficients in Table A.9 in the Appendix. † Without prices > 168.39 (101.52) or < -38.98 (-17.25) Euros per MWh on the French (German-Austrian) market.

Table 5 presents the results with the German-Austrian electricity spot market price as the dependent variable. The first estimation model (1) estimates the average effect of the inspection period as the treatment. With on average 2.57 Euros per MWh the coefficient is significant at the 0.1% level. In the dataset without outliers the average effect is 3.07 Euros per MWh and also significant at the 0.1% level.

To claim that these results represent a causal relation and not just a correlation, the treatment needs to be linked to the cross-border trade. As stated before, the transmission capacities are limited. Therefore, the second model estimates (2) the interaction effect between the inspection period as treatment and the cross-border trade between Germany and France. The expectation is that the price effects of cross-border trade differ between the control and treatment group.

	Estimation model			
	full sample		**without outliers** †	
	(1)	(2)	(1†)	(2†)
# of observations	2,366	2,366	2,344	2,344
Electricity price Germany-Austria in € per MWh				
Inspection period				
$T_i = 1$	2.566*** (0.666)		3.066*** (0.734)	
Inspection period × exports in GWh (to France)				
$T_i = 0$		2.854* (1.073)		2.401 (0.943)
$T_i = 1$		5.046*** (0.495)		4.889*** (0.480)
Inspection period × imports in GWh (from France)				
$T_i = 0$		−0.602 (0.369)		−0.762 (0.377)
$T_i = 1$		−2.459*** (0.362)		−1.790*** (0.364)
Load France in GWh	×	×	×	×
Load Germany in GWh	×	×	×	×
Solar and wind Germany in GWh	×	×	×	×
CO_2 price in € per ton	×	×	×	×
Coal price € per ton	×	×	×	×
Gas price in € per MWh	×	×	×	×
Hour	×	×	×	×

Table 5: *Price effects of the inspections in affected nuclear power plants on the German-Austrian electricity price*

All prices in 2015 Euros. Standard errors in parentheses clustered at the level of the hour. ***, **, * indicate statistical significance at the 0.1%, 1%, 5% levels. Model includes hour fixed effects. Full report of all coefficients in Table A.10 in the Appendix. † Without prices > 167.41 (101.52) or < −38.85 (−17.25) Euros per MWh on the French (German-Austrian) market.

The coefficient for the average effect of electricity exports from Germany to France in the control group outside the inspection period is, at 2.85 Euros per MWh, rather small and only statistically significant at the 5% level. In contrast to this result, in the treatment group within the inspection period, the export of 1 GWh to France increases on average the German-Austrian electricity price by 5.05 Euros per MWh. With a standard error of 0.495, the coefficient is statistically significant at the 0.1% level. For the dataset without outliers, the coefficient for exports from Germany to France outside of the inspection period is again small and not statistically significant. But within the inspection period, the average effect of exporting 1 GWh is 4.89 Euros per MWh for the dataset without outliers and statistically significant at the 0.1% level. This indicates that the missing capacity in France due to the inspections was partially compensated for with electricity bought from the German market, thereby increasing the German-Austrian electricity price.

The interaction effect between the treatment and imports to Germany from France exhibits a different pattern. In the control group outside the inspection period, the average effect of 1 GWh electricity imported to Germany from France is −0.60 Euros per MWh and not statistically significant. This price decreasing effect is stronger in the treatment group. The coefficient is −2.46 Euros per MWh and statistically significant at the 0.1% level. For the adjusted dataset, the imports to Germany from France affect the German-Austrian electricity price on average by −0.76 Euros per MWh. Again, this estimator is not statistically significant. In the treatment group, the average effect of 1 GWh imports to Germany from France changes to on average −1.79 Euros per MWh for the adjusted dataset.

	average		**average effect**		**absolute effect**	
Dataset	full sample	without outliers†	full sample	without outlier†	full sample	without outlier†
Electricity price Germany-Austria in € per MWh						
Exports in GWh (from Germany to France)						
$T_i = 0$	0.106	0.099	2.854*	2.401	0.303	0.238
$T_i = 1$	0.400	0.404	5.046***	4.889***	2.018	1.975
Δ	0.294	0.305	2.192*	2.488*	1.715	1.737
Imports in GWh (to Germany from France)						
$T_i = 0$	1.179	1.195	−0.602	−0.762	−0.710	−0.911
$T_i = 1$	0.524	0.521	−2.459*	−1.790***	−1.289	−0.933
Δ	−0.655	−0.674	−1.857**	−1.028	−0.579	−0.022

Table 6: *Summary of the price effects on the German-Austrian electricity price*

All prices in 2015 Euros. Standard errors in parentheses clustered at the level of the hour. ***, **, * indicate statistical significance at the 0.1%, 1%, 5% levels. † Without prices > 167.41 (101.52) or < −38.85 (−17.25) Euros per MWh on the French (German-Austrian) market.

To put these average estimators in perspective, Table 6 summarizes the treatment effects. For the German-Austrian electricity price, the average estimators from model (2) are expressed in absolute terms. The exports of on average 0.400 GWh in the treatment group increase the German-Austrian electricity price by 2.02 Euros per MWh ($0.400 \times 5.046 = 2.018$). For the adjusted dataset, with exports of on average 0.404 GWh, the effect is, in absolute terms, 2.35 Euros per MWh. Moreover, the average estimators for the effect of exports inside and outside the inspection period differ significantly. Indeed, the German-Austrian electricity price increased by 2.19 Euros per MWh in the full dataset and 2.49 Euros per MWh in the adjusted dataset, due to the higher exports caused by the inspections.

In contrast, the imports of on average 1.179 GWh in the control group decreased the German-Austrian electricity price by 0.71 Euros per MWh ($1.179 \times -0.602 = -0.710$). In the adjusted dataset without outliers, the average imports of 1.195 GWh in the control group had a price-decreasing effect of 0.91 Euros per MWh. In the treatment group, the imports of, on average, 0.524 GWh, lowered the German-Austrian electricity price by only 1.29 Euros per MWh. In the dataset without outliers, the coefficient decreases the German-Austrian electricity price by 0.93 Euros per MWh. Moreover, the average estimators are only statistically significant from each other in the full sample but not in the sample without outliers. Hence, although the average exports from France to Germany were reduced in the inspection period, no statistically significant effect can be derived from the estimation model.

All in all, the effect on the German-Austrian electricity price caused by cross-border trade sums up to 1.72 Euros per MWh for the full dataset and 1.74 Euros per MWh for the dataset without outliers.

5.2. Tests for internal and external validity

In order to claim that the estimated price effects in the treatment and control groups represent the price effects of the inspection period, two important conditions need to be fulfilled. First, the control group has to model the counterfactual situation of the treatment group. Hence, the control and treatment groups have to be very similar in terms of the control variables. Second, the treatment group has to be representative of the inspection period. If the treatment group differs substantially from the inspection period, conclusions drawn from the estimation results are not valid for the actual events. Moreover, doubts can be raised about other exogenous events that coincide with the inspection period.

Variables	10 categories t-test t	10 categories Ksmirnov D	15 categories t-test t	15 categories Ksmirnov D	20 categories t-test t	20 categories Ksmirnov D
Load France	−0.401	0.020	−0.116	0.015	−0.020	0.017
	(0.689)	(0.885)	(0.908)	(1.000)	(0.984)	(1.000)
Load Germany	−0.658	0.040	−0.259	0.020	−0.230	0.023
	(0.511)	(0.121)	(0.796)	(0.968)	(0.818)	(0.989)
Solar and wind electricity Germany	1.441	0.087***	0.405	0.047	0.039	0.048
	(0.180)	(0.000)	(0.686)	(0.141)	(0.969)	(0.369)
Load France†	−0.663	0.026	−0.023	0.015	0.032	0.020
	(0.507)	(0.592)	(0.982)	(1.000)	(0.974)	(0.999)
Load Germany†	−0.582	0.043	−0.246	0.021	−0.195	0.018
	(0.561)	(0.078)	(0.805)	(0.967)	(0.846)	(1.000)
Solar and wind† electricity Germany	1.391	0.092***	0.400	0.049	0.046	0.043
	(0.164)	(0.000)	(0.690)	(0.125)	(0.964)	(0.511)

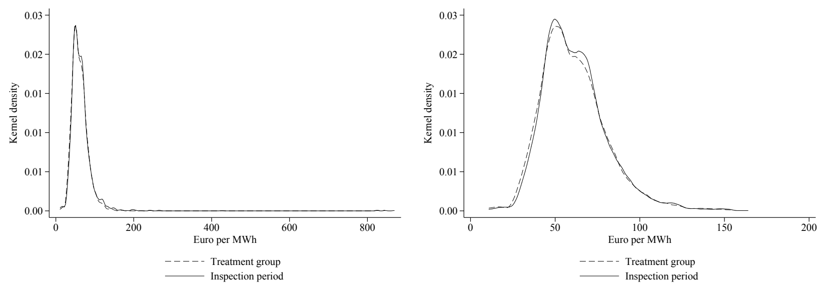
Table 7: *Results of the t-tests and Kolmogorov–Smirnov tests for equality of distributions of the control and treatment groups.*

p-values in parentheses. ***, **, * indicate statistical significance at the 0.1%, 1%, 5% levels. † Without prices > 167.41 (101.52) or < −38.85 (−17.25) Euros per MWh on the French (German-Austrian) market.

The matched dataset is tested for differences between the treatment and control groups regarding the control variables. The results of the *t*-tests and the Kolmogorov–Smirnov tests for equality of distribution are presented in Table 7. Whereas *t*-tests focus on the variables' means, the Kolmogorov–Smirnov test for equality of distribution considers the variables' overall distribution. The estimation results in Section 5.1 are based on the matching algorithm with 15 categories for each control variable. The *t*-tests and the Kolmogorov–Smirnov tests for equality of distribution show no significant evidence for differences between the control and treatment group. With only 10 categories, the Kolmogorov–Smirnov test indicates differences for the distribution of the solar and wind electricity between the control and treatment groups. Although the statistical significance increases for all control variables with 20 categories, the matching algorithm with 15 categories is used in favor of more matched observations.

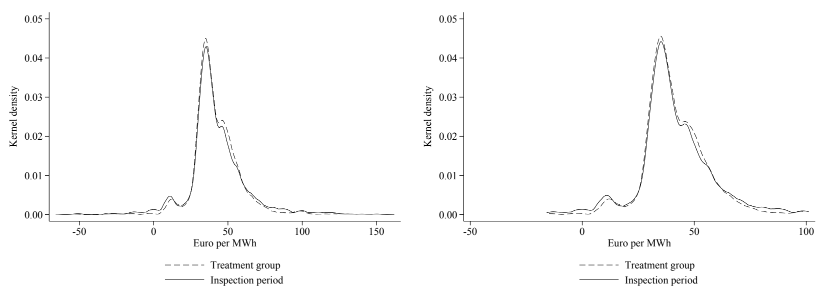
In order to gain insights into the effects of the inspections on the dependent variables, the observations in the treatment group have to be representative for the inspection period. Figures 7 and 8 compare the distributions of the electricity price for the French and German-Austrian markets in the treatment group and the inspection period. For both markets, the overall distribution of the dependent variables remains very similar after the matching.

The third concern regarding the estimation results relates to possible ex-



(a) *Full dataset* **(b)** *Adjusted dataset*

Figure 7: *Distribution of the French electricity price in Euros per MWh in the treatment group and inspection period*



(a) *Full dataset* **(b)** *Adjusted dataset*

Figure 8: *Distribution of the German-Austrian electricity price in Euros per MWh in the treatment group and inspection period*

ogenous events other than the inspection period. Due to the matching and the estimation model, it was possible to disentangle the influence of the overall load, generation of renewable electricity, commodity prices, and hour of the day, on the electricity prices. Therefore, the results from Section 5.1 provide valuable insights into the economic effect of the outages in the affected French nuclear power plants on the French and German-Austrian electricity prices.

6. Conclusion

Are nuclear power plant outages in France contagious to the German electricity price? Yes, they are if the outages are of a magnitude and an extent such as the ones caused by the extensive inspections from October 2016 to February 2017. The security concerns in the 12 nuclear power plants affected not only the French but also the German-Austrian electricity price. The French day-ahead electricity price increased by 14.15 Euros per MWh due to the extensive inspections. The effect on the German-Austrian day-ahead electricity price relates to the cross-border trade. Due to the increased electricity exports from Germany to France, the German-Austrian electricity price increased by 1.72 Euros per MWh. Despite an ex-post analysis of the capacity shock, this paper contributes to the literature on the electricity generated from nuclear power plants and the state of the integration of the European electricity market regarding cross-border trade.

The merits and demerits of nuclear electricity generation are an ongoing topic in energy economics. The cost effectiveness of nuclear electricity generation is debated (Davis, 2012; Linares and Conchado, 2013; Dhaeseleer, 2013). In the case of France, the focus lies on finding an affordable alternative to nuclear electricity generation in accordance with the climate goals (Boccard, 2014; Maïzi and Assoumou, 2014; Lorenz et al., 2016; Malischek and Trüby, 2016; Lykidi and Gourdel, 2017). Although nuclear electricity generation is dispatchable, in contrast to solar and wind electricity generation, the reliability of nuclear power plants can be interfered with. The security concerns regarding one specific component affected at once 20% of the French nuclear power plants. As shown in this analysis, this capacity shock increased the French electricity price substantially. Hence, a stronger diversification of the electricity mix in France might have reduced the price effect.

In addition, the analysis of the cross-border trade between France and Germany during the inspection period sheds light on the potential and current limitations of an integrated European electricity market. During the inspection period, the capacity loss on the French market was partly compensated for by electricity imports from the German market. Nevertheless, the French day-ahead electricity price increased considerably due to the extensive inspection to achieve a security of supply during winter. Hence, European electricity markets are likely to profit from an extension of the cross-border trade to maintain the security of supply at lower costs.

AppendixA.

Capacity in GW		Capacity in GW		Capacity in GW	
Belleville 1	1.310	Cruas 1	0.915	Paluel 1	1.330
Belleville 2	1.310	Cruas 2	0.915	Paluel 2	1.330
Blayais 1	0.910	Cruas 3	0.915	Paluel 3	1.330
Blayais 2	0.910	Cruas 4	0.915	Paluel 4	1.330
Blayais 3	0.910	Dampierre 1	0.890	Penly 1	1.330
Blayais 4	0.910	Dampierre 2	0.890	Penly 2	1.330
Bugey 2	0.910	Dampierre 3‡	0.890	St. Alban 1	1.335
Bugey 3	0.910	Dampierre 4	0.890	St. Alban 2	1.335
Bugey 4‡	0.880	Fessenheim 1‡	0.880	St. Laurent 1‡	0.915
Bugey 5	0.880	Fessenheim 2	0.880	St. Laurent 2	0.915
Cattenom 1	1.300	Flamanville 1	1.330	Tricastin 1‡	0.915
Cattenom 2	1.300	Flamanville 2	1.330	Tricastin 2‡	0.915
Cattenom 3	1.300	Golfech 1	1.310	Tricastin 3‡	0.915
Cattenom 4	1.300	Golfech 2	1.310	Tricastin 4‡	0.915
Chinon 1	0.905	Gravelines 1	0.910		
Chinon 2	0.905	Gravelines 2‡	0.910		
Chinon 3	0.905	Gravelines 3	0.910		
Chinon 4	0.905	Gravelines 4‡	0.910		
Chooz 1	1.500	Gravelines 5	0.910		
Chooz 2	1.500	Gravelines 6	0.910		
Civaux 1‡	1.495	Nogent 1	1.310		
Civaux 2‡	1.495	Nogent 2	1.310		

Table A.8: *French nuclear power plant fleet at the end of 2015 (Source: ENTSO-E).*
‡ Plants affected by the inspections from 18.10.2016 to 24.02.2017.

	Estimation model	
	full sample	**without outliers †**
	(1)	(1†)
# of observations	2,366	2,344
Electricity price France in € per MWh		
Inspection period		
$T_i = 1$	14.146***	13.786***
	(1.213)	(1.119)
Load France in GWh	0.640*	0.459***
	(0.192)	(0.469)
Load Germany in GWh	0.907***	0.912***
	(0.060)	(0.065)
Solar and wind in Germany in GWh	−1.009	−1.056*
	(0.350)	(0.328)
CO_2 price in € per ton	5.801***	5.040***
	(1.293)	(0.496)
Coal price in € per ton	1.490***	1.234***
	(0.326)	(0.80)
Gas price in € per MWh	−1.822**	−1.278***
	(0.746)	(0.215)
Hour		
1	0.9665	0.137
2	−0.810	−1.506***
3	−1.292	−2.633***
4	−4.065*	−5.630***
5	−3.166	−4.586***
6	−2.268*	−2.570***
7	0.794	1.516
8	−3.019*	−1.174
9	−1.072	−0.344
10	−0.742	0.980
11	−0.512	0.408
12	−2.674	−1.744
13	−5.310*	−3.237
14	−5.093**	−3.636*
15	−5.037***	−4.856***
16	−6.221***	−5.980***
17	−0.368	−0.048
18	18.445***	5.142***
19	4.857***	6.208***
20	0.690	2.050*
21	−0.878	−0.828
22	0.332	−0.079
23	0.425	−0.957***
Constant	−129.232***	−109.207***
	(23.315)	(7.117)

Table A.9: *Full report: Price effects of the inspections in affected nuclear power plants on the French electricity price*

All prices in 2015 Euros. Standard errors in parentheses clustered at the level of the hour. ***, **, * indicate statistical significance at the 0.1%, 1%, 5% levels. Model includes hour fixed effects. † Without prices > 167.41 (101.52) or < −38.85 (−17.25) Euros per MWh on the French (German-Austrian) market.

	Estimation model			
	full sample		**without outliers †**	
	(1)	(2)	(1†)	(2†)
# of observations	2,366	2,366	2,344	2,344
Electricity price Germany-Austria in € per MWh				
Inspection period				
$T_i = 1$	2.566***		3.066***	
	(0.666)		(0.734)	
Inspection period × exports in GWh (to France)				
$T_i = 0$		2.854*		2.401*
		(1.073)		(0.943)
$T_i = 1$		5.046***		4.889***
		(0.495)		(0.480)
Inspection period × imports in GWh (from France)				
$T_i = 0$		−0.602		−0.762
		(0.369)		(0.377)
$T_i = 1$		−2.459***		−1.790***
		(0.362)		(0.398)
Load France in GWh	0.184***	0.105*	0.149**	0.076
	(0.050)	(0.040)	(0.047)	(0.041)
Load Germany in GWh	0.808***	0.915***	0.738***	0.848***
	(0.078)	(0.066)	(0.066)	(0.056)
Solar and wind Germany in GWh	−3.245***	−3.442***	−2.977***	−3.192***
	(0.649)	(0.570)	(0.575)	(0.497)
CO_2 price in € per ton	0.996***	0.289	1.171***	0.597*
	(0.246)	(0.222)	(0.234)	(0.217)
Coal price in € per ton	0.399***	0.311***	0.360***	0.293***
	(0.044)	(0.045)	(0.041)	(0.041)
Gas price in € per MWh	0.309*	0.713***	0.308*	0.627***
	(0.140)	(0.144)	(0.118)	(0.123)
Hour				
1	1.479***	1.280***	1.203***	1.032***
2	−0.121	0.543*	−0.378	0.215
3	0.923*	1.990***	0.537	1.473***
4	0.649	2.086***	0.253	1.514**
5	0.428	1.056**	0.277	0.789*
6	−0.028	0.098	1.035	0.968*
7	3.957***	3.588***	4.605***	4.178***
8	3.285**	3.049***	4.750***	4.560***
9	7.489***	7.020***	7.742***	7.185***
10	9.017***	8.677***	9.807***	9.489**
11	11.713***	11.518***	11.976***	11.928***
12	11.550**	10.988***	11.446***	10.795***
13	9.970**	9.971***	10.729***	10.785***
14	6.690**	7.592***	7.357**	8.156***
15	5.913***	6.963***	6.413***	7.351***
16	4.280***	5.212***	5.354***	6.009***
17	8.442***	8.388***	8.662***	8.397***
18	7.779***	6.427***	7.884***	6.506***
19	5.609***	3.779**	6.328***	4.514***
20	1.473	0.120	3.090**	1.632*
21	−1.521	−1.901**	−0.656	−1.171*
22	−1.283*	−1.724**	−0.256	−0.718
23	−1.948***	−2.156***	−2.000***	−2.309***
Constant	−53.020***	−50.748***	−46.781***	−45.154***
	(5.909)	(5.140)	(5.597)	(5.068)

Table A.10: *Full report: Price effects of the inspections in affected nuclear power plants on the German-Austrian electricity price*

All prices in 2015 Euros. Standard errors in parentheses clustered at the level of the hour. ***, **, * indicate statistical significance at the 0.1%, 1%, 5% levels. Model includes hour fixed effects. † Without prices > 167.41 (101.52) or < −38.85 (−17.25) Euros per MWh on the French (German-Austrian) market.

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References

Abrell, J., Rausch, S., 2016. Cross-country electricity trade, renewable energy and European transmission infrastructure policy. Journal of Environmental Economics and Management 79, 87–113.

ACER, CEER, 2017. Annual Report on the Results of Monotoring the Internal Electricity and Gas Markets in 2016.

AGEB, 2017. Bruttostromerzeugung in Deutschland ab 1990 nach Energieträgern.

Alberini, A., Towe, C., 2015. Information vs. energy efficiency incentives: Evidence from residential electricity consumption in Maryland. Energy Economics 52, S30–S40.

Allcott, H., 2011. Social norms and energy conservation. Journal of Public Economics 95 (9-10), 1082–1095.

Allcott, H., Rogers, T., 2014. The short-run and long-run effects of behavioral interventions: Experimental evidence from energy conservation. American Economic Review 104 (10), 3003–37.

Andor, M. A., Frondel, M., Rinne, S., 2015. Wie unbeliebt ist Kohle und wie beliebt sind die Erneuerbaren? RWI Materialien (93).

Antweiler, W., 2016. Cross-border trade in electricity. Journal of International Economics 101, 42–51.

ASN, 2016. Certain EDF reactor steam generators in service could contain an anomaly similar to that affecting the Flamanville EPR vessel. Press release 28.06.2016.

ASN, 2017a. Anomaly in the carbon concentration of the steel: after inspection, ASN has authorised restarting of the reactors concerned. Press release 15.03.2017.

ASN, 2017b. ASN presents its position regarding the Flamanville EPR reactor vessel anomaly. Press release 28.07.2017.

Betzer, A., Doumet, M., Rinne, U., 2013. How policy changes affect shareholder wealth: the case of the Fukushima Dai-ichi nuclear disaster. Applied Economics Letters 20 (8), 799–803.

Bizet, R., Lévêque, F., 2015. Early decommissioning of nuclear power plants: Is there an economic rationale? The Electricity Journal 28 (2), 53–62.

Boccard, N., 2014. The cost of nuclear electricity: France after Fukushima. Energy Policy 66, 450–461.

Böckers, V. F. P., Haucap, J., Heimeshoff, U., 2013. Benefits of an integrated European electricity market. No. 109.

Borenstein, S., Bushnell, J., Stoft, S., 1997. The competitive effects of transmission capacity in a deregulated electricity industry. Tech. rep., National Bureau of Economic Research.

Bosco, B., Parisio, L., Pelagatti, M., Baldi, F., 2010. Long-run relations in European electricity prices. Journal of Applied Econometrics 25 (5), 805–832.

Brouard, S., Gougou, F., Guinaudeau, I., Persico, S., 2012. Les Français, le nucléaire et la campagne présidentielle 2012.

Bundestag, D., 2011. Entwurf eines Dreizehnten Gesetzes zur Änderung des Atomgesetzes. Drucksache 17/6070.

Conejo, A. J., Plazas, M. A., Espinola, R., Molina, A. B., 2005. Day-ahead electricity price forecasting using the wavelet transform and ARIMA models. IEEE transactions on power systems 20 (2), 1035–1042.

Cox, D. R., 1958. Planning of experiments. Wiley, New York.

Csereklyei, Z., Thurner, P. W., Langer, J., Küchenhoff, H., 2017. Energy paths in the European Union: A model-based clustering approach. Energy Economics 65, 442–457.

Davis, L., Hausman, C., 2016. Market impacts of a nuclear power plant closure. American Economic Journal: Applied Economics 8 (2), 92–122.

Davis, L. W., 2012. Prospects for nuclear power. Journal of Economic Perspectives 26 (1), 49–66.

Dhaeseleer, W. D., 2013. Synthesis on the economics of nuclear energy. Study for the European Commission, DG Energy, Final Report, European Commission, Brussels.

DNVGL, 2014. Potential interactions between capacity mechanisms in france and germany. descriptive overview, cross-border impacts and challenges.

Eberlein, B., 2008. The making of the European energy market: The interplay of governance and government. Journal of Public Policy 28 (1), 73–92.

EPEX, 2018. Market coupling. a major step towards market integration. Tech. rep., EPEX SPOT.

Ferstl, R., Utz, S., Wimmer, M., 2012. The effect of the Japan 2011 disaster on nuclear and alternative energy stocks worldwide: An event study.

Fisher, R. A., 1935. The design of experiments. Oliver and Boyd, Edinburgh.

Gebhardt, G., Höffler, F., 2013. How competitive is cross-border trade of electricity? theory and evidence from European electricity markets. The Energy Journal 34 (1), 125.

Grossi, L., Heim, S., Waterson, M., 2017. The impact of the German response to the Fukushima earthquake. Energy Economics 66 (C), 450–465.

Hadjilambrinos, C., 2000. Understanding technology choice in electricity industries: a comparative study of France and Denmark. Energy policy 28 (15), 1111–1126.

Haxhimusa, A., 2018. The effects of german wind and solar electricity on french spot price volatility: An empirical investigation.

Heckman, J. J., 2005. The scientific model of causality. Sociological methodology 35 (1), 1–97.

Heckman, J. J., 2008. Econometric causality. International Statistical Review 76 (1), 1–27.

Ho, D. E., Imai, K., King, G., Stuart, E. A., 2007. Matching as nonparametric preprocessing for reducing model dependence in parametric causal inference. Political Analysis 15 (3), 199–236.

Iacus, S. M., King, G., Porro, G., 2011. Multivariate matching methods that are monotonic imbalance bounding. Journal of the American Statistical Association 106 (493), 345–361.

Iacus, S. M., King, G., Porro, G., 2012. Causal inference without balance checking: Coarsened exact matching. Political Analysis, 1–24.

Jamasb, T., Pollitt, M., 2005. Electricity market reform in the European Union: review of progress toward liberalization & integration. The Energy Journal, 11–41.

Jessoe, K., Rapson, D., 2014. Knowledge is (less) power: Experimental evidence from residential energy use. American Economic Review 104 (4), 1417–38.

Joskow, P. L., Parsons, J. E., 2012. The future of nuclear power after Fukushima. Economics of Energy & Environmental Policy 1 (2), 99–114.

Joskow, P. L., Tirole, J., 2000. Transmission rights and market power on electric power networks. The Rand Journal of Economics, 450–487.

Keppler, J. H., Phan, S., Le Pen, Y., Boureau, C., 2017. The impact of intermittent renewable production and market coupling on the convergence of French and German electricity prices.

Linares, P., Conchado, A., 2013. The economics of new nuclear power plants in liberalized electricity markets. Energy Economics 40, S119–S125.

Lorenz, C., Brauers, H., Gerbaulet, C., von Hirschhausen, C. R., Kemfert, C., Kendziorski, M., Oei, P.-Y., 2016. Nuclear power is not competitive: Climate protection in UK and France also viable without it. DIW Economic Bulletin 6 (44), 505–512.

Lykidi, M., Gourdel, P., 2017. Optimal management of flexible nuclear power plants in a decarbonising competitive electricity market: The French case. Energy 132, 171–185.

Maïzi, N., Assoumou, E., 2014. Future prospects for nuclear power in France. Applied Energy 136, 849–859.

Malischek, R., Trüby, J., 2016. The future of nuclear power in France: an analysis of the costs of phasing-out. Energy 116, 908–921.

Neuhoff, K., Barquin, J., Bialek, J. W., Boyd, R., Dent, C. J., Echavarren, F., Grau, T., von Hirschhausen, C., Hobbs, B. F., Kunz, F., et al., 2013. Renewable electric energy integration: Quantifying the value of design of markets for international transmission capacity. Energy Economics 40, 760–772.

Oren, S. S., 1997. Economic inefficiency of passive transmission rights in congested electricity systems with competitive generation. The Energy Journal, 63–83.

Phan, S., Roques, F., 2015. Is the depressive effect of renewables on power prices contagious? A cross border econometric analysis.

Pukelsheim, F., 1994. The three sigma rule. The American Statistician 48 (2), 88–91.

Qiu, Y., Wang, Y. D., Wang, J., 2017. Soak up the sun: Impact of solar energy systems on residential home values in Arizona. Energy Economics 66, 328–336.

Rintamäki, T., Siddiqui, A. S., Salo, A., 2017. Does renewable energy generation decrease the volatility of electricity prices? An analysis of Denmark and Germany. Energy Economics 62, 270–282.

RTE, 2016. Annual electricity report 2015.

Rubin, D. B., 1974. Estimating causal effects of treatments in randomized and nonrandomized studies. Journal of educational Psychology 66 (5), 688.

Schaber, K., Steinke, F., Hamacher, T., 2012. Transmission grid extensions for the integration of variable renewable energies in Europe: Who benefits where? Energy Policy 43, 123–135.

Simcoe, T., Toffel, M. W., 2014. Government green procurement spillovers: Evidence from municipal building policies in California. Journal of Environmental Economics and Management 68 (3), 411–434.

Spiecker, S., Vogel, P., Weber, C., 2013. Evaluating interconnector investments in the north European electricity system considering fluctuating wind power penetration. Energy Economics 37, 114–127.

Splawa-Neyman, J., Dabrowska, D., Speed, T., 1990. On the application of probability theory to agricultural experiments. Essay on principles. Statistical Science 5 (4), 465–472.

Torriti, J., 2014. Privatisation and cross-border electricity trade: From internal market to European Supergrid? Energy 77, 635–640.

Uniejewski, B., Marcjasz, G., Weron, R., et al., 2017. On the importance of the long-term seasonal component in day-ahead electricity price forecasting. Part II–probabilistic forecasting. Tech. rep., Hugo Steinhaus Center, Wroclaw University of Technology.

Van Hertem, D., Ghandhari, M., 2010. Multi-terminal VSC HVDC for the European supergrid: Obstacles. Renewable and Sustainable Energy Reviews 14 (9), 3156–3163.

Würzburg, 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.

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