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Abstract: We examine the *relationship between German wind and solar electricity and French spot price volatility. Using hourly data, we find that French imports from Germany driven by German wind and solar electricity have an ambiguous effect on the volatility of French spot prices depending on the shape of the French supply function and on the French demand. We, therefore, estimate different coefficients for imports depending on demand. We acknowledge the endogeneity problem in identifying these effects and employ instrumental variable techniques to circumvent this problem. Our results show the urgent need for further coordination of national energy policies in order to reduce the potential for negative spill over effects of nationally driven energy policies in neighbouring countries as European electricity markets are becoming more integrated.*

Keywords: Wind and Solar Electricity, Price Volatility, Market Integration, Electricity Markets

JEL Codes: F15, L81, L98, Q42, Q48

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1. Introduction

The aim of promoting the integration of European electricity markets is to increase the overall efficiency by having access to a very diversified European electricity generation mix (Directive 96/92/EC, Directive 2003/54/EC, Directive 2009/72/EC).Among other things, many structural changes have been implemented to foster integration of electricity markets toward an internal European market. National/regional power exchanges have been established where trading takes place for each hour of the day. Nowadays, over nineteen European electricity markets have implemented market coupling, which represents a mechanism to ensure efficient allocation of traded electricity and cross-border capacities via implicit auctions. In this way, market coupling enables a faster absorption of supply and demand shocks among electricity markets.

The dynamics of electricity prices have been changing rapidly over the last decade, among other factors,[1] because more intermittent wind and solar electricity has been feeding into the grid. The existing literature has comprehensively analysed the impact of intermittent renewables on the dynamics (e.g. volatility and mean) of electricity prices within a country (e.g. Green and Vasilakos, 2010; Jonsson et al., 2010; Woo et al., 2011; Kalantzis and Milonas, 2013; Tashpulatov, 2013; Tveten et al., 2013; Paraschiv et al., 2014; Pape et al., 2016; Paschen, 2016; Wozabal et al., 2016). Despite this interest, no one as far as we know has considered that with increasing international integration of electricity markets, unilateral changes of national supply structures may also cross the borders and affect wholesale prices in neighbouring markets. Hence, as European electricity markets have been becoming better integrated (Böckers et al., 2013; Gugler et al., 2016a; Pellini, 2014; Zachman, 2008) intermittent wind and solar electricity might change the dynamics of spot prices in neighbouring electricity markets including their volatility. However, its magnitude depends essentially on the availability of cross border transmission capacities to export/import intermittent wind and solar electricity. The contribution of this paper is to fill this gap in the literature by investigating the impacts of French imports from Germany,[2] which are mainly driven by wind and solar electricity generation in Germany, on the volatility of French spot prices.

In the electric power industry, like in other industries, the volatility of electricity spot prices is an important indicator for investment in different electricity generation technologies. Investment in storage power plants (e.g. pump storages and batteries) are a classic case whose

[1] Market power, market design, trading inefficiencies, etc. (Wolak and Patrick, 2001; Borenstein et al., 2002; Karakatsani and Bunn, 2010).

[2] During the period of investigation Germany and Austria constitute one day-ahead market area. Therefore, we refer to this market area as Germany.

profits depend essentially on the short-term spot price volatility, because their core business is to buy electricity and store it when spot prices are low and to sell it when spot prices go up (Löhndorf et al., 2013). Hence, it is reasonable to expect that high spot price volatility increases the incentives to invest in electricity storage capacities (Muche, 2009; Conolly et al., 2011). Gugler et al. (2016b) found that spot price volatility – as a measure of aggregate uncertainty – increases investment incentives in base load technologies too (e.g. nuclear, coal and run of river power plants) since aggregate uncertainty increases the value of being active in the future (Bar-Ilan and Strange, 1996). As a result, the volatility of spot prices seems to be an important driver of investment in a broader range of electricity generation technologies. Moreover, investment in flexible storage capacities, e.g. pump-storages, are also necessary to ensure network stability and security of electricity supply, while the share of intermittent renewables is increasing (DENA, 2010; Sinn, 2017).

In electricity markets, in contrast to other industries, electricity supply and demand have to be balanced at every point in time. Therefore, high short-term (intraday) volatilities in supply and demand trigger some problems for both transmission and distribution system operators with respect to network stability and security of electricity supply (Abrell, 2016).[3] Previous empirical studies that discusses electricity spot price volatility employ the standard measure of the (daily) spot price variance. However, by constructing daily averages for wind and solar electricity and demand, many information relating to minimum, maximum and values between them will be lost. Moreover, this information that gets lost by taking daily averages represents the (exact) drivers of spot price volatility. For this reason, we create a measure of volatility that includes more information and is thus superior to previous studies. Hence, we take the absolute value of the deviation of the actual hourly spot price from the daily mean and construct an hourly *volatility measure* of French spot prices (see section 5).

A feature of two neighbouring and interconnected electricity markets (especially with market coupling[4]) is that electricity flows from the low price market area (i.e. market area with high share of intermittent renewables) to the high price market area (Weber et al., 2010; Gugler et al., 2016a). This insinuates the following:

- On the one hand, when demand is low in the high spot price market area and hence its spot price is below its daily average, additional electricity imports from the low price market area would further decrease the spot price in the high spot price market area. This would

[3] The ANOVA test also shows that that there is no significant spot price variance across-days after we control for weekend, month, year and holiday fixed-effects. The results are available upon request.

[4] Market coupling (implicit auctioning) enables simultaneous allocation of interconnection capacities and electricity. It eliminates all inefficiencies relating to allocation of cross-border capacities. Without market coupling, allocation of interconnection capacities and electricity trade occur separately (see Meeus et al., 2009; Pellini, 2012).

increase the distance of the actual spot price to the daily mean, and as a result spot price volatility increases.

- On the other hand, when demand is high in the high spot price market area and correspondingly the spot price is above its daily average, additional electricity imports from the low price market area would decrease the electricity spot price in the high spot price market area. As a result, the distance of the actual spot price to the daily mean decreases, which in turn translates to a lower spot price volatility.

The magnitude of these two opposing effects on the volatility of spot prices depends also on the *shape of the electricity supply curve* at the intersection point with the electricity demand (Wozabal et al., 2016) (see Section 4). Therefore, following Davis and Hausman (2016), we constructed three different French demand categories (low, medium and high) in order to identify these two opposing effects of electricity imports from Germany on the French spot price volatility and quantify their magnitudes. Our dataset contains hourly data on spot prices, electricity demand, imports, nuclear generation and day-ahead forecasts for wind and solar generation. We conduct our empirical exercise for the two biggest electricity markets in the European Union, Germany and France[5], for the hourly period 25.01.2011-31.12.2014. We acknowledge the endogeneity problem of potential joint causality between imports and spot prices. Hence, we employ instrumental variable (IV) techniques and use day-ahead generation forecasts for German wind and solar generation and dummies for holidays in Germany and France as exogenous instruments. This approach allows us to identify the effects of German wind and solar electricity, which translate through the channel of imports on the volatility of French spot prices.

We find that both wind and solar electricity in Germany increase French imports from Germany. Our findings support our hypothesis that French imports from Germany have two opposing effects of the volatility of French spot prices depending on the French electricity demand and the shape of the electricity supply curve. On the one hand, we find that when demand in France is high, cheap wind and solar electricity imports from Germany *decrease* the volatility of French spot prices. On the other hand, our results show that when demand in France is low, cheap wind and solar electricity imports from Germany *increase* French spot price volatility. This effect is more pronounced during times of very low demand, because firms that own generation technologies with low flexibility, e.g. nuclear power plants, find it it more reasonable to lower their bid prices (even to bid negative prices and make losses than switching

[5] Both countries have relatively different power plant fleets; while France mainly generates electricity using nuclear and water energy sources and has quite stable electricity generation, Germany has a more diversified power plant fleet using nuclear, coal, gas, wind and solar energy sources with high volatility due to high shares of wind and solar generation.

off the plant), because of longer down times and higher start-up costs (Sensfuß, 2007). This, of course, leads to a further increase of French spot price volatility, because low demand intersects the supply curve at the very beginning (Pape et al., 2016) (see Section 4).

Our results show that the impact of a unilateral decision in an EU member state may create severe distortions in other countries when electricity markets are well integrated. However, while the externality is sometimes negative, it is often positive (during high French demand). Thus, supporting at the same time both the deployment of renewable generation capacities and the integration of European electricity markets call for better coordination and harmonization of national energy policies in order to tackle (negative) external effects.

This paper is organised as follows. We review the literature on electricity price dynamics in Section 2. Section 3 thoroughly analyses both French and German electricity markets. We illustrate the relationship between imports and spot price volatility in Section 4. Our employed data and variables are discussed in Section 5. The empirical model is explained in Section 6, and empirical findings are discussed in Section 7. Section 8 concludes.

2. Literature review on price volatility

Various empirical studies have shown that electricity spot prices, in contrast to other commodities, exhibit high inter- and intra-day correlations, mean reversion, heavy tails, and positive skewness. They also have shown that the deployment of wind and solar generation capacities have changed the dynamics of electricity spot prices (e.g. Jonsson et al., 2010; Paschen, 2016). In this section, we show the main findings of selected empirical findings concerning the impact of wind and solar electricity on the dynamics of electricity spot prices, especially on volatility.

In the last decade, many EU member states have implemented different support schemes[6] for investment in renewable energy sources (mainly wind and solar generation capacities) as a response to global climate change. This has resulted in massive investment in wind and solar generation capacities in Europe, with Germany paving the way.[7] Besides, the large deployment of wind and solar generation capacities calls for further market integration by investing in additional transmission and interconnection capacities in order to obtain the benefits of the spatial diversity of renewable energy sources and the potential complementarity between and

[6] For more information regarding support schemes for investment in renewable energy sources see (DiaCore, 2016)

[7] Total wind and solar generation capacities in Europe grew from 34.805 and 1.327 MW in 2004 to 148.042 and 89.025 MW in 2014, respectively. In 2014 Germany contributed about 30% and 43% of total European wind and solar electricity generation capacities, respectively (BP, 2016).

within wind and solar generation profiles across EU member states. Under such circumstances, market integration over larger remote areas is expected to smooth output variability and reduce the price effects of wind and solar forecasting errors across the EU (OECD/IEA, 2014; Agora-Energiewende, 2015). We consider Germany and France, because of their high degree of market integration and the peculiarities of their electricity systems. The data show that France has a very small proportion of wind and solar capacities (see Figure 1) and meets its demand mainly using nuclear power plants with low generation volatility and flexibility. On the contrary, Germany has a large pool of wind and solar capacities (see Figure 2). Germany's price variability, which heavily depends on the intermittency of generation from renewables, is thus smoothed through the possibility to export part of this volatile production to its neighbours (like France) (Ketterer, 2014). This, in turn, means that wind and solar output variability would decrease (increase) in countries with high (low) shares of wind and solar generation with increasing market integration. In this regard, Denny et al. (2010) found that increasing interconnection capacity and thus trade between Great Britain and Ireland, with a large share of wind generation capacities, would reduce both the average price and the variability of Irish spot prices. Bask and Widerberg (2009) also found that integration of Scandinavian energy markets has led to a more stable and less volatile electricity spot prices particularly due to the increased competition.

Phan and Roques (2015) were the first to show explicitly the effects of German wind and solar electricity on the French spot price level and volatility using GARCH models. Utilizing hourly data on German and French electricity markets from 01.01.2012 to 30.06.2014 they found that German wind electricity decreases the average French spot price but it increases spot price volatility. In contrast to Phan and Roques (2015), we make an additional step and consider different electricity demand categories to estimate the effects of French electricity imports driven by German wind and solar generation on French spot price volatility. This allows us to identify two opposing effects whose magnitudes are heavily dependent on the French electricity demand and the shape of the electricity supply curve.

Grossi et al. (2015) paid attention to one of the most important issues in supporting two simultaneous objectives of establishing an internal European electricity market and deploying large amounts of wind and solar capacities; while the former is driven by the European Commission and the later is a competence of national energy policies. They have investigated the impacts of unilateral German reforms in phasing out nuclear power plants after the Fukushima earthquake and in expanding wind and solar capacities via fixed feed-in tariffs on neighbouring markets. They found that the highest costs of both German unilateral decisions were not found in Germany but in France, caused by negative externalities, with additional 2.21 billion Euro per year. As a result, the authors called for a more harmonized national European energy policy as European electricity markets are becoming more integrated.

As already mentioned, so far the existing literature has mainly focused on identifying the impacts of wind and solar electricity on the dynamics of electricity prices within a country. While some articles used daily averages, others recognized that hourly data are more informative. In this line, Ketterer (2014) employed a GARCH model with daily data from January 2006 to January 2012 to examine the effects of German wind electricity generation on the level and the volatility of German spot prices. She found that wind electricity generation reduces spot price levels but increases the volatility of spot prices. As a result, she called for more investment in interconnection capacities within Europe in order to reduce the augmenting effects of wind electricity on the price volatility. Despite its shortcomings of using daily averages it remains an open question, whether the export of intermittent wind and solar electricity to neighbouring countries has an augmenting or dampening effect on the price volatility of the importing market. An asset of our study is that we are able to fill this gap.

In addition, Wozabal et al. (2016) also used daily German data on wind and solar electricity generation and electricity spot prices from 2007 to 2013. They found that both wind and solar electricity generation in Germany not only increase but also decrease the volatility of German spot prices depending on the shape of the supply curve and the amount of wind and solar electricity generation. This is why we put particular emphasis on the supply structure in our empirical approach. Another study by Hartner and Permoser (2017) also showed a non-linear relationship between solar penetration and German spot price variance. Ederer (2016) found that the effect on volatility of German spot prices is less pronounced with offshore wind than with onshore wind.

3. French and German electricity markets

The geographic focus of this study is on two particularly relevant electricity markets in Europe, Germany and France, which make up almost 40% of total EU-28 generation in 2014 (Eurostat, 2016). The two countries are quite dissimilar in their supply structures (i.e. electricity generation mixes) to meet their national demand for electricity. Figures 1 and 2 give a broad picture regarding the evolution of the generation structures of both French and German electricity markets from 2002 to 2014, respectively. Figure 1 shows French generation capacities by technology and shares of wind and solar capacities as percentages in total generation capacity. It can be seen that France mainly fulfills its demand using nuclear and hydropower plants[8], and its generation capacities do not vary much over the years. Yet, France has installed additional 18 GW generation capacities, namely around 5 GW gas, 4.5 GW solar, 8.5 GW wind, and has removed around 3.5 GW coal generation capacities between 2002 and 2014. The shares of wind and solar generation have increased from around 0.1% and 0% in 2002 to 7.1% and 3.5% in 2014, respectively.

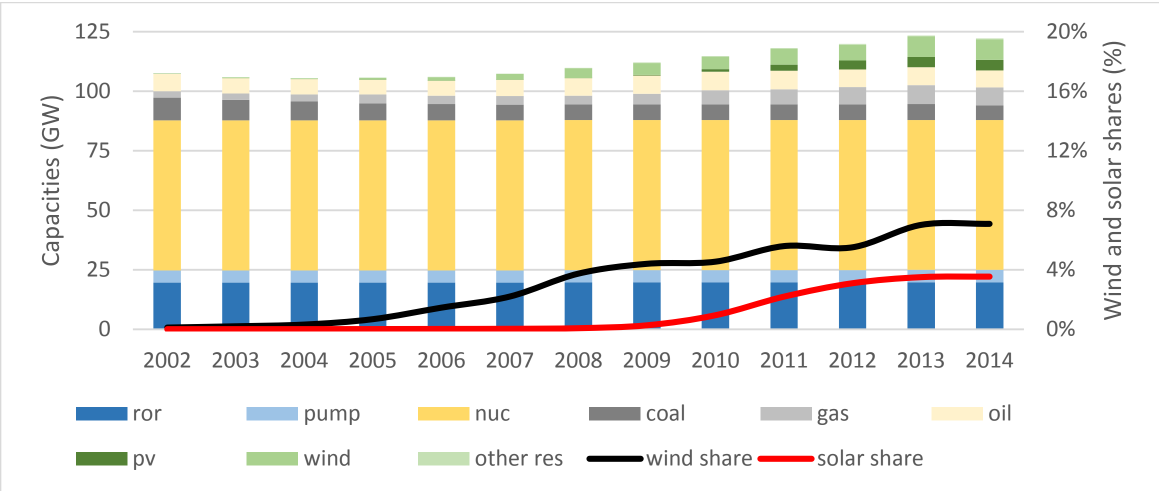

Figure 1. Generation capacities by technology in France, 2002-2014

Figure 2 shows the evolution of German generation capacities by technology and shares of wind and solar capacities in total generation capacity from 2002 to 2014. In contrast to France, with only 0.13 GW wind capacity in 2002, Germany has already installed 12 GW of wind capacity, which make up almost 10% of its total generation capacity. In contrast to France, generation structure in Germany is more diversified and has been subject to many changes because of Germany's nuclear phase-out[9] (as a response to the Fukushima reactor accident in Japan) and the new energy policy to decarbonize electricity generation through the massive deployment of wind and solar generation capacities.[10] The later ensures priority dispatch and fixed feed-in tariffs for all renewable electricity generation technologies. Consequently, wind and solar power together make up almost 40% of Germany's installed capacity in the year 2014.

[8] Nuclear and hydro power plants account for almost 55% and 17% of total generation capacities, respectively.
[9] 5.5 out of 17.5 GW nuclear generation capacities have been permanently closed by end of May 2011.
[10] Graf and Marcantonini (2017) thoroughly discuss the effects of intermittent renewables on the emission factors of conventional generators.

Germany's massive share of intermittent renewables, its geographic location in the heart of Europe with a strong interconnection with France, and the dissimilar supply structures between the two countries altogether represent a compelling coulisse for the empirical investigation of the external effects of Germany's massive build-up of renewables on the volatility of French spot prices through electricity trade.

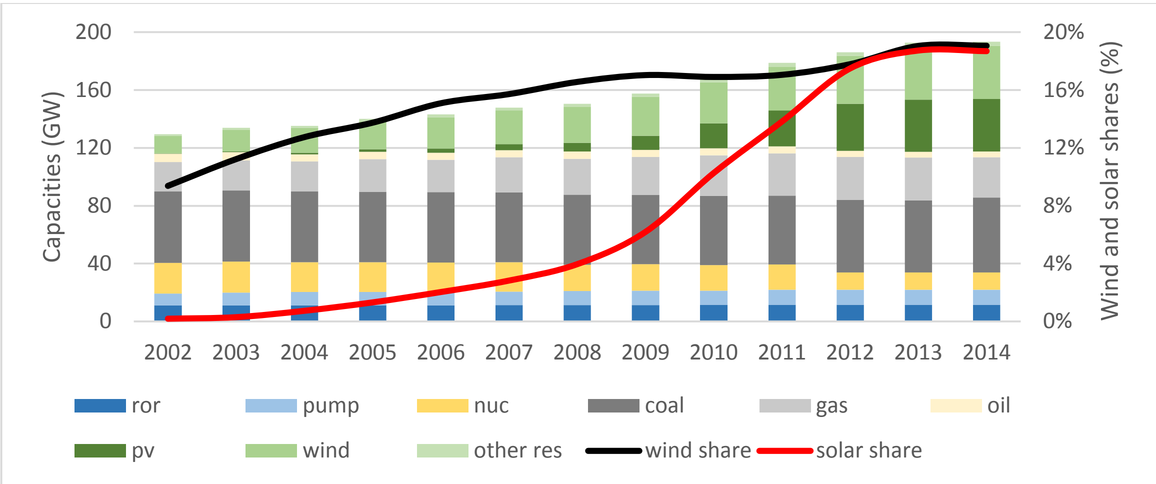

Figure 2. Generation capacities by technology in Germany, 2002-2014

Figures 3 and 4 show day-ahead generation forecasts for German wind and solar electricity, respectively, and French imports from Germany at each hour of the day in 2014. Solar (Figure 3) and wind (Figure 4) generation forecasts are depicted with dotted and dashed lines, respectively, and their unit labels appear on the left axis, while imports from Germany are depicted with a black line whose unit labels appear on the right axis of both figures. From Figure 3 and 4, it can be seen that French imports from Germany are highly correlated with Germany's wind and solar electricity production during peak times and off-peak times, respectively.

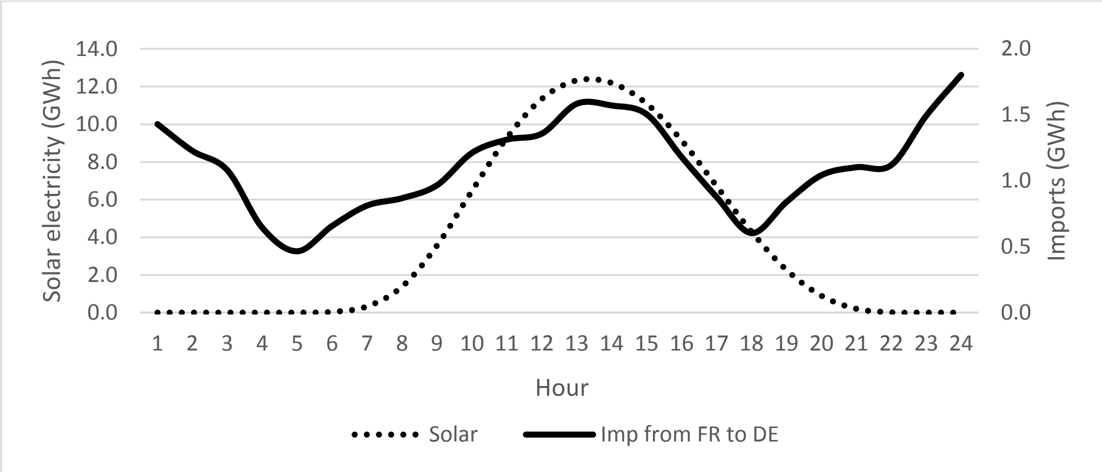

Figure 3. Day-ahead solar forecast in DE and imports from DE to FR by hour, 2014

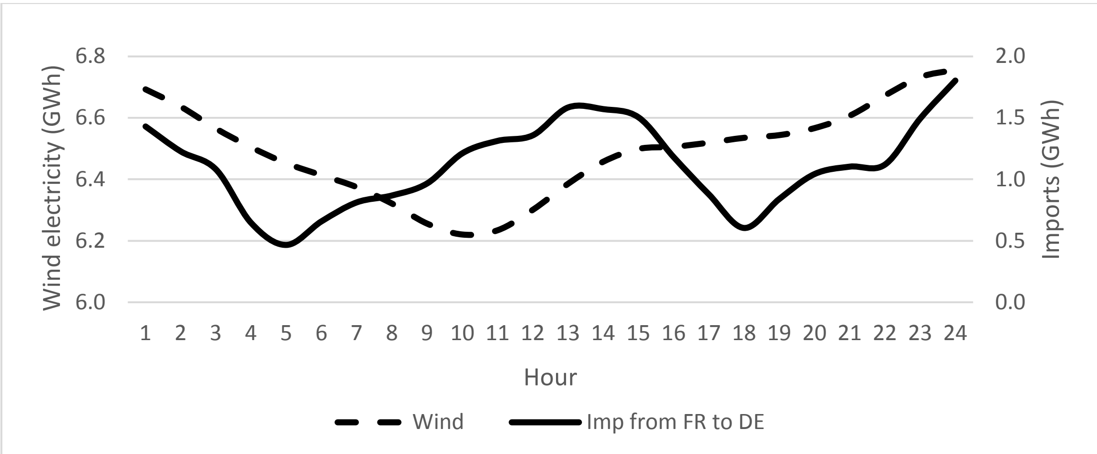

Figure 4. Day-ahead wind forecast in DE and imports from DE to FR by hour, 2014

4. Imports and spot price volatility

In the last two decades, the EC put a lot of effort (Directive 96/92/EC, Directive 2003/54/EC, and Directive 2009/72/EC) into establishing an internal European electricity market. For example, the Directive 2009/72/EC calls EU member states to increase interconnection capacities and to introduce market coupling in order to foster cross-border trade. In this regard, many empirical studies have been conducted and found that interdependencies between European electricity markets have increased in the last decade (e.g. Zachman, 2008; Gugler et al., 2016a). Among other European markets, market coupling between France and Germany was launched very successfully at the end of 2010 with the immediate consequence that price convergence and the number of hours with unconstrained electricity trade (i.e. equal prices) have increased significantly (Gugler and Haxhimusa, 2016).

In this section, we graphically illustrate the way how French electricity imports from Germany, which are mainly driven by German wind and solar electricity generation, affect the deviation of hourly French spot prices from the daily mean, which we interpret as price volatility. We first assume that French national demand for electricity is exogenous, because of its strong short run inelasticity (see Green and Newbery, 1992; Borenstein, 2009; Fabra and Reguant, 2014). We also assume that both French and German spot markets are competitive (Graf and Wozabal, 2013) with an inverse S-shaped supply function, which corresponds to the aggregate industry cost function (Wozabal, et al., 2016). German and French day-ahead spot market prices in any hour equal the marginal costs of the last operating power plant necessary to meet demand (Borenstein et al., 2002). Nuclear and hydro power plants with very low marginal costs make up over 70% of installed capacity in France, which make its merit-order curve flat followed by a steep part at its end with a relatively low share of generation technologies with high marginal costs (e.g. coal, gas, and oil). Like Wozabal et al. (2016) and based on actual generation capacity data we show in Figure 5 an inverse S-shaped stylized merit-order curve for France, which considers the dynamic aspects of dispatching power plants. This means that in hours with low electricity demand and corresponding low spot prices it is more economical for firms that own generation technologies with low flexibility, like nuclear plants, to lower their bid price (even bidding negative prices) and make losses rather than switching off due to their longer down times and higher start-up costs (Nicolosi, 2010; Sensfuß, 2007; Troy et al., 2010). As a result, the supply curve in Figure 5 becomes steeper in the first part.

The demand that has to be covered by French producers is calculated as total national demand subtracted by electricity imports (i.e. residual demand).[11] According to trade theory, after market coupling France imports from Germany only during hours where German spot prices are lower than French spot prices (regardless of their levels) (Baldwin and Wyplosz, 2015). Intuitively, this implies that imports from Germany are always cheaper than the actual French spot price.

According to Green and Vasilakos (2010) and Wozabal et al. (2016), in Figure 5 we show two opposing effects that imports from Germany have on the French spot price volatility depending on the level of electricity demand and on the shape of the French supply curve (merit-

[11] In our case, shifting the demand or the supply function for the quantity of imported electricity does not make any difference (Wozabal et al., 2016; Sensfuß et al., 2008).

order). Evidently, imports from Germany affect the deviation of actual hourly French spot prices ($P_{FR,h}$) from their daily means ($\overline{P}_{FR,d}$)[12] depending both on the demand for elelctricity and the shape of the supply curve. For high (H) electricity demand in hour h ($D^H_{FR,h}$), the corresponding price is $P^H_{FR,h}$ and its deviation from the daily mean is $\Delta P^H_{FR,h} = P^H_{FR,h} - \overline{P}_{FR,d}$. Clearly, imports from Germany shift the demand to the left ($D^{H'}_{FR,h}$) and thus the French spot price level drops to $P^{H'}_{FR,h}$. As a result, the deviation from the daily spot price mean ($\overline{P}_{FR,d}$) considerably decreases from $\Delta P^H_{FR,h}$ to $\Delta P^{H'}_{FR,h}$,[13] because the high demand intersects the supply curve in its steep part. However, the story changes for low French electricity demand levels intersecting the supply curve in its flat part. During hours with low levels of electricity demand in France ($D^L_{FR,h}$) the price ($P^L_{FR,h}$) is below its daily average: $\overline{P}_{FR,d} > P^L_{FR,h}$. As a result, importing electricity from Germany during these times decreases the price level from $P^L_{FR,h}$ to $P^{L'}_{FR,h}$, and thus the deviation from the daily mean increases ($\Delta P^L_{FR,h} < \Delta P^{L'}_{FR,h}$). The consequence is an increase in the volatility of spot prices. Besides, in the rare circumstances of very low demand, intersecting the merit-order curve in its very beginning, importing cheap wind and solar electricity from Germany is expected to further increase the deviation from the French spot price daily mean, and thus the volatility of French spot prices.

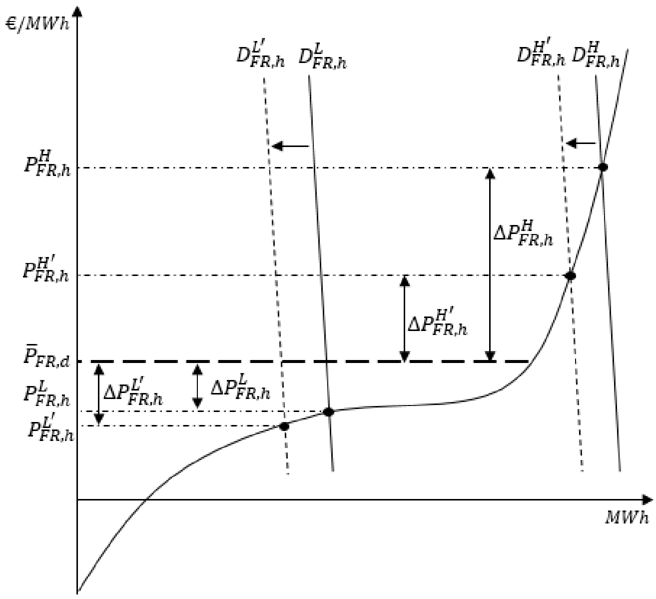

Figure 5. Exports and the departure of prices from their mean

[12] For the sake of simplicity we neglect the negative effect of imports from Germany on the daily spot price mean, $\overline{P}_{FR,d}$, and thus consider it as fixed.

[13] $P^{H'}_{FR,h} - \overline{P}_{FR,d} = \Delta P^{H'}_{FR,h} < \Delta P^H_{FR,h} = P^H_{FR,h} - \overline{P}_{FR,d}$

Finally, depending on the shape of the supply function and the level of electricity demand there are two opposing effects, which either augment or decrease price volatility. We expect that the dampening effect of imports on volatility (i.e. during times of high demand) outweights the volatility-augmenting effect over time. In other words, integration of electricity markets may either increase or decrease price volatility in neighbouring markets, given unilateral policies in other exporting countries.

5. Data and variables

5.1. Data sources

We employ a very rich dataset for the hourly period from 25.01.2011 to 31.12.2014. The data stem from various sources. Hourly data regarding French spot prices are acquired from the European Power Exchange Spot (EPEX Spot). The central office for cross-border transmission capacity allocation for Central Europe (CASC) provided us with hourly data regarding allocated cross-border capacities from Germany to France ($AC_{DE \rightarrow FR}$). We obtained hourly data on nuclear generation and hourly day-ahead forecasts for wind electricity generation in France from the French transmission system operator (TSO), Réseau de Transport d'Électricité (RTE). We got hourly data on day-ahead forecasts for wind and solar electricity generation in Germany from the four German TSOs, 50hertz Amprion, Tennet, and TransnetBW, and the Austrian TSO, Austrian Power Grid (APG). Data on national holidays are provided by www.feiertagskalender.ch. Finally, hourly French load data, which represent the aggregate French demand, are obtained from the European Network of Transmission System Operators for Electricity (ENTSO-E).

5.2. Variables

Our *dependent variable* is the absolute value of the deviation of the actual hourly French spot price $(P_{FR,h})$ from its daily mean $(\overline{P}_{FR,d})$, which represents a measure of *price volatility*: $PV_{FR,h} = |P_{FR,h} - \overline{P}_{FR,d}|$. In contrast to other empirical studies (e.g. Ketterer, 2014; Paschen, 2016; Wozabal et al., 2016), we do not use the standard measure of price variance, which can at least be calculated for the daily frequency, and thus would result in a loss of substantial information by taking daily averages of hourly observations of our main variables of interest (i.e. imports, demand, wind and solar). Our *hourly* measure of price volatility $(PV_{FR,h})$ allows us to easily disentangle the intra-day impacts of imports from Germany and other control variables on the French price volatility with respect to different demand levels. This is an asset over other related literatures. In line with other empirical studies, we filter values that exceed three times the standard deviation of the French spot price series $\left(P_{FR,h}\right)$ in order to exclude outliers (Ketterer, 2014 and Wozabal et al., 2016).[14]

The aim of this study is to show the impact of French *imports* from Germany, which are mainly driven by German wind and solar electricity, on the French spot price volatility $\left(PV_{FR,h}\right)$. We obtained imports from Germany to France, $Imp_{DE\rightarrow FR,h}$, from the allocated capacities from Germany to France, $AC_{DE\rightarrow FR,h}$, which correspond to traded electricity flows on the day-ahead spot market ($Imp_{DE\rightarrow FR,h} = AC_{DE\rightarrow FR,h}$). The maximum value of $AC_{DE\rightarrow FR,h}$ in a certain hour is constrained by the available transfer capacity ($ATC_{DE\rightarrow FR,h}$) from Germany to France for that hour (see also Gugler and Haxhimusa, 2016). For hours with traded flows from France to Germany, our measure for imports takes the value of zero.[15]

As explained in Section 4, we expect different impacts of electricity imports on the French spot price volatility depending on the French demand. For high and medium demand levels, we expect that an increase in imports from Germany would put a downward pressure on the French spot prices, and consequently spot prices converge towards the daily average price. Hence, this would cause a decrease in the French spot price volatility. The opposite effect is expected for low French electricity demand. In order to get these different effects, we split demand into bins of equal widths, which we call demand categories (see Davis and Hausman, 2016). Therefore, we construct three different demand categories of low, medium and high demand. From Table 2, it can be seen that the minimum and maximum French demand $\left(D_{FR,h}\right)$ are around 30 and 100 GWh, respectively, and the mean is about 55 GWh. Following this, we define the bin width as 20 GWh and construct three dummy variables. (1) A dummy for low demand ($D^{L}_{FR,h}$) between 30 and 50 GWh; (2) a dummy for medium demand ($D^{M}_{FR,h}$) for values between 50 and 70 GWh; (3) a dummy for high demand ($D^{H}_{FR,h}$) for all values above 70 GWh.[16] Next, we interact imports ($Imp_{DE\rightarrow FR,h}$) with $D^{M}_{FR,h}$ and $D^{H}_{FR,h}$, while $D^{L}_{FR,h}$ is our reference category in the regression analysis. This allows us to get different coefficient estimates on the impact of electricity imports on price volatility depending on the demand categories ($D^{M}_{FR,h}$ and $D^{H}_{FR,h}$) compared with our reference category ($D^{L}_{FR,h}$).

Besides, we introduce other control variables like nuclear and wind generation in France. Nuclear generation in France, $N_{FR,h}$, is introduced to control for high amounts of French

[14] The results remained stable after we leave outliers in the sample.
[15] In around 63% of hours, France has imported electricity from Germany between 25.01.2011 and 31.12.2014.
[16] In only 136 hours, demand is larger than 90 GWh. Once we drop these outliers, our results remain robust.

nuclear generation with very low marginal costs. It is intuitive that nuclear generation puts a downward pressure on the French spot price. Nevertheless, like imports, we expect that the effect of nuclear generation on the French spot price volatility may differ depending on the demand category, for which reason we interact nuclear generation with our demand categories (see equation (2) in section 6). In order to control for increasing wind generation capacities in France, we introduce day-ahead forecasts for wind electricity generation ($W_{FR,h}$), which we also interact with our demand cathegories, following the same reasoning.

5.3. *Identification*

Given the potential reverse causality between electricity imports and spot price volatility, endogeneity is an issue. We thus employ an instrumental variable technique to circumvent this problem. In this case, we utilize variables that only determine the endogenous variable (i.e. imports), but have no impact on the dependent variable (i.e. price volatility) other than through the endogenous variable. We use the following exogenous instruments:

a) Day-ahead forecasts for German wind ($W_{DE,h}$) and solar ($S_{DE,h}$) electricity generation. Day-ahead forecasts for both wind and solar generation together with electricity generation from other technologies are used in the EPEX day-ahead market to determine electricity spot prices.[17] We emphasize that the exogenous drivers of imports from Germany to France are the abundant (forecasted) solar and wind electricity in Germany, as already discussed in Section 3 (see also Figures 3 and 4). Regarding the fact that both German wind and solar electricity decrease German spot prices due to the well-known merit-order effect (Hirth, 2016; Jensen and Skytte, 2002; Sensfuß et al., 2008; Würzburg et al., 2013), the amount of electricity that is necessary to be traded to achieve full price convergence between Germany and France increases as well.[18]

b) Dummy for holidays in Germany $\left(Hol_{DE,h}\right)$. The binary indicator takes up the values of one for national holidays in Germany and zero otherwise. The intuition is that a national holiday represents a negative schock on the domestic demand leading to a decline of domestic spot prices. As a result, if German spot price drops below the French spot price, French imports from Germany increases. However, in order to get a better measure of the effects of holidays in

[17] According to the so-called "Ausgleichsmechanismusverordnung" (balancing mechanism decree), all German TSOs are responsible to make forecast about electricity generation from renewables one day before delivery and sell the forecasted electricity on the day-ahead markets (Ketterer, 2014). The TSOs publish these data on their official homepages. Moreover, they also publish data on actual wind and solar electricity generation.

[18] However, the required amount of electricity to achieve full price convergence cannot always be traded as French imports are subject to interconnection capacity limitations.

Germany on the French imports, we recode all holidays to zero whenever there is a national holiday in France at the same day.

c) Dummy for holidays in France $\left(Hol_{FR,h}\right)$. Like the dummy for holidays in Germany, we replace all holidays with zero, which are paralleled by a national holiday in Germany. Our adjusted dummy for holidays in France, thus, represents a negative demand schock in the French electricity market leading to a decline in the French spot price. As a result, French imports from Germany are expected to decrease.

Table 1 defines our variables and shows the data sources. Table 2 presents descriptive statistics. Imports from Germany, $Imp_{DE\rightarrow FR,h}$, take values between 0 and 3.5 GWh. In the year 2011, France has imported from Germany in around 41% of the hours. This may be a result of the German government to phase-out 6.3 GW of nuclear generation capacity with relatively low marginal costs after the Fukushima nuclear incident in March 2011. This caused a price increase in Germany (Grossi et al., 2015). From 2012 to 2014 France has imported from Germany in about 70% of the hours. In addition, from Table 2 we can see that French demand falls in the low demand category in 39% of the hours and it falls in the middle and high demand category in 48% and 13% of the hours, respectively.

Table 1. Variables definitions and sources

Variable	*Description*	*Source*
Dependent		
$PV_{FR,h}$	Price volatility measure: absolute value of the deviation of actual hourly price from the daily mean, in $€/MWh$	*EPEX*
Explanatory		
$Imp_{DE\rightarrow FR,h}$	Imports from Germany to France, which we obtained from allocated capacities from Germany to France ($Imp_{DE\rightarrow FR,h} = AC_{DE\rightarrow FR,h}$), in GWh.	*CASC*
$N_{FR,h}$	Nuclear generation in France, in GWh	*RTE*
$W_{FR,h}$	Day-ahead forecasts for wind generation in France, in GWh	*RTE*
$D_{FR,h}$	Aggregate demand in France, in GWh	*ENTSO-E*
Instruments		
$W_{DE,h}$	Day-ahead forecasts for wind generation in Germany, in GWh	*German TSOs*[a)]
$S_{DE,h}$	Day-ahead forecasts for solar electricity generation in Germany, in GWh	*German TSOs*
$Hol_{DE,h}$	Dummy for holidays only in Germany (but not in France)	*Feiertags-kalender*
$Hol_{FR,h}$	Dummy for holidays only in France (but not in Germany)	*Feiertags-kalender*

[b)] APG (Austrian Power Grid), TransnetBW, Tennet, 50hertz, and Amprion.

Table 2. Descriptive statistics

Variable	Observations	Mean	Std. Dev.	Min	Max
$P_{FR,h}$	34,394	42.91	17.16	-29.00	116.70
Dependent					
$PV_{FR,h}$	34,394	8.52	7.02	0.00	54.02
Explanatory					
$Imp_{DE\to FR,h}$	34,488	1.08	1.09	0.00	3.50
$N_{FR,h}$	34,488	46.58	6.46	14.25	61.04
$W_{FR,h}$	34,488	1.62	1.10	0.10	7.37
$D_{FR,h}$	34,488	54.64	12.15	29.70	102.10
$D^{L}_{FR,h}$	34,488	0.39	0.49	0.00	1.00
$D^{M}_{FR,h}$	34,488	0.48	0.50	0.00	1.00
$D^{H}_{FR,h}$	34,488	0.13	0.33	0.00	1.00
Instruments					
$W_{DE,h}$	34,488	5.87	4.81	0.32	29.30
$S_{DE,h}$	34,488	3.15	4.92	0.00	24.50
$Hol_{DE,h}$	34,488	0.02	0.14	0.00	1.00
$Hol_{FR,h}$	34,488	0.01	0.09	0.00	1.00

Note: The data relating to imports, nuclear, wind, solar and demand are in GWh. $P_{FR,h}$ and $PV_{FR,h}$ are in $€/MWh$. Our demand categories and national holidays in Germany and France are dummies.

6. Empirical model

The aim of this study is to estimate the impact of importing German wind and solar electricity, $Imp_{DE\to FR,h}$, on the French spot price volatility, $PV_{FR,h}$. In the previous section, we have acknowledged the endogeneity problem in identifying this relationship due to potential reverse causality between imports and spot prices. However, the causal link of German wind and solar electricity generation to the French spot price volatility goes through imports. Therefore, we employ an intrumental variable (IV) approach and use German wind and solar generation and national holidays in Germany and France as exogenous instruments. The first stage regression equation is:

$$Imp_{DE\to FR,h} = \beta_0 W_{DE,h} + \beta_1 S_{DE,h} + \beta_2 Hol_{DE,h} + \beta_3 Hol_{FR,h} + X_h\varphi_5 + D'_h\delta_6 + \varepsilon_{h1} \quad (1)$$

French imports, $Imp_{DE\to FR,h}$, are a function of a constant, α_1, day-ahead forecasts for wind electricity in Germany ($W_{DE,h}$), day-ahead forecasts for solar electricity in Germany ($S_{DE,h}$), a dummy for holidays in Germany ($Hol_{DE,h}$), a dummy for holidays in France ($Hol_{FR,h}$), and a vector of control variables (X_h) (nuclear and wind generation in France) that are involved in the second stage, as well as hourly, day of week, monthly and yearly fixed effects (D) and the error term (ε_{h1}).

The second-stage equation is:

$$\begin{aligned} PV_{FR,h} = {} & \gamma_1 PV_{FR,h-1} + \gamma_2 \widehat{Imp}_{DE\rightarrow FR,h} + \gamma_3 D^{M}_{FR,h} + \gamma_4 D^{H}_{FR,h} + \gamma_5 \widehat{Imp}_{DE\rightarrow FR,h} \\ & \times D^{M}_{FR,h} + \gamma_6 \widehat{Imp}_{DE\rightarrow FR,h} \times D^{H}_{FR,h} + \gamma_7 N_{FR,h} + \gamma_8 N_{FR,h} \times D^{M}_{FR,h} \\ & + \gamma_9 N_{FR,h} \times D^{H}_{FR,h} + \gamma_{10} W_{FR,h} + \gamma_{11} W_{FR,h} \times D^{M}_{FR,h} + \gamma_{12} W_{FR,h} \\ & \times D^{H}_{FR,h} + D_h' \delta_2 + \varepsilon_{h2} \end{aligned} \tag{2}$$

We introduce the one hour lagged dependent variable to control for potential intraday demand and supply rigidities, which may come from the lack of flexibility of conventional power plants (i.e. nuclear and coal) in adjusting their generation level from hour-to-hour over the day, e.g. due to fixed start-up and ramping costs.

The French spot price volatility, $PV_{FR,h}$, is a function of lagged dependent variable ($PV_{FR,h-1}$), instrumented imports ($\widehat{Imp}_{DE\rightarrow FR,h}$), dummies for middle and high demand category ($D^{M}_{FR,h}$ and $D^{H}_{FR,h}$), interaction of dummies for middle and high demand category with instrumented imports ($\widehat{Imp}_{DE\rightarrow FR,h} \times D^{M}_{FR,h}$ and $\widehat{Imp}_{DE\rightarrow FR,h} \times D^{H}_{FR,h}$), nuclear electricity, interaction of dummies for middle and high demand category with nuclear electricity ($N_{FR,h} \times D^{M}_{FR,h}$ and $N_{FR,h} \times D^{H}_{FR,h}$), wind electricity, interaction of dummies for middle and high demand category with wind electricity ($W_{FR,h} \times D^{M}_{FR,h}$ and $W_{FR,h} \times D^{H}_{FR,h}$), respectively, as well as hourly, day of week, monthly and yearly fixed effects (D) and the error term (ε_{h2}).

7. Results

In this section, we discuss our main empirical findings. We interpret both first- and second-stage results regarding the causal link of German wind and solar electricity generation through imports to the French spot price volatility. Moreover, we report OLS estimates to show that IV comes to different findings suggesting that endogeneity is an issue.

Tables 3 and 4 shows the estimation results of the first- and second-stage regression, respectively. We report in both tables robust standard errors to heteroscedasticity and autocorrelation. As presented in Table 4, the Durbin-Wu-Hausman test rejects the null hypothesis that imports ($Imp_{DE\rightarrow FR,h}$) and price volatility ($PV_{FR,h}$) are exogenous variables and, thus, justifies our identification strategy of using IV. The first-stage results (Table 3) show that our instruments ($W_{DE,h}$, $S_{DE,h}$, $Hol_{DE,h}$ and $Hol_{FR,h}$) have a significant impact on our endogenous variable ($Imp_{DE\rightarrow FR,h}$). In addition, the Hansen J test (see Table 4) does not reject the null hypothesis that our instruments are valid (i.e. uncorrelated with the error term).

We first discuss our first stage estimation results, bacause the causal effect of French imports ($Imp_{DE\rightarrow FR,h}$) on the French spot price volatility ($PV_{FR,h}$) is mainly driven by German wind and solar electricity and demand schocks originating from holidays in Germany and France. As expected, Table 3 shows that day-ahead forecasts for wind and solar electricity in Germany have a positive and significant impact on French imports from Germany ($Imp_{DE\rightarrow FR,h}$), because of their downward pressure on the German spot price (merit order effect). France in turn benefits by importing cheap wind and solar electricity from Germany[19] in terms of lower spot prices. In this regard, we find that the impact of German solar electricity was higher than the the impact of German wind electricity on French imports from Germany. The larger effect of solar electricity generation can be explained by the fact that both German solar electricity generation and French demand peak at noon associated with high electricity spot prices in France (Paschen, 2016). Figure 3 also shows that German solar electricity generation and French imports have higher correlation patterns during daylight hours. As expected, our dummies for holidays in Germany and France have significant positive and negative impacts on French imports from Germany, respectively.

Table 3. First-Stage Results

Dep. Var.: $Imp_{DE\rightarrow FR,h}$		
$W_{DE,h}$	0.0149	***
	(0.0011)	
$S_{DE,h}$	0.0788	***
	(0.0018)	
$Hol_{DE,h}$	0.2641	***
	(0.0400)	
$Hol_{FR,h}$	-0.1682	***
	(0.0413)	
$Hourly\ FE$	Yes	
$Day\ of\ week\ FE$	Yes	
$Monthly\ FE$	Yes	
$Yearly\ FE$	Yes	
$Observations$	34,393	
$R-squared$	0.464	

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

[19] This only holds if French spot prices are higher than German spot prices.

As expected, our regression results from the second stage (Table 4, column (2))confirm that there are two opposing effects of imports from Germany on the French spot price volatility, as their impact depends on the level of electricity demand. We also find two opposing effects for both French wind and nuclear electricity. The significant and positive impact of the lagged dependent variable is evidence that there exist some volatility originating in intraday supply and demand rigidities for reasons we elaborate in Section 4.

The positive and significant coefficient of $Imp_{DE \to FR,h}$ show that French imports from Germany have a positive impact on the French spot price volatility for demand levels between $30\ GWh$ and $50\ GWh$. This shows that for low French demand levels and thus low spot prices (below the daily mean), importing additional electricity from Germany further reduces French spot prices and, as a result, increase the volatility of French spot prices. On the other hand, the coefficients of the interactions of imports with dummies for middle and high demand categories ($\widehat{Imp}_{DE \to FR,h} \times D^{M}_{FR,h}$ and $\widehat{Imp}_{DE \to FR,h} \times D^{H}_{FR,h}$) are negative and significant showing the negative impact of French imports from Germany on the French spot price volatility for both middle[20] and high demand category. Hence, for middle and high French demand associated with high spot prices (above the daily mean), additional electricity imports from Germany put downward pressure on French spot prices toward the daily mean and, thus, reduce the volatility of French spot prices. Our data show that France has imported electricity from Germany in around 62.3% of the hours from 25.01.2011 to 31.12.2014. In this regard, the volatility of French spot prices has decreased in around 47.2% of the hours, since France imported from Germany during hours with middle and high demand in 35.6% and 11.6% of the hours, respectively. Whereas imported wind and solar electricity during hours with low French demand has increased the volatility of French spot prices in around 15.1% of the hours.

[20] The coefficient equals the sum of $Imp_{DE \to FR}$ and $Imp_{DE \to FR} \times M\_D_{FR,h}$, namely $2.1006 + (-4.0900) = -1.9894$, while the intercept is the sum of coefficients for $D^{M}_{FR,h}$ and $Constant$ (see Geyer, 2013; Griffiths et al., 1993). The same applies for demand categories between 70 GWh and 90 GWh: $2.1006 + (-5.7235) = -3.6229$.

Table 4. OLS and IV Results

Dep. Var.: $PV_{FR,h}$	(1) OLS		(2) IV	
$PV_{FR,h-1}$	0.6065	***	0.6037	***
	(0.0072)		(0.0075)	
$\widehat{Imp}_{DE\to FR,h}$	0.1605	***	2.1006	*
	(0.0417)		(1.2736)	
$\widehat{Imp}_{DE\to FR,h} \times D^{M}_{FR,h}$	-0.2587	***	-4.0900	*
	(0.0508)		(2.1550)	
$\widehat{Imp}_{DE\to FR,h} \times D^{H}_{FR,h}$	-0.9685	***	-5.7235	***
	(0.0994)		(1.2249)	
$D^{M}_{FR,h}$	4.2317	***	10.9911	***
	(0.5770)		(3.9828)	
$D^{H}_{FR,h}$	18.0619	***	34.3229	***
	(2.4095)		(6.6197)	
$N_{FR,h}$	0.0691	***	0.2011	***
	(0.0118)		(0.0645)	
$N_{FR,h} \times D^{M}_{FR,h}$	-0.0839	***	-0.1531	***
	(0.0131)		(0.0493)	
$N_{FR,h} \times D^{H}_{FR,h}$	-0.2900	***	-0.4700	***
	(0.0415)		(0.0797)	
$W_{FR,h}$	0.1354	***	0.0907	
	(0.0484)		(0.0595)	
$W_{FR,h} \times D^{M}_{FR,h}$	-0.1465	***	-0.2239	***
	(0.0547)		(0.0831)	
$W_{FR,h} \times D^{H}_{FR,h}$	-0.3456	***	-0.6621	***
	(0.0819)		(0.1915)	
$Hourly\ FE$	Yes		Yes	
$Day\ of\ week\ FE$	Yes		Yes	
$Monthly\ FE$	Yes		Yes	
$Yearly\ FE$	Yes		Yes	
$Hansen\ J\ stat. (p-val.)$	-		0.1998	
$Wu-Hausman\ Test\ (p-val.)$	-		0.0000	
$Observations$	34,359		34,359	
$R-squared$	0.598		-	

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Next, we obtain the effects of German wind and solar electricity on the French spot price volatility through imports depending on the French demand level. In the first stage, we find that when both day-ahead forecast for German wind ($W_{DE,h}$) and solar ($S_{DE,h}$) electricity increase by 1 GWh, French imports from Germany ($Imp_{DE\to FR,h}$) increase by 0.0149 and 0.0788 GWh, respectively. In the second stage, we differentiate the effects of imports from Germany, which are driven by German wind and solar electricity, depending on the French demand category. Hence, for the middle French demand category, a day-ahead forecast of one additional GWh of wind or solar electricity in Germany reduces the volatility of French spot prices by 0.03 or 0.16 $€/MWh$,[21] respectively. Moreover, for the high French demand category, a day-ahead forecast of one additional GWh of wind or solar electricity in Germany decreases the volatility of French spot prices by 0.05 or 0.29 $€/MWh$, respectively. The supply curve is steeper during high demand, thus leading to a higher impact of imports on spot price volatility. On the other hand, for a low demand level, a day-ahead forecast of one additional GWh of wind or solar electricity in Germany increases the volatility of French spot prices by 0.03 or 0.17 $€/MWh$, respectively.

Besides, the impact of nuclear electricity on the French spot price volatility is strongly dependent on the demand category as can be seen from the baseline term of $N_{FR,h}$, and the respective coefficients of the interaction terms of $N_{FR,h}$ with middle and high demand categories ($N_{FR,h} \times D^M_{FR,h}$ and $N_{FR,h} \times D^H_{FR,h}$). The same also holds for the French day-ahead wind forecast.

To conclude, we empirically find that German wind and solar electricity increase French imports from Germany. In addition, we find that French imports from Germany, which are mainly driven by German abundant wind and solar electricity generation, either significantly increase or decrease French spot price volatility depending on the French demand category and the shape of the French supply curve. This showes that the effects of nationally driven energy policies (i.e. German "Energiewende") transpose across the border and have ambiguous external effects on neighbouring markets. Hence, this finding is particularly important with respect to policies that promote investment in wind and solar generation capacities and integration of European electricity markets. Overall, this calls for a better coordination of internal policies *between* the EU Member States.

5.4. Robustness

Next, we slightly modify our second stage specification. We start by droping all dummies for demand categories and their interactions and then introduce French demand ($D_{FR,h}$) and its interaction with French imports from Germany, $\widehat{Imp}_{DE\rightarrow FR,h} \times D_{FR,h}$ (see equation (3)). Moreover, we allow for a nonlinear relationship between French demand and French spot price volatility by introducing the squared term of French demand (${D_{FR,h}}^2$). We additionally interact

[21] In order to obtain the effect of 1 GWh additional wind electricity in Germany on the French spot price volatility for demand level between 50 GWh and 70 GWh, we multiply the coefficient for wind in Germany ($W_{DE,h}$) obtained in the first stage and the coefficients of imports for the corresponding demand level obtained on the second stage and, hence, we get: $0.0149 \times (2.1006 + (-4.0900)) = -0.02964\, MWh$ (see Angrist and Pischke, 2009).

both French nuclear ($N_{FR,h}$) and wind electricity generation ($W_{FR,h}$) with French demand. While the first stage regression equation is the same as equation (1), the second stage equation is:

$$\begin{aligned} PV_{FR,h} = \; & \theta_1 PV_{FR,h-1} + \theta_2 \widehat{Imp}_{DE\to FR,h} + \theta_3 L_{FR,h} + \theta_4 \widehat{Imp}_{DE\to FR,h} \times L_{FR,h} \\ & + \theta_5 L_{FR,h}^2 + \theta_6 N_{FR,h} + \theta_7 N_{FR,h} \times L_{FR,h} + \theta_8 W_{FR,h} + \theta_9 W_{FR,h} \times L_{FR,h} \\ & + D_h' \delta_3 + \varepsilon_{h3} \end{aligned} \quad (3)$$

This allows us to estimate the effects of imports from Germany, nuclear, and wind electricity generation in France on French spot price volatility depending on the level of French demand. For example, the parameter θ_4 shows the effect of French imports from Germany on the volatility of French spot prices depending on the French electricity demand.

In Table 5, we report both OLS and IV estimation results.[22] The lagged dependent variable is positive and significant and the magnitude of the coefficient is almost the same to IV estimation of equation (2) (see Table 4, column (2)). As discussed in section 4, our results show that there exist two opposing effects of imports on spot price volatility depending on the level of demand. The coefficient of $\widehat{Imp}_{DE\to FR,h}$ show that French imports from Germany increase French spot price volatility, while the coefficient of $\widehat{Imp}_{DE\to FR,h} \times D_{FR,h}$ indicates that the effect of imports are heavily dependent on the level of demand. As a result, the negative coefficients show that when demand increases, additional imports from Germany decrease French spot price volatility.

[22] As a further robustness check, we take out year, month and day of week fixed effects from equation (3). In another specification, we estimate equation (3) without the interaction of both french nuclear ($N_{FR,h}$) and wind electricity generation ($W_{FR,h}$) with french demand ($D_{FR,h}$). The results remains robust and are available upon request.

Table 5. Robustness check, OLS and IV[23] results

Dep. Var.: $PV_{FR,h}$	(1) OLS		(2) IV	
$PV_{FR,h-1}$	0.5934	***	0.5900	***
	(0.0072)		(0.0075)	
$\widehat{Imp}_{DE\rightarrow FR,h}$	1.6558	***	8.9605	***
	(0.1627)		(1.6408)	
$\widehat{Imp}_{DE\rightarrow FR,h} \times D_{FR,h}$	-0.0324	***	-0.1732	***
	(0.0029)		(0.0292)	
$D_{FR,h}$	-0.0332		-0.2995	***
	(0.0277)		(0.0785)	
${D_{FR,h}}^2$	0.0071	***	0.0150	***
	(0.0005)		(0.0019)	
$N_{FR,h}$	0.7632	***	1.2422	***
	(0.0555)		(0.1338)	
$N_{FR,h} \times D_{FR,h}$	-0.0142	***	-0.0226	***
	(0.0010)		(0.0022)	
$W_{FR,h}$	0.5112	***	1.0687	***
	(0.1408)		(0.2159)	
$W_{FR,h} \times D_{FR,h}$	-0.0087	***	-0.0205	***
	(0.0024)		(0.0038)	
$Hourly\ FE$	Yes		Yes	
$Day\ of\ week\ FE$	Yes		Yes	
$Monthly\ FE$	Yes		Yes	
$Yearly\ FE$	Yes		Yes	
$Hansen\ J\ stat. (p-val.)$	-		0.4507	
$Wu-Hausman\ Test\ (p-val.)$	-		0.0000	
$Observations$	34,359		34,359	
$R-squared$	0.603		-	

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Figure 6 shows how the predicted spot price volatility is affected by the average amount of imports. It can be seen that for very low import levels both low and high demand lead to relatively high volatility of spot prices. However, the volatility of spot prices decreases (increases) in situations with simultaneous occurrence of high (low) demand and very high imports. This is because low demand intersects the supply curve in its steep part and additional imports pushes (residual) demand deeper into the steep area of the inverse S-shaped supply curve (see Figure 5) (Wozabal et al., 2016). On the other hand, the co-occurrence of a high demand and high imports pushes the (residual) demand toward the flat area of the inverse S-shaped supply curve, and as a results the volatility of spot prices decreases.

[23] The results of the first stage are similar to those presented on Table 3, except for the coefficient of $Hol_{FR,h}$, which is insignificant.

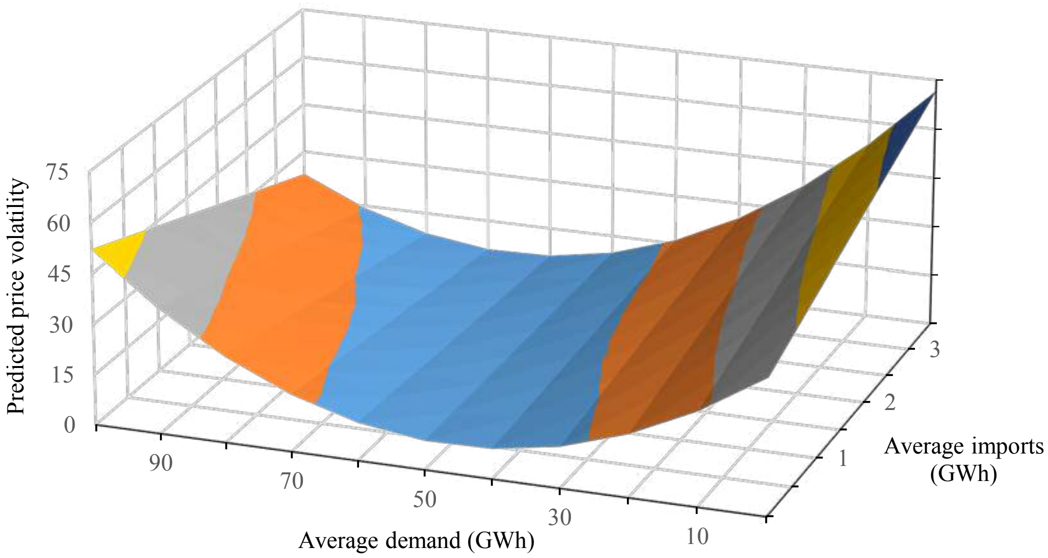

Figure 6. Predicted spot price volatility for different demand and import levels [24]

In additon, the estimated marginal effects of demand and imports on the volatility of spot prices are depicted on Figure 7. The results show that electricity imports from Germany increase French spot price volatility for demand levels above 52 GWh, while for demand levels below 52 GWh, it reduces French spot price volatility. This effect becomes larger for higher imports levels.

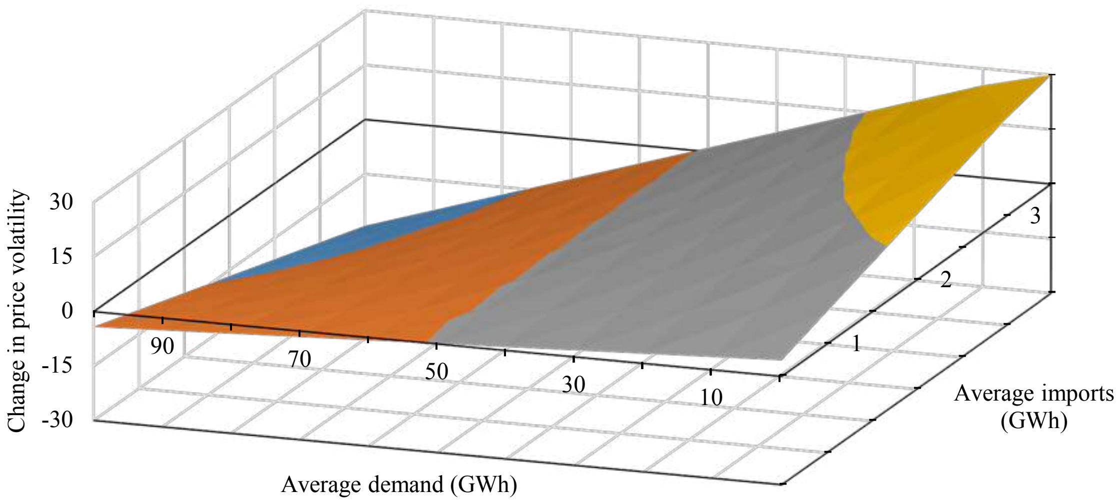

Figure 7. Marginal effects of demand and imports on the volatility of spot prices [25]

[24] All other regressors are set to zero.
[25] All other regressors are set to zero.

8. Conclusions

In this article, we empirically investigate the effects of electricity imports from Germany to France (largely driven by wind and solar generation in Germany) on the French spot price volatility. An essential part of the paper is that we circumvent the endogeneity problem by instrumenting imports with truly exogenous variables.

Overall, we find that German wind and solar electricity increase French imports from Germany, which at some time decrease and at other times increase the volatility of French spot price depending on the French demand for electricity and the shape of the French supply curve. Besides, we find that German solar electricity tend to have a stronger effect on the French spot price volatility do to stronger effect on imports, compared to German wind electricity. This result highlights strong externalities of national policies regarding intermittent renewable capacity building, whereas effects are particularly pronounced with solar electricity.

Our results support the hypothesis that in times of high or medium French demand, importing additional cheap wind and solar electricity from Germany decreases the volatility of French spot prices. We find that the volatility of French spot prices decreases in around 47.2% of the hours, because France imports from Germany during times of middle and high demand. On the other hand, French spot price volatility increased in around 15.06% of hours by importing additional wind and solar electricity during hours with low French demand. Overall, French imports from Germany tend to have a dampening effect on the volatility of French spot prices. Moreover, in line with previous empirical research findings (e.g. Wozabal et al., 2016), we find that French nuclear and wind electricity generation either increase or decrease the volatility of French spot prices.

We show that unilateral energy policies are crossing the borders and have a significant impact on neighbouring electricity markets. This topic is hardly discussed in the academic literature on the promotion of an integrated European electricity market, with energy policies largely relying on national governments with unilateral decisions. In this regard, unilateral German energy policies to promote investment in wind and solar generation capacities have partly positive, partly negative effects (through French imports) on the volatility of French spot prices. According to Muche (2009), Conolly et al. (2011) and Gugler et al. (2016b) incentives to invest in storage capacities (i.e. pump storages and batteries) and base load technologies (i.e. hydro run of river, nuclear and coal power plants) are strongly dependent on the volatility of spot prices. Therefore, these spillover effects of energy policies driven by national governments (such as the promotion of renewables, the introduction of capacity markets, etc.) in an increasingly integrated European electricity market call for further coordination of national energy policies in order to internalize (positive and/or negative) external effects on other markets in a more and more integrated electricity market.

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