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INTERMITTENCY AND UNCERTAINTY IN WIND AND SOLAR ENERGY GENERATION: AN ECONOMETRIC APPROACH TO THEIR IMPACT ON THE FRENCH INTRADAY MARKET PRICE

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Intermittency and uncertainty in wind and solar energy generation: An econometric approach to their impact on the French intraday market price

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Abstract

Renewable energy sources (RES) play an important role in the effort to decarbonize the energy system. Despite discussions of their zero marginal cost in reducing electricity prices, there is a gap in understanding the uncertainty associated with forecast errors in renewable energy generation in the intra-day market. Using a fixed-effect regression, this study explores how uncertainties in wind and solar generation affect prices in France from 2015 to 2018. It also examines variations in residual demand and corresponding price changes. The results show that wind uncertainty and solar intermittency have a greater impact on prices than their generation forecasts. The study reveals that the electricity price stability depends on the shape of the merit order curve, the use of interconnections and the conventional generation.

Keywords: Wholesale electricity market - Electricity price volatility – RES Uncertainty/ Intermittency - Residual electricity demand – Isolated / interconnected markets – Conventional generation.

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I. Introduction

In the fight against climate change, the European Union has adopted two primary objectives. These objectives center on promoting renewable energy sources and implementing an emissions trading scheme del Río González (2007). Member countries have taken various measures to encourage the adoption of renewable energies in order to achieve these goals. These promotional methods are classified into three groups: Feed-in tariffs, feed-in premiums, and green certificates Percebois (2014). Subsidies are provided to these renewable energy sources with the explicit aim of achieving zero emissions. However, the increasing penetration of renewable energies, especially wind, and solar power, is leading to decentralized renewable energy production and posing new challenges for the entire energy system.

In the upcoming years, there is an anticipated growth in the share of renewable energies. For example, in France; the aim is to achieve carbon neutrality by 2050 using 100% RES in the mix (PPE). The increasing integration of renewable into the energy system in the coming years will serve as a pivotal factor in establishing a non-polluting and sustainable electricity supply. A number of studies have demonstrated the positive contribution of these energies .These advantages, which we describe as short-term, show the economic (notably lower energy prices), environmental and collective benefits of these energies[Sakaguchi and Fujii (2021) , Cludius, Hermann, Matthes, and Graichen (2014), Gelabert, Labandeira, and Linares (2011)]. However, the transition towards renewable energy sources(RES) has far-reaching implications for energy security S. Jensen and Skytte (2002), climate change, and the global economy due to their inherent characteristics of intermittency and uncertainty (generation error). These characteristics can have a profound impact on the electricity market price, as changes in renewable generation can disrupt the balance between supply and demand Würzburg, Labandeira, and Linares (2013). Unfortunately, The pros and cons of renewable energy sources (RES) studies do not consider these aspects. Hence, it is crucial to examine the impact of renewable energies uncertainty and intermittency on energy prices in France.

The choice of France for this study is significant because existing literature on the subject highlights the crucial role of the energy mix Sáenz de Miera, del Río González, and Vizcaíno (2008) ;Jónsson, Pinson, and Madsen (2010), and France is one of the countries with a 50% dominance of nuclear energy in its mix, which has high fixed costs as a base load energy source. Furthermore, in France, RES impact are mostly addressed from a legal Darson (2015) or technical standpoint by sciences Haessig (2011), and to a lesser extent, from an economic standpoint González-Aparicio and Zucker (2015).

To delve into the analysis of how uncertainty affects prices in France, the upcoming sections of the paper will follow this structure: Section II will provide a concise overview of the existing research landscape in this field. Subsequently, the initial part of Section 3.2 will outline the chosen methodology and expound on the process of data analysis. Moving forward, the latter portion of the same section, labeled as Section 3.3, will take a deep dive into the models and outcomes derived from our regression analysis. Finally, these findings will lead us to the concluding insights presented in Section IV

II. Literature review

The scientific community is well aware of the climate benefits associated with the use of renewable energies, which have long been regarded as one of the most effective solutions for reducing dependence on fossil fuels S. Jensen and Skytte (2002). Given their zero marginal cost Hogan (2022), renewable energies benefit from the merit-order effect Zipp (2017), which enables them to compete more effectively in the energy market against conventional energy sources.

The importance of renewable energies in the fight against climate change, particularly in the decarbonization of the power system, has been widely acknowledged. However, the intensification of efforts to increase their use since the 2000s has brought to the fore several challenges Bird, Milligan, and Lew (2013); Elavarasan et al. (2020). This raises questions about the impact of renewable energies on the grid Alam, Al-Ismail, Salem, and Abido (2020); Phuangpornpitak and Tia (2013) ; Shah and Chatterjee (2020); Zahedi (2011) specifically, how their introduction affects the transmission and distribution network, and how their impact on prices can be measured.

The interplay between renewable energy and energy prices is a subject of great interest to researchers, policymakers, and industry stakeholders alike. While the relationship between these two factors is not straightforward, it is clear that they are interconnected in complex ways. Several studies have attempted to model and analyze this relationship, using various quantitative and qualitative methods. Their results, showing the short-term negative effect of renewable energies on price S. Jensen and Skytte (2002), have been the basis for the intensification of policies supporting these so-called decarbonized energies, thus promoting their integration into the power system.

In order to provide insights into the complex interplay between renewable energies and energy prices, we conduct a comprehensive review of existing literature by analysing the short-term effect of renewable energies on prices and the compensation between renewable energy and subsidies. Additionally, we examine the impact of renewable energies and conventional power plants. Finally, we delve into the long-term effect of renewable energies on energy prices over time. By synthesizing the findings of these studies, we aim to provide a better understanding of the relationship between renewable energies and energy prices, which can inform policy decisions regarding the integration of renewable energies into the power system.

2.1. Short-term effect of RES on prices

The existing literature has extensively explored the short-term effect, which pertains to the direct influence of integrating renewable energy sources (RES) on the market structure and its various stakeholders. This effect has been thoroughly examined in most developed countries that have embraced RES. Our objective is to provide a comprehensive overview of the progression within this literature.

In their research concerning the impact of renewable energies on pricing, Würzburg et al. (2013) estimate that the price effect of adding an extra 1 GWh of wind power can range from $4to13$ per MWh in Germany and Austria. Cludius et al. (2014) explores merit order effects in Germany, while Clò, Cataldi, and Zoppoli (2015) delve into these effects in Italy. Similarly, Sakaguchi and Fujii (2021) investigate the merit-order impacts of wind and solar in Japan using data spanning from 2016 to 2020. They find that wind power exhibits a substantial price effect during peak load hours, utilizing quantile regression binning to analyze price variations.

Furthermore, Jónsson et al. (2010) investigated the influence of day-ahead wind power forecasts on the Nord Pool's Elspot market's dispersion of the West Denmark energy price using a non-parametric regression between January 4, 2006, and October 31, 2007. The findings supported prior research, indicating the negative coloration between wind power and the energy price in the market. They discovered that wind power generation initially lowers the energy price, starting at a production level of 4%, which can reach zero when wind power generation reaches 40%. However, the authors of the study emphasized day-ahead forecasts, which often do not reflect the reality of the market, as these forecasts are updated up to an hour before daily consumption. Considering this detail, Gelabert et al. (2011) conducted an ex-post empirical analysis of the impact of wind and cogeneration on hourly wholesale electricity prices in Spain between 2005 and 2010. They used ordinary least squares in a multiple regression model to estimate that, in the absence of market power and ceteris paribus, the introduction of one GWh of renewable energy reduces the price of one MWh by approximately € (1.69 - 2), corresponding to a price decrease of 3.7%. However, their results failed to dissociate the impact of the high variable cost of cogeneration on the market price, potentially biasing the estimated amount of price reduction resulting from the impact of wind power. Therefore, in our study, we will estimate the impact of solar and wind power on energy prices in France, and then separately examine the marginal impact of each energy source on prices to determine which one presents a greater risk for the French system. Furthermore, the study was conducted during a time when the promotion of renewable energy sources in Europe was under scrutiny. Their results did not address whether the estimated annual decrease in price of around €474.7 million resulting from the introduction of renewable energy (short-term effect) would be equivalent to their subsidies.

2.2. RES subsidies and prices

Beyond the short-term effects of renewable energy on energy prices, it is important to consider how the gains from lower prices can offset the support mechanisms for renewable energy Nicolini and Tavoni (2017). One way that governments promote the upfront costs of renewable energy adoption is through subsidies. These subsidies are intended to make renewable energy more competitive with traditional fossil fuels and support the transition to a low-carbon economy Ouyang and Lin (2014). In this section, we will examine how this offset may be possible.

Percebois (2014) observed that EU countries use different terminology to refer to their renewable energy support mechanisms, but such mechanisms can generally be classified into three types: Feed-In-Tariff Couture and Gagnon (2010), Feed-In-Premium Xydis and Vlachakis (2019), and green certificates. These three mechanisms arise from the adoption of renewable energy support policy known as RES-E -renewable energy sources electricity- by the European Parliament in 2001. This RES-E policy is often complemented in Europe by a second approach: the Emission Trading System (EU ETS).

These two policies mix has given rise to a number of criticisms. Firstly, the fact that the source of financing is not borne solely by public authorities results in a higher social cost for consumers due to higher retail energy prices, reducing the competitive advantage of energy-intensive industries Bode (2006). In addition, this approach can lead to regulatory adjustments in some countries, such as Germany, resulting in changes to their operational frameworks Directive (2003). Another criticism levelled at the promotion of renewable energies (RES-E) and the optimal allocation of emission allowances (EU-ETS) concerns the substitution effect Böhringer and Rosendahl (2010);S. G. Jensen and Skytte (2003) ; Morthorst (2001). While the promotion of these two systems (RES-E and ETS) is aimed at reducing emissions from energy generation, the allocation market allows other sectors, such as industry and transport, to emit these pollutants through the purchase of permits or emission rights. As a result, overall efficiency is mitigated by the actions of these other sectors.

While the aforementioned studies highlight the negative effects of a joint approach to both renewable energy support policies on retail prices, arguing for an end for this mix Frondel, Ritter, and Schmidt (2008); Hiroux and Saguan (2010), other academic research highlight the possibility of a coexistence of these two policies under certain conditions, pointing technological advances and market dynamics Lehmann and Gawel (2013). In addition, these policies have had a positive impact on wholesale price dynamics [43 ; 44]. These price effects enabled Sáenz de Miera et al. (2008) to examine the trade-off between the subsidies associated with supporting renewable energy and the reduction in electricity prices resulting from the RES introduction particularly wind power, into the Spanish energy landscape over the years 2005 to 2007.

They compare two market scenarios (one with wind power and the other without wind power).The results show that the introduction of wind power resulted in a reduction of wholesale prices ranging from 4.75€ to 12.44€ per MWh, leading to a consumer surplus of 4294 M€. This reduction in price was significant enough to largely offset the estimated support costs of 2150 M€ for renewable energy and generate a net profit of 2146 M€. However, it is important to note that the model used did not account for potential future variations in demand. As demand increases, ceteris paribus, the margin for price reduction will decrease due to an increase in residual demand, which will result in longer operating hours for technologies with high variable costs. At a given level of demand, the price reduction may not be sufficient to offset the support costs, especially if wind power penetration decreases due to uncontrollable exogenous factors like weather and temperature. Furthermore, the model did not consider the lifespan of the underlying technology, and restrictions on the construction of new power plants can hinder these results.

As the share of renewable energies in the energy mix increases, their production can be affected by uncertainty/intermittence. Conventional power plants may undergo several changes in their operation. These could have a different impact on the market, conventional operating hours and revenues. These transformations can have significant economic and technical implications for conventional power plants (see section 2.4). They also have an impact on overall grid stability and reliability [Ameur, Berrada, Loudiyi, and Aggour (2019) ; Lin and Li (2015) ; Merzougui (2014)] and on the capacity market Cany (2017), Nicholson, Rogers, and Porter (2010). Consequently, a thorough understanding of the long-term impact of RES on prices (see section 2.3) is crucial to formulating effective policies and strategies. These initiatives are essential to ensure the long-term sustainability and efficiency of the energy system.

2.3. Long term effect on prices

With the exception of a few studies, all of the aforementioned research explained how RES lead to a decrease in energy prices [Sakaguchi and Fujii (2021); Würzburg et al. (2013)]. However, it should be noted that this price decrease might send a negative message. While the short-term price reduction does not affect renewable energy producers, who are supported by incentive mechanisms, it does affect conventional energy producers by reducing their operating hours and therefore their output Sáenz de Miera et al. (2008). This drop in conventional technologies output, reduces their profitability and makes difficult the recovery of their investment costs Gelabert et al. (2011). As a result, these producers may be incentivized to reduce their investments in order to exert market power and maintain or even increase prices. Furthermore, most studies [Macedo, Marques, and Damette (2022) ; Maniatis and Milonas (2022)] tend to assume renewable generation as a fixed factor and do not consider their characteristics that can cause fluctuations in their generation. This poses new challenges for the energy system, highlighting the need for flexible capacities to mitigate the uncertain variability of renewable production.

Very few studies, to our knowledge, have attempted to address the long-term impact of Renewable Energy Sources (RES) on energy prices. The first study, Weber and Woerman (in press), demonstrated in the United States that, in reality, renewable energies have a dual effect on market prices. Firstly, in the short term, renewable energies reduce market prices through the "merit-order" effect (approximately \$2). Secondly, they increase price change due to uncertainty caused by forecasting errors in the long term. The relationship between uncertainty and price becomes more evident as uncertainty increases, leading to higher price dispersion. Empirical validation of this hypothesis reveals that an unforeseen decrease of 1 GWh in wind energy correlates with a price reduction of approximately \$5.05 per MWh. Conversely, an unanticipated increase of 1 GWh in wind energy corresponds to a price hike of around \$4.86 per MWh. Both of these figures surpass the \$2 threshold. This escalation in price is primarily attributed to the incurred costs of starting up and shutting down conventional power plants, which act as a backup to mitigate the instability arising from the uncertainty associated with renewable energy generation in the market.

The second study, the most recent by Hosius, Seebaß, Wacker, and Schlüter (2023), analyzes the impact of offshore wind power on energy prices and compares it to onshore wind power between 2015-2018, considering three modalities (daily, intra-daily, and weekly) in three countries: Germany, western Denmark, and Great Britain. They reached the same conclusions as Weber and Woerman (in press) in the sense that wind power forecast errors increase price volatility, but this effect is more significant for onshore wind than offshore wind. These studies [Hosius et al. (2023) ; Weber and Woerman (in press)], also show a positive correlation between electric demand and prices. This can help to examine how demand flexibility can be used to offset the cost of uncertainty associated with RES.

2.4. Impact of RES on Conventional Energy

Whether in the short or long term, the integration of renewable energy sources induces a noticeable shift of the supply curve to the right Hirth (2018). This shift, commonly referred to as the merit order effect Clò et al. (2015), leads to a reduction in the demand that must be met by fossil fuel-based generation, often referred to as residual demand. This phenomenon impacts in several ways conventional generation. Percebois and Pommeret (2016) summarized in two distinct effects the repercussions felt by conventional producers: the volume effect and the price effect.

The volume effect means a perceptible reduction in the quantity of fossil fuel-based production due to the introduction of RES on the market. This may take the form of a reduction in the operating hours of conventional generators, or the substitution of specific high variable-cost technologies by renewable alternatives [Sáenz de Miera et al. (2008) ; Gelabert et al. (2011) ; Hosius et al. (2023)]. Secondly, the price effect means a tangible loss of income caused by falling market prices. RES introduction into the market reduces the wholesale price [Jónsson et al. (2010) ; Nicholson et al. (2010)], resulting in lower profits for fossil fuel producers. This loss of turnover is the consequence of certain high variable-cost technologies being pushed out of the market.

The results of [Gelabert et al. (2011) ; Gianfreda, Parisio, and Pelagatti (2019)] highlight this substitution effect between RES and fossil fuels, especially coal and gas on the Spain and northern Italian electricity market. Specifically, during the years 2006 to 2008, a modest influx of renewable energy sources was associated with a perceptible reduction in fossil fuel-based generation, mainly involving coal and gas. Remarkably, during the years 2013 to 2015, these effects became significantly more pronounced due to an increased penetration of renewable energy generation. Their regression analyses reveal that the price of these fossil fuels tends to fall in parallel with the increase in renewable energy power generation.

III. Methodology and Results

Our research objective is to explore the impact of renewable energy sources, specifically wind and solar power uncertainty, on energy prices in France. Our study builds upon the research conducted by Weber and Woerman (in press), which focused on the influence of wind power uncertainty on prices in Texas between 2012 and 2019. However, we extend their work by incorporating solar energy into our analysis. The reason for the absence of solar energy in their model was simply that solar generation during the studied period was less than 2 GWh per year. To fulfil our objective, we are conducting an econometric analysis using regression with fixed effects on a time series dataset that focuses on the French electricity market from 2015 to 2018. But before delving into the analysis, it is crucial to provide an overview of the design and structure of the French electricity market.

3.1. French electricity market

Like in most European countries, there are different types of energy markets based on competition. We can classify them into two main groups: wholesale and retail markets. The retail electricity market involves the sale of electricity to end consumers. Electricity suppliers, whether traditional like EDF (Electricité de France)[1] or alternative, offer contracts and tariffs to residential, commercial, and industrial customers. Consumers have the option to choose their electricity supplier based on their needs and market conditions. On the other hand, the wholesale electricity market is where producers, suppliers, and brokers negotiate and exchange large quantities of electricity at prices determined by supply and demand. Various types of wholesale markets exist in France, including exchanges, over-the-counter markets, capacity markets , etc. According to RTE , two electricity exchanges operate in the French electricity market: EPEX Spot and Nord Pool Spot . In France, the wholesale electricity market primarily operates through the electricity exchange EPEX SPOT, where short-term transactions (day-ahead and intraday markets) take place and where our price data is collected. In France, control and regulation of these various markets are assigned to an independent commission (CRE)[2] designated by

[1]EDF, as a historical producer, holds the nuclear power plants in France and supplies electricity to a large part of the French territory. In addition to nuclear power, EDF also produces electricity from RES, including wind, solar, and hydropower.

[2]CRE: Commission de Régulation de l'Énergie

the French government.

3.2. Data

For this study, we gathered data from two distinct and reputable sources. Firstly, we obtained essential information from the Eco2mix platform, operated by RTE, the French electricity transmission system operator (TSO), covering the period from 2015 to 2018. This platform offers comprehensive data on electricity demand, renewable energy generation (particularly wind and solar), as well as forecasts of renewable energy and electricity demand. Secondly, we acquired price data from the EPEX SPOT exchange, renowned for its reliability and accuracy in capturing market trends. The data collected from these sources were initially in megawatt-hours (MWh) and segmented into fifteen-minute intervals. However, to align with our analytical objectives and adhere to our reference article, we deemed it necessary to convert these estimates into hourly intervals and adjust the unit of measurement to gigawatt-hours (GWh) for the econometrical regression. This conversion ensured consistency and facilitated comparisons within our study. Furthermore, because of the COVID-19 and high prices observed during this period, we have not included recent data in our analysis to avoid biasing our results.

3.2.1 Wind and Solar generation

Evolution of renewables energies generation

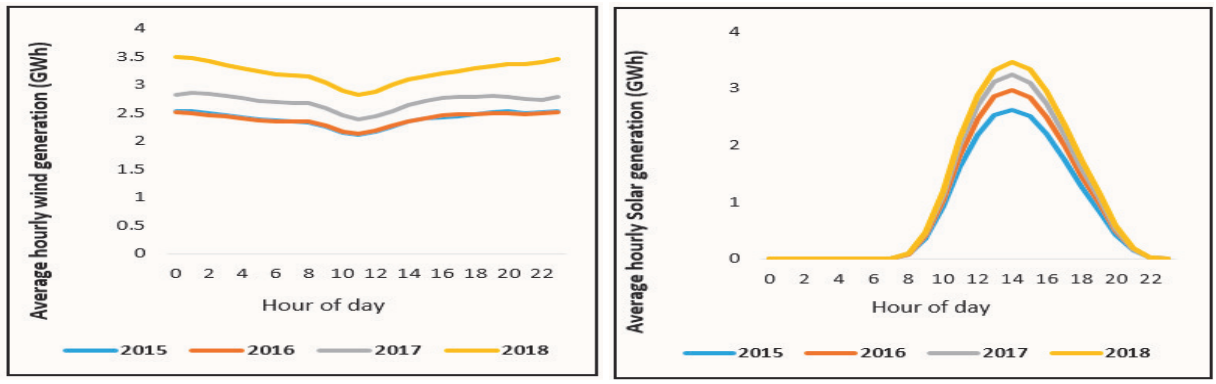
Solar and wind generation are the exogenous variables in our study. We study them in order to determine their variation over the studied period. Figures 1a and 1b depict the annual wind energy and solar power generated in France from 2015 to 2018, respectively. Solar generation experienced significant growth during the studied period, amounting to an increase of 3.1 TWh, with an average annual hourly increase of 1 GWh. Similarly, wind generation demonstrated a substantial increase of 7 TWh over the same timeframe, exhibiting a nearly consistent annual average hourly growth of approximately 2 to 3 GWh. Moreover, within the same period, the installed capacity of solar power expanded by 2.4 GW (from 6.2 GW to 8.6 GW)[3], while wind power witnessed a growth of 3.2 GW (from 10.3 GW to 13.5 GW) . These data emphasize the rapid expansion of wind power generation and show France commitment to RES development[4]

By 2022, we witnessed an impressive transformation of the renewable energies sector. Wind power generation increased by 17.6 TWh, a remarkable growth rate of around 83% in the space of eight years while solar power generation has increased by an even more substantial 151%. These developments are followed by a significant increase in installed capacity. Indeed, by 2022, figures A1 shows that France have 21.2 GW of installed wind capacity and 15.7 GW of installed solar capacity. In particular, installed capacity has seen extraordinary growth rates of around 105% for wind power and an impressive 153% for solar power, compared with 2015.

Future trends in renewable energy generation in France

[3]See Figure A.1 in appendix

[4]France aimed to replace its fossil generation by RES generation through different policies (LTECV ; SNBC). To date, according to EDF, France' fleet is the fourth largest in Europe, trailing behind Germany, Spain, and the United Kingdom.



(a) **Wind generation** (b) **Solar generation**

Figure 1: **Average hourly renewable generation in France by year**

France has set ambitious targets for expanding its renewable energy capacity, with projections pointing towards continued growth in the coming years. This growth is set to be propelled by advancements in wind turbine, solar panel technology and the development of both new wind and solar farm projects. The installation of larger and more efficient wind turbines and solar PV is predicted to increase the output of renewable energy per plant, thereby enabling wind and solar farms to generate more electricity. Additionally, offshore wind energy is poised to play a pivotal role in France's future renewable energy mix. With its extensive coastline, France has ample potential for the development of offshore wind projects, which could provide a significant and reliable source of energy. By reducing its reliance on fossil fuels and achieving its emissions reduction targets, France aims to further its transition towards a greener and more sustainable energy future.

The increasing contribution of wind and solar energies to France's electricity mix is a positive trend, as it helps to reduce the country's dependence on fossil fuels and lower its carbon emissions. This is particularly important in light of the growing global concern over climate change and the need to transition to a more sustainable energy system and more sustainable energy production. Furthermore, the development of renewable energy creates new jobs and supports the economic growth of the country. However, despite the significant growth of wind and solar energies in France, the variability of either wind or solar patterns remains a challenge for the integration of those energies into the electricity market. The unpredictable nature of their patterns can lead to fluctuations in their energy generation, making it difficult for energy producers to plan and manage their operations, and for consumers to budget for their electricity usage. For example, on Thursday, March 14, 2019 at 2:30 p.m., wind generation was the second largest source of generation after nuclear, reaching a record of 12.3 GWh or 18% of electricity consumption (67.6 GWh). The weather condition has shifted the wind to the second source of power generation meaning that an important forecast error can put the whole system at risk. From the grid operator to the consumer, forecasting difficulties will have a significant impact on the market price of energy. Studying the characteristics[5] of renewable energies, particularly wind and solar power, and identifying the factors that can influence their energy generation is of paramount importance.

[5]RES have three characteristics to consider : zero marginal cost, intermittency, and uncertainty.

3.2.2 Renewables energies characteristics

3.2.2.1 Marginal Cost .

The marginal cost of RES refers to the additional cost required to produce one more unit of electricity using a renewable energy source, such as wind or solar power Percebois (2014).The variable cost associated with RES is nearly zero as they harness energy from freely available resources such as wind and solar.. Weber and Woerman (in press). This unique characteristic grants them priority on the spot market, thereby disrupting the proper functioning of the merit order mechanism. For example, in France, RES are often dispatched after hydroelectric power, leading to the displacement of the supply curve within the market Benhmad and Percebois (2013). This phenomenon is often referred to as the "residual demand effect" or as the "switching" of the merit order and reduce market price [Benhmad and Percebois (2013) ;Weber and Woerman (in press)] .

The occurrence of this effect is a consequence of the near-inelastic nature of consumer demand in the renewable energy market. By receiving priority, renewable energies reduce the quantity of demand that needs to be met by conventional technologies, prompting the latter to decrease their supply in order to meet the residual demand . Consequently, the introduction of renewable energy sources results in a rightward shift in the supply curve of other technologies, particularly conventional technologies.

3.2.2.2 RES Intermittency .

In our study, we focus on intermittency which is hourly variation in generation or demand on a given time scale. Another explanatory variable of price change. The temporary variation can be a quarter of an hour (15 minutes), a half hour, an hour, a day, a week, a month, etc., so intermittency can be calculated hourly, daily, weekly, etc. The time scale includes the 'temporary variation'. On a time scale of one month (30 days) for example, we can calculate the hourly intermittency (24h x 30 days = 720 hourly variations). For our study, we have chosen the hourly intermittency for each year, i.e. 8760 hourly variations per year.

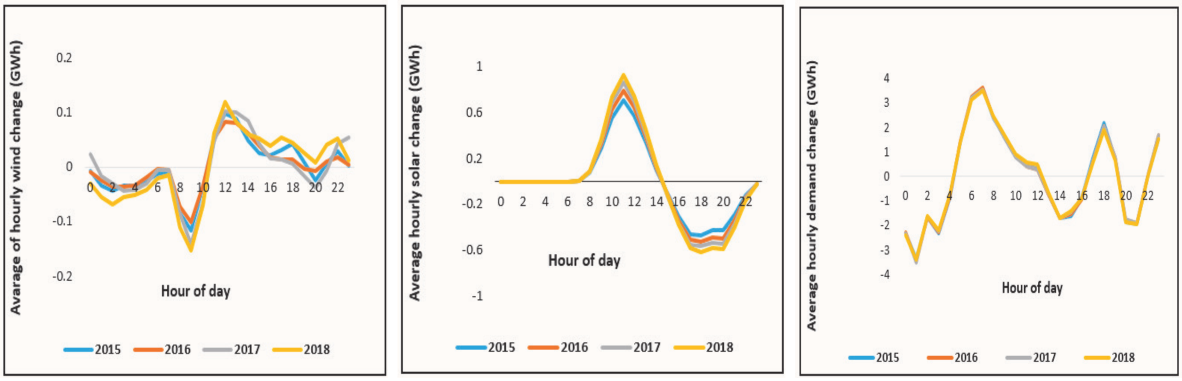
Temporary variation (intermittency), in our case study, refers to the difference between hourly electricity generation / demand at hours h and (h-1) within the same day, as depicted in equations [(1) - (3)]. Equation (1) represents the calculation formula for wind intermittency (WI) at a specific hour (h), which equals the wind generation (WG) on day d at hour h less the wind generation at the previous hour (h-1), while equations (2) and (3) illustrate solar and demand intermittency. These results are shown in figure 2.

$$WI_{d,h} = WG_{d,h} - WG_{d,(h-1)} \tag{1}$$

$$SI_{d,h} = SG_{d,h} - SG_{d,(h-1)} \tag{2}$$

$$DI_{d,h} = D_{d,h} - D_{d,(h-1)} \tag{3}$$

The hourly variations observed in wind and solar generation surpass the percentage variations in demand, indicating a higher level of variability in renewable energy generation. Despite the fact that demand in France consistently remains five to six times higher than the generation from renewable sources, it exhibits minimal variation over the



(a) **Wind Intermittency** (b) **Solar Intermittency** (c) **Demand Intermittency**

Figure 2: **RES and demand intermittency in France over time**

years (figure 3). This can potentially be attributed to predictable consumption patterns facilitated by advanced technologies and energy efficiency measures. However, renewable energy sources demonstrate several factors contributing to their instability.

Firstly, during the morning hours, figure (2a) displays a decrease in wind generation leading up to the midday peak, while figure (2c) exhibits an increase in solar generation. This can be attributed to the wind speeds[6], which tend to be lower in the morning, as reported by the French weather agency. Simultaneously, this period coincides with the onset of sunlight and the resumption of economic activities, explaining the opposite effect observed for solar power and demand. Secondly, the first peak in electricity demand usually occurs around mid-day when solar generation reaches its maximum, and wind power contributes significantly to the grid[7].

Conversely, during the second peak, renewable energy generation is lower due to decreased wind speeds and the absence of sunlight. Additionally, when analyzing the overall intermittency pattern of RES, it becomes evident that wind intermittency is more unstable in the evening over the four-year period, as depicted in figure (2a), compared to solar intermittency in figure (2c). However, the midday period remains the most crucial in terms of solar intermittency

It is evident that the intermittency of renewable energy sources can have a significant impact on the stability of the electricity grid and the integration of renewable energy power into the electricity market. Another aspect of this impact is the uncertainty associated with the accurate forecasting of renewable energy generation, which can lead to forecasting errors. It is crucial to analyze and understand the implications of these forecasting errors on the overall system, as they can have significant consequences on grid reliability and operational planning.

3.2.2.3 RES Uncertainty .

As Weber and Woerman (in press) did, we decided to differentiate uncertainty from intermittency. Thus, uncertainty represents forecast error and is equal to the difference between the generation in hour h and its forecast in (h-1). Equations ((4) - (6)) show the

[6]Studies show a correlation between temperature and wind speed. As temperature rises, wind speed is likely to increase. At night, temperatures are generally low Escourrou (1989)

[7]France is a well interconnected country and receive wind energy from neighbours countries, especially Germany Percebois and Pommeret (2016)

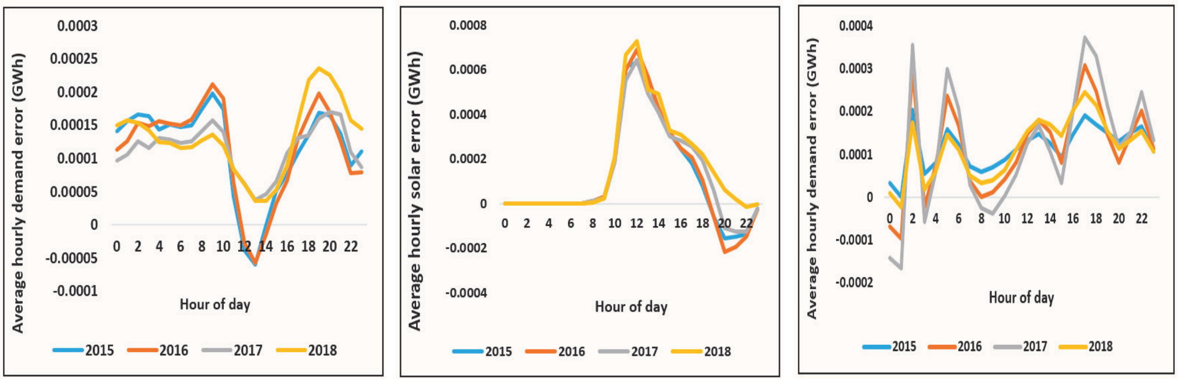
calculation of the error related to wind (WU), solar (SU) generation and French electricity demand (DU) on day d at a given hour h.

$$WU_{d,h} = WG_{d,h} - WF_{d,(h-1)} \tag{4}$$

$$SU_{d,h} = SG_{d,h} - SF_{d,(h-1)} \tag{5}$$

$$DU_{d,h} = D_{d,h} - DF_{d,(h-1)} \tag{6}$$

With WF, the wind forecast, SF solar forecast and DF demand hour-ahead forecast, which means forecasts made at the previous hour (h-1) for the next hour h of the same day. To better understand the scale of errors, figure (3) depicts the proportion of errors in relation to production.



(a) **Wind Error** (b) **Solar Error** (c) **Demand Error**

Figure 3: **RES and Demand Uncertainty (forecast error) in France**

Figure (3a) clearly demonstrates that during the initial peak hours, wind hour-ahead forecasts decrease, especially in 2015 and 2016 and increase during the second peak[8]. In contrast to wind error, as shown in figure (3b), solar error increase during the first peak and then decrease for the rest of the day[9] . Figure (3c) reveals a higher degree of demand flexibility throughout the study period because electricity demand rarely exceeds its hour-ahead forecasts, suggesting effective control over demand and a good understanding of the factors that influence it. This control and understanding contribute to the efficient operation of the power system and guarantee its reliability. This control can also make the demand a means of slowing down the effects of RES.

Furthermore, in terms of uncertainty - forecast error - the share of the wind error relative to its production is between (-0.01 -0.03)% versus (-0.04 -0.08)% for the solar error and (-0.02 -0.04)% for the demand error. It can be seen that the solar error fluctuates widely during its production peak, but remains smaller in quantity than the wind and demand errors (figures A.2a – A.3a). Moreover, wind power exhibits a greater magnitude

[8]The presence of negative values in figures indicates that the hour-ahead forecasts exceed the power generation and corresponds to an over-forecast, while a positive sign indicates under-forecast of generation.We provide more clarification in figure 1.3

[9]The first peak corresponds to the solar production peak, contributing to an increase in the solar error. Thereafter, as solar energy becomes less available, its production decreases, reaching the lowest point and explaining the observed decrease in its error.

than demand and solar in absolute value (figures A.2b - A.3b). Wind error is approximately twice as large as demand error, despite demand being over six time greater than RES. Additionally, wind error increases over the study period while solar error shows in absolute value a monotone increase with focus during the last part of the day, as illustrated in figure (A.2d). We are then expecting wind error marginal impact on price to be greater than solar and demand errors. Finally, demand error decreases (figure A.3b) over the same period. This is also another point that inform on the demand control and the challenge of controlling renewable energy because of exogenous factors .

3.2.3 Electricity demand

Here, we focus on one of our explanatory variable, which is demand. The aim is to study the evolution of intraday hourly demand and residual demand over the studied period in France. This will enable us to determine how conventional generators will react to this residual demand, in order to understand the change in price following the introduction of RES.

Electricity demand in France appears to have varied little over the period studied. Figure (4a) shows a remarkable similarity in hourly demand over the four years. In 2015, electricity demand in France stood at around 473 terawatt-hours (TWh). This electricity consumption, in 2016, demand rose slightly to around 476 TWh. This modest increase can be explained by economic growth, weather conditions, and seasonal fluctuations. Electricity demand slightly decreased in 2017 compared to the previous year, at around 473 TWh, as in 2015. The reasons behind may be factors such as improved energy efficiency measures, energy-saving policies, and fluctuations in economic activity. Finally, in 2018, electricity demand rose slightly around 477 TWh. This upturn is linked to several factors, such as economic recovery, extreme weather conditions and variations in energy consumption across sectors.

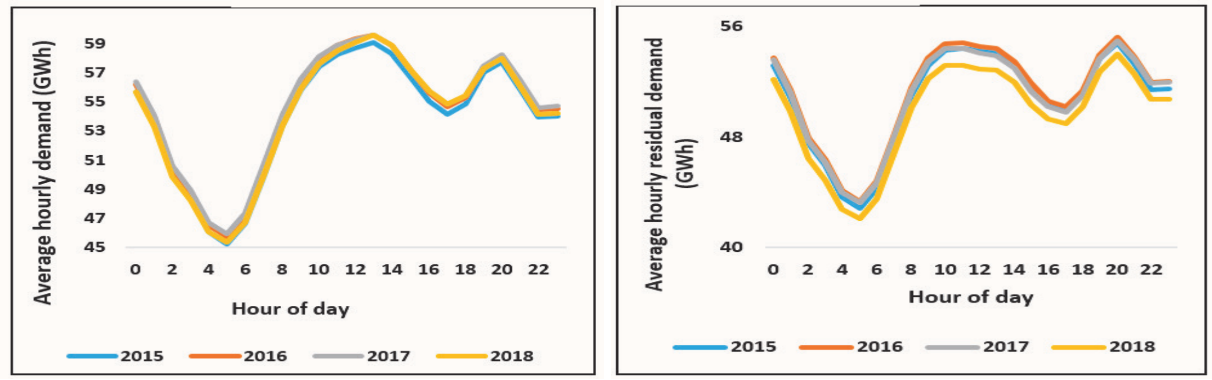
Conversely, Figure (4b) plots the evolution of residual demand over the same period. Notably, the variability of residual demand does not follow a monotonic trend and is due to the impact of RES on demand. Renewable energies, which benefit from priority access in the order of merit, reduce the availability of conventional generation. Consequently, residual demand (RD), as expressed in equation (7), represents the difference between electricity demand (D) and renewable energy generation (REG).

$$RD = D - \sum_{i}^{n} REG \tag{7}$$

With REG = Renewable Energies Generation and n = 2 in our study because we only take into account wind and solar generation in our study.REG can therefore be written as REG = WG +SG

The market price will then be determined by the match between residual demand and the supply of conventional generators. The more unstable RD is, the more the price will change.

For example, in the case of a positive error (underestimation of renewable energy production), the market is supplied with more renewable energy than initially anticipated. Consequently, the residual demand (RD) decreases, necessitating conventional producers to curtail their output to align with the adjusted RD. This results in incurring shutdown costs that alter the shape of the supply curve. As a result, the price rises. On the other hand, a negative error means a reduction in renewable production and an increase



(a) **Demand** (b) **Residual demand**

Figure 4: **Average hourly demand and residual demand in France**

of RD . During this period, conventional generators face start-up costs. Due to these increased costs for certain generators and the impracticality for others to stop and restart an hour later, conventional producers continue to generate at reduced prices, resulting in a downward effect on the market price. The presence RES error can decrease and increase prices[10].

3.2.4 French electricity prices

The main variable of interest in this study is the price change upon the entry of renewable energy generation.Figure (5) plots the average hourly wholesale price between 2015 and 2018. Hourly prices range from €(20 - 70) depending on the period. The graph shows a low period between 00:00 am – 6:00 am. With a recovery of activities from 07:00 am, this resumption increases the consumption, which reaches a first peak between 10:00 am – 13:00 pm before starting a new downturn for a second low period around 14:00 pm. From 7:00 pm, a second peak period, the most important of the day, lasts until 10:00 pm. Finally, consumption falls back down to reach a third off-peak period. The maximum prices are reached during the two daily peak periods and the minimum price during the off-peak periods.Moreover, figure (5) also shows that energy price on EPEX Spot Exchange gradually increase over years. During peak periods, high average prices are reached in 2018 (approximately €/MWh 70) and low average price are reached in 2015-2016 and are less than €/MWh 60.

We also see that price did not follow the same trend as wind and solar, meaning that renewable energy resources' impact on the electricity price in France is a complex and multifaceted issue that depends on several factors. The price change can be explained by several factors related to the characteristics of renewable energies, demand, the price of other resources like fuel, gas etc... Nicholson et al. (2010) .In general, renewable energy sources, including wind and solar, can have a downward impact on the price of electricity by reducing the need for expensive fossil fuels and increasing competition in the energy market.

[10]Figure (3) shows that in France, we have more positive errors, meaning that production is underestimated. On average, we therefore expect a price decrease. (See section 3.2)

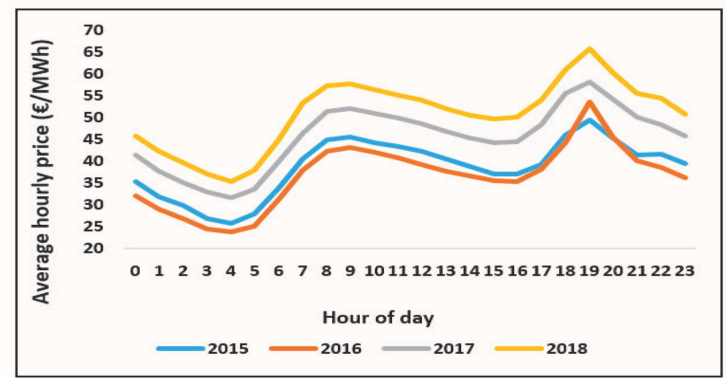


Figure 5: **EPEX Hourly Prices in France**

3.3. Model and Results

To assess the impact of renewable energies on prices, a two-step fixed-effects regression is used. The two-step time fixed-effects regression approach allows for a comprehensive analysis of the relationship between renewable energies and prices over time. In the first step, factors such as demand and renewable generation (solar and wind) are considered to evaluate the overall effect of these variables on daily prices between 2015 and 2018. By accounting for demand and renewable generation, the first step captures the general influence of these variables on prices. This step provides an initial assessment of the overall impact of renewable energies on prices during the study period. In the second step, these variables are decomposed using their characteristics to estimate the marginal effect of each characteristic on prices. This allows a more detailed assessment of the specificities of renewable and their contribution to price variation. We then discussed and supported the results with further analyses.

3.3.1 Overall estimation

To estimate the causal effects of wind generation, solar generation, and electric demand on wholesale price, we specified a regression model as follows:

$$P_h = \beta_1 WG_h + \beta_2 SG_h + \beta_3 D_h + \sigma_h + \sigma_m + \sigma_y + \epsilon_y \tag{8}$$

By including the fixed effects $(\sigma_h, \sigma_m, \sigma_y)$ in the model, the analysis accounts for time-specific patterns and similarities observed in the data, such as hourly trends, monthly and yearly variations. This helps to avoid biasing the estimated causal effects between the variables of interest. The coefficients β_1, β_2 and β_3 correspond to the estimated causal effects. They quantify the impact of variations in wind generation, solar generation, and electric demand on the wholesale price while accounting for other factors and time-related patterns. The fixed effects coefficients, as displayed in table A.1, capture the influence of fixed factors in the regression analysis. Table 1 displays the coefficients of the regression.

3.3.1.1 Overall effect .

Column (1) presents the overall effect of the exogenous variables on price. Results show a negative correlation between renewable energy (wind and solar) generation and price, while demand has a positive impact on price. These results confirm the existing literature on the impact of RES and demand on merit-order curve. The marginal average

	Heterogeneity by Residual Demand						
	All	<25th %	25-75th %	75-90th %	90-95th %	95-99th %	>99th %
VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Wind generation (GWh)	-2.12***	-2.37***	-2.06***	-1.70***	-2.50***	-1.52**	-5.40***
	(0.07)	(0.08)	(0.04)	(0.11)	(0.74)	(0.54)	(0.59)
Solar generation (GWh)	-3.18***	-3.28***	-2.29***	-1.91**	-3.05**	-5.12**	-9.61**
	(0.35)	(0.23)	(0.25)	(0.76)	(1.42)	(2.08)	(2.59)
Demand (GWh)	1.67***	2.06***	1.34***	1.47***	2.50***	3.23***	7.29***
	(0.04)	(0.17)	(0.04)	(0.08)	(0.66)	(0.37)	(0.52)
Observations	34,872	8,716	17,438	5,230	1,743	1,396	345
R-squared	0.60	0.68	0.66	0.58	0.32	0.32	0.51

Table 1: Price effect with heterogeneity by residual demand

impact of the reduction on price for each additional GWh of RES introduced to the market during our study period is, ceteris paribus, €2.12/MWh for wind, €3.18/MWh for solar. On the other hand, an increase in demand raises the price by an average of €1.67/MWh. Our aim is to study how RES intermittency and uncertainty will impact the merit-order and therefore on the price. The results in table 2 will give us more details on this subject.

3.3.1.2 Residual Demand Analysis .

Another objective of this work is to see how the price changes with the increase in residual demand. To this end, we divide our data set into percentiles and regress the model with the increase in residual demand. The coefficients for this analysis are also presented in table 1, from the second column to the seventh column. It also provide further support for the relationship between residual demand and the effect of RES on price, as previously discussed. Introducing one GWh of wind/solar power reduces the price by €5.40/ 9.61 per MWh when the residual demand is above the 99th percentile, which is higher than the € 2.37/ 3.28 per MWh decrease when the residual demand is below the 25th percentile. An increase of one GWh in demand raises the price by approximately €7.29 per MWh when the residual demand is above the 99th percentile, compared to €2.06 per MWh when the residual demand is below the 25th percentile. During the period of extreme peak demand, prices are high, which means that the fossil energy that makes the market price is expensive. Introducing renewable production cuts residual demand, reducing dependence on costly fossil energies and, consequently, lowering market prices significantly.

However, beyond the level of residual demand, price variation also depends on the shape of the merit curve. Looking at the regression results in table 1, we see that price variation is not exponential when residual demand is between (25 99)%, which differs from the results of other studiesWeber and Woerman (in press). To explain this phenomenon, figure 6 shows the French merit order curve for January 16, 2018 at 1 pm. The aim is to see the trajectory of this curve during this peak hour.

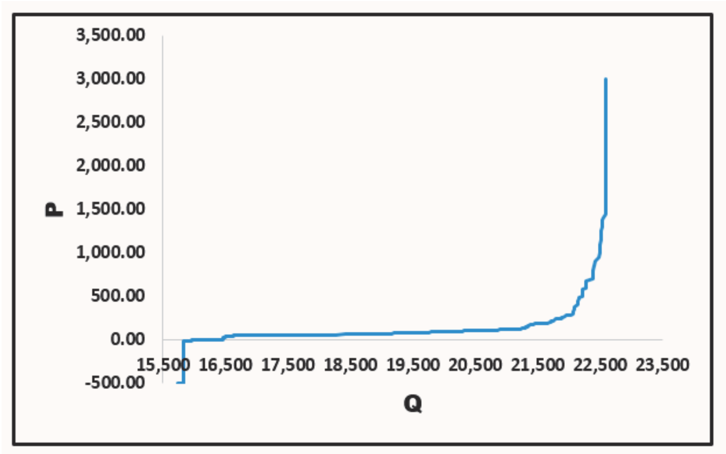


Figure 6: **France Merit-order curve of January 16, 2018 at 1 p.m**

We observe minimal price variation when supply is in the MWh(16500 - 21500) range[11]. In this interval, the energies called are relatively cheaper, and any additional demand or renewable generation on the market has a negligible influence on price. This pattern is evident in the results of table 1 when residual demand is between (25-99)th%. Conversely, between MWh(21500 - 22500) , supply has increased by 1 GWh, leading to an exponential increase in price. Consequently, any excess demand or additional renewable generation has a similar impact on price. This trend is also observed in our regression when residual demand exceeds 99th%, resulting in a price reduction of over 250% compared to when residual demand is below 99th%, as marginally expensive energies will be excluded from the market.

These results show that the additional introduction of 1 GWh of RES generation or demand has an impact on price depending on the level of residual demand, but also on the shape of the merit order curve. These results may therefore differ from one region to another, depending on the energy orientation of the region and its conventional generation mix.

3.3.2 Decomposition of exogenous variables in *intermittency* and *uncertainty*

Furthermore, we aim to decompose the variables WG_h and SG_h , which represent wind and solar generation introduced to the market at hour h, respectively, and D_h, which represents the electricity demand in the market at the same hour t. By focusing on these main variables WG_h ,SG_h and D_h in equation (8), we incorporate the characteristics (intermittency and error) studied in figures (2 and 3). To simplify the analysis, let explain the decomposition of one variable (wind generation) and then extend the analysis to the other two explanatory variables: demand (D_h) and solar generation (SG_h).

In fact, wind generation at a given hour (h) of the day (d), denoted as (WG_h), as shown in equation (9), is equal to the forecasted wind generation $WF_{(d;h)}$ plus the wind error ($WE_{(d;h)}$) of hour h. We then write equations (10) and (11) for solar generation (SG_h) and demand (D_h) using the same analysis.

[11]On average, during peak hours, the french merit order follows the same trend

$$WG_h = WF_{(d;h)} + WE_{(d;h)} \tag{9}$$

$$SG_h = SF_{(d;h)} + SE_{(d;h)} \tag{10}$$

$$D_h = DF_{(d;h)} + DE_{(d;h)} \tag{11}$$

The wind forecast for hour h $WF_{(d;h)}$ is first made at the previous hour (h-1). The previously made forecast $WF_{d;(h-1)}$ undergoes a fluctuation from (h-1) to h. This fluctuation, which we refer to as $\triangle\ WF_{(d;t)}$ and represents the change in wind forecast $WF_{(d;(h-1))}$ from hour (h-1) to h. The following three equations show the decomposition of the forecast for wind $WF_{(d;h)}$, solar $SF_{(d;h)}$ and electricity demand $DF_{(d;h)}$.

$$WF_{(d;h)} = WF_{d;(h-1)} + \triangle WF_{(d;t)} \tag{12}$$

$$SF_{(d;h)} = SF_{d;(h-1)} + \triangle SF_{(d;t)} \tag{13}$$

$$DF_{(d;h)} = DF_{d;(h-1)} + \triangle DF_{(d;t)} \tag{14}$$

As the wind forecast $WF_{d;(h-1)}$ made at (h-1) fluctuates between hour (h-1) and h, so does the wind error $WE_{d;(h-1)}$ between these same frame. We call it $\triangle\ WE_{(d;t)}$ and represents the change in wind error between time h-1 and time h. By conducting the same analysis for wind errors, we obtain equations (15), (16), and (17) as follows:

$$WE_{(d;h)} = WE_{d;(h-1)} + \triangle WE_{(d;t)} \tag{15}$$

$$SE_{(d;h)} = SE_{d;(h-1)} + \triangle SE_{(d;t)} \tag{16}$$

$$DE_{(d;h)} = DE_{d;(h-1)} + \triangle DE_{(d;t)} \tag{17}$$

With $SE_{d;(h-1)}$; $DE_{d;(h-1)}$ representing the hour-ahead forecast error for solar and demand, respectively, and $\triangle SE_{(d;t)}$ and $\triangle DE_{(d;t)}$ indicating the change in solar and demand errors from (h-1) to h.

We substitute equations (12) and (15) into equation (9) for wind; equations (13) and (16) into (10) for solar; and finally (14) and (17) into equation (11) for demand, we obtain the decomposition of wind generation (WG_h), solar generation (SG_h), and demand (D_t) from intermittency and uncertainty, grouped as equations [(18) , (20)].

$$WG_h = WF_{d;(h-1)} + \triangle WF_{(d;t)} + WE_{d;(h-1)} + \triangle WE_{(d;t)} \tag{18}$$

$$SG_h = SF_{d;(h-1)} + \triangle SF_{(d;t)} + SE_{d;(h-1)} + \triangle SE_{(d;t)} \tag{19}$$

$$D_h = DF_{d;(h-1)} + \triangle DF_{(d;t)} + DE_{d;(h-1)} + \triangle DE_{(d;t)} \tag{20}$$

Therefore, we can rewrite (8) by substituting the decomposed WG_h, SG_h, and D_t from equations [(18) , (20)].

$$
\begin{aligned}
P_t =& \beta_1 WF_{d_{(h-1)}} + \beta_2 \triangle WF_{(d_t)} + \beta_3 WE_{d_{(h-1)}} + \beta_4 \triangle WE_{(d_t)} \\
&+ \beta_5 SF_{d_{(h-1)}} + \beta_6 \triangle SF_{(d_t)} + \beta_7 SE_{d_{(h-1)}} + \beta_8 \triangle SE_{(d_t)} \\
&+ \beta_9 DF_{d_{(h-1)}} + \beta_{10} \triangle DF_{(d_t)} + \beta_{11} DE_{d_{(h-1)}} + \beta_{12} \triangle DE_{(d_t)} \\
&+ \sigma_h + \sigma_m + \sigma_y + \epsilon_h
\end{aligned} \tag{21}
$$

- β_1 (β_5 , β_9) establishes the impact of wind forecast (solar - demand) made at hour (h-1) for hour h and on price
- β_2 (β_6;$\beta_1$0) elucidates the correlation between the change in wind forecast (solar - demand) from hour (h-1) to h and price
- β_3 (β_7 ;$\beta_1$1) examines the causal effect between wind error (solar - demand) at hour (h-1) and price, while
- β_4 (β_8 ;$\beta_1$2) investigates how the change in wind error (solar - demand) affect price.

Results are displayed in table (2) :

VARIABLES	All (1)	< 25th % (2)	< 25-75th % (3)	> 75th % (4)
Wind forecast in previous hour (GWh)	-2.12***	-2.24***	-2.14***	-1.76***
	(0.06)	(0.06)	(0.05)	(0.13)
Wind forecast hourly change (GWh)	-2.36**	-1.75***	-0.90	-1.97***
	(0.49)	(0.59)	(0.54)	(0.59)
Wind error in previous hour (GWh)	-4.92***	-4.90***	-3.81***	-6.51***
	(0.09)	(0.08)	(0.05)	(0.14)
Wind error hourly change (GWh)	-3.54***	-2.65***	-2.35**	-4.25
	(0.49)	(0.40)	(0.49)	(0.80)
Solar forecast in previous hour (GWh)	-3.18***	-3.81***	-2.45***	-2.02
	(0.37)	(0.26)	(0.24)	(1.22)
Solar forecast hourly change (GWh)	-8.57***	-9.17***	-6.78***	-7.02*
	(1.00)	(1.64)	(0.97)	(2.42)
Solar error in previous hour (GWh)	-0.52**	-0.84**	-0.22**	-0.11
	(0.21)	(0.40)	(0.23)	(0.38)
Solar forecast hourly change (GWh)	-1.83**	-2.80***	-1.80**	-2.08
	(0.76)	(0.67)	(0.86)	(1.87)
Demand forecast in previous hour (GWh)	1.69***	1.89***	1.36***	1.48***
	(0.04)	(0.09)	(0.04)	(0.08)
Demand forecast hourly change (GWh)	2.03***	3.53***	1.81***	1.68***
	(0.22)	(0.55)	(0.24)	(0.34)
Demand error in previous hour (GWh)	1.66***	0.16	1.30***	1.51***
	(0.05)	(0.30)	(0.06)	(0.10)
Demand error hourly change (GWh)	1.37**	0.56	1.40***	1.48
	(0.58)	(0.78)	(0.37)	(0.91)
Observations	34,871	8,716	17,438	5,230
R-squared	0.61	0.69	0.67	0.58

Table 2: Full decomposition of price effect

The results show that the uncertainty associated with wind power, in the case of an additional 1 GWh of wind power, has a larger effect on the price than wind forecast. The wind error ($WE_{d_{(h-1)}}$) in the third row leads to a price reduction of €4.92 per MWh, while its hourly change ($\triangle WE_{(d_t)}$) in the fourth row contributed to a price decrease of €3.54 per MWh. Both impacts are higher than the influence of wind forecast ($WF_{d_{(h-1)}}$)and its hourly change ($\triangle WF_{(d_t)}$) on the price, which are €2.12 and €2.36 per MWh, respectively, as indicated in the first two rows.

The reason behind this greater effect of error on price is that, in the event of one-hour uncertainty, additional unplanned renewable generation is injected into the grid, reducing residual demand. [12]. In this case, conventional generators have to reduce their output to

[12]Similarly, uncertainty can lead to a reduction in renewable generation, increasing residual demand.

cope with the reduction in residual demand. Some are shut down and excluded from the market. Other generators are unable to stop during this hour and continue to produce at a lower price, which changes the slope of the supply curve and lowers the market price.

We further focus on the results for solar energy illustrate on rows 5 to 8. These findings reveal that the error associated with solar energy ($SE_{d_{(h-1)}}$) has a comparatively smaller impact on price compared to its forecast ($SF_{d_{(h-1)}}$). The absolute impact is estimated to be €0.52/MWh, while the hourly fluctuation ($\triangle SE_{(d_t)}$) decreases the price by €1.83/MWh. Both of these values are lower than the forecast ($SF_{d_{(h-1)}}$) and its change in hour ($\triangle SF_{(d_t)}$), which lead to price decrease of €8.57/MWh and €3.18/MWh, respectively.

There are several reasons that can explain the nearly negligible effect of uncertainty. Firstly, in France, our data analyses show that solar energy is more predictable compared to wind energy. As a result, solar errors tend to be less significant than those for wind energy are. Secondly, in France, solar energy is not only generated by solar power plants but also by end consumers for their personal use (self-consumption). Consequently, the uncertainty surrounding solar generation is managed through two distinct methods Lienhart (2018). The solar producers (end consumers) either draw any additional required energy from the grid or inject surplus energy into the grid when available. Moreover, energy storage mechanisms, such as batteries, play a role in regulating the amount of surplus energy injected into the grid. As result, this process has a minimal impact on the overall grid stability and performance[13]. Furthermore, solar panels only produce energy for a few hours during the day, reaching their maximum production levels during the first daily peak (between 12 and 14 hours). The errors associated with solar generation, can be offset by other energy sources such as base-load (nuclear), as well as wind, hydro and thermal power.

Furthermore, we observe in lines 9 and 10 the impact of demand forecast ($DF_{d_{(h-1)}}$) and its hourly change ($\triangle DF_{(d_t)}$) on price, estimated at €1.69/MWh and €2.03/MWh, respectively. When compared to its error ($DE_{d_{(h-1)}}$) indicated in line 11 and its change ($\triangle DE_{(d_t)}$) in ligne 12, we note that the effects are almost similar, resulting in price reductions of €1.66/MWh and €1.37/MWh, respectively. This highlights a proportional impact of demand forecast and error on price and effective management of demand-related uncertainties in France.

3.3.3 The role of interconnection and generation mix in the change of price variation

In Tables (1) and (2), the results show a homogeneous impact on price with the increase in residual demand following the introduction of renewable energies, which differs from results in other countriesWeber and Woerman (in press). There are several reasons for this unique situation in France, not least the presence of interconnections and a mix of available capacities. These two points will be analyzed in the following subsection of this paper.

Thus, our aim is to study the impact of interconnection and of energy mix on prices

In this case, planned production is not injected into the grid, and conventional generators must respond within the hour to this excess residual demand. Some power plants cannot start up in time, and others will incur start-up costs. This will change the slope of supply curve and increase the market price. This also applies to unplanned additional demand

[13]Results in appendix A.13 show the period of solar generation does not affect our analysis

stability, taking into account the increase in residual demand and RES. In this way, we can show how interconnection and generation help France to maintain stable grid price following exogenous shocks such as the error of RES (wind and solar..). This can act as an incentive to invest in new interconnections and reinforce existing ones.

3.3.3.1 A Well interconnected country .

France is connected to several countries, and this connection could help improve energy prices, as mentioned in CRE's 2016 report[14]. Currently, five links connect France to six nearby countries such as Belgium-Germany, Italy, Switzerland, Spain and the UK. These interconnections, as RTE, the French grid operator, points out, promote energy solidarity between countries and make it easier for consumers to obtain electricity at competitive prices. For example, during winter 2019, France relied on imports in January to cope with a cold snap at a competitive price around 7pm. Similarly, in February, French exports enabled Italy and Spain to cover their energy consumption while their wind generation fell drastically(RTE). This illustrates the crucial role interconnections can play in facilitating the development of renewable energies and mitigating their impact on prices during periods of high demand. Therefore, an in-depth study of these interconnections, particularly when residual demand is high and generation errors occur, would help to understand their significant implications on energy price competitiveness.

.

To do this, we first analyze hourly net interconnection data (NI_h), which represents the difference between energy imports (I_h) and exports (E_h) at the same hour h between France and its neighboring countries [equation(22)]. Next, we run a regression of net interconnection to see how the explanatory variables influence it.

$$NI_h = I_h - E_h \tag{22}$$

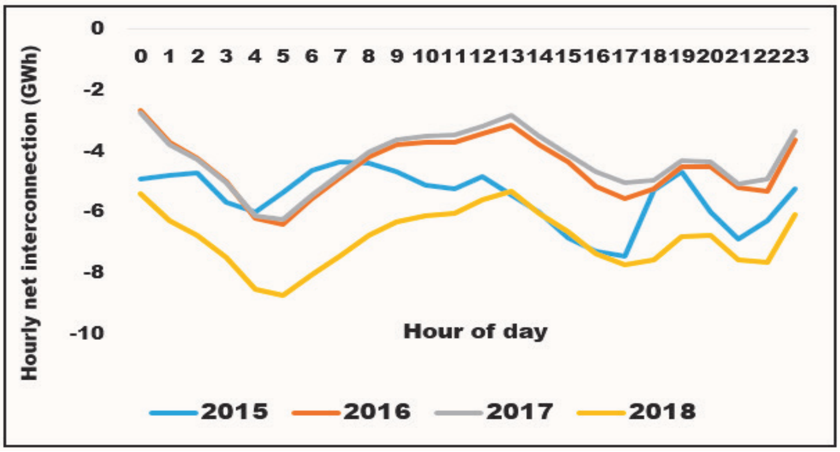


Figure 7: **France Net interconnection over years**

Net Interconnection data analysis .

[14]See CRE's 2016 Report "Les interconnection électriques et gazière en France, un outil au service de la construction d'un marché européen intégré" Pages 16-27

Figure 7 shows that, on average over the period studied, France is a net exporter of energy.[15] Looking at off-peak hours (between 00:00 - 7:00, then between 15:00-18:00), France increases its exports to its neighbors, which means that France produces relatively cheaper energy that benefits industries in neighbouring countries. On the other hand, during peak hours, we see a reduction in exports. This reduction will certainly be used to offset additional french demand.

We also note a lack of homogeneity in capacity transited on interconnections over the years. The trends for 2016 and 2017 are similar, and there is considerable variability between 2015 and 2018. This can be explained by two factors. On the one hand, demand from outside France is not stable and probably depends on a trade-off between French and neighboring energy prices [16], weather conditions which can influence production variability, etc... Secondly, this instability also shows the uncertainty facing interconnections and their regulatory role in energy stability.

An in-depth analysis of interconnections by year and by country (A.4) shows a similar result, with the exception of the interconnection linking France to Germany-Belgium, from which France imports energy. Germany, one of Europe's leading renewable energy producers ahead of France, injects a great quantity of energy into the grid according to its production, which impact the interconnection balance between France and these countriesPercebois and Pommeret (2016). In our regression results, we are expecting France to be small net importer and a great net exporter.

Net Interconnection regression analysis .

Now, we study how interconnection can be impacted by residual demand level, solar and wind generation by formulating the fixed effect equation as follows :

$$NI_h = \beta_1 WG_h + \beta_2 SG_h + \beta_3 D_h + \sigma_h + \sigma_m + \sigma_y + \epsilon_y \quad (23)$$

Results of equation (23) are depicted in table (3) :

VARIABLES	(1) All	(2) < 25th %	(3) 25-75th %	(4) > 75th %	(5) 75-90th %	(6) 90-95th %	(7) 95-99th %	(8) >99th %
Wind generation (GWh)	-0.40***	0.17***	-0.36***	-0.58***	-0.59***	-0.54***	-0.45***	-0.17**
	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)	(0.05)	(0.04)	(0.07)
Solar generation (GWh)	0.17**	0.20***	-0.09*	0.03	-0.15	0.40**	0.44***	0.38*
	(0.06)	(0.04)	(0.05)	(0.07)	(0.09)	(0.17)	(0.14)	(0.20)
Demand (GWh)	0.30***	0.06***	0.30***	0.40***	0.36***	0.38***	0.43***	0.26***
	(0.01)	(0.02)	(0.02)	(0.01)	(0.01)	(0.04)	(0.02)	(0.05)
Observations	34,871	8,714	17,435	8,721	5,236	1,739	1,399	345
R-squared	0.55	0.38	0.45	0.66	0.61	0.67	0.67	0.65

Table 3: Hourly Net Interconnection Marginal effect with heterogeneity by residual demand

The results demonstrate that, ceteris paribus, over the four years, France can export on average (400 MWh) and import (170 MWh) energy from its nearby countries. An additional 1 GWh of renewable generation (wind/solar), France tends to be sometimes

[15] Negative signs mean that energy exports are greater than energy imports

[16] Consumers demand energy where the price is lower. Thus, the market price will be less affected by exogenous variations

a net electricity importer (170 MWh) and in most cases, a net electricity exporter (400 MWh), except in the case of Germany-Belgium during periods of extreme demand[17] confirming the CRE report and the analysis of figure 7.

As residual demand increases, there are disparities in the results. For example, when residual demand is below 25%, despite the increase in wind generation, France imports 170 MWh of energy. The appendices (A.2 - A.6) show that France imports energy from Belgium, Italy, Spain and UK . Similarly, for solar energy, the results show that France imports energy from its neighbors as residual demand increases . There are two possible reasons for this trend. Despite a production surplus, French demand is high and domestic production is insufficient to meet it, so France has to import energy from its neighbors [Bushnell and Novan (2021) , Jha and Leslie (2021)]. Moreover, to prevent prices from rising due to start-up cost, energy import remains the most economically advantageous solution.

Another observation is the export of energy over certain hours during additional renewable generation. This is the case for RES when residual demand is between 25% and 75% of the table (3), and most of the results of countries in appendix (A.2 - A.6). Again, there are two possible reasons for this. Firstly, the conventional mix (see next regression), and then storage constraints, may force producers to export their energy in order to earn an economic return and avoid wastage.

Finally, with an additional demand of 1 GWh, ceteris paribus, energy imports would be induced. The detailed analysis by country, presented in the appendix (A.2 - A.6), shows in few case that France can export energy sometimes even though residual demand increase. From these findings, we can infer that, during certain hours, France has the flexibility to both import and export energy with different countries, regardless the demand level[18]. This led us to analyze the conventional energy mix.

3.3.3.2 Conventional Mix .

To delve deeper into this phenomenon, we conduct a fixed regression analysis with Conventional Generation in hour t (CGt) as endogenous variable, in order to scrutinize how conventional mix responds to variations in renewable energy generation and demand.

$$CG_h = \beta_1 WG_h + \beta_2 SG_h + \beta_3 D_h + \sigma_h + \sigma_m + \sigma_y + \epsilon_y \tag{24}$$

[17]France mainly receives surplus renewable energy (especially wind) injected into the grid by Germany

[18]An analysis of the French fleet shows that installed capacity far exceeds France's electricity needs.See table A.7

VARIABLES	(1) All	(2) < 25th %	(3) 25-75th %	(4) > 75th %	(5) 75-90th %	(6) 90-95th %	(7) 95-99th %	(8) >99th %
Wind generation (GWh)	-0.47***	-0.68***	-0.52***	-0.30***	-0.31***	-0.34***	-0.30***	-0.50***
	(0.02)	(0.03)	(0.01)	(0.01)	(0.02)	(0.05)	(0.03)	(0.06)
Solar generation (GWh)	-0.60***	-0.91***	-0.49***	-0.30***	-0.23***	-0.49***	-0.63***	-0.59***
	(0.08)	(0.07)	(0.06)	(0.05)	(0.07)	(0.14)	(0.12)	(0.11)
Demand (GWh)	0.46***	0.76***	0.51***	0.37***	0.39***	0.37***	0.34***	0.41***
	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)	(0.04)	(0.02)	(0.03)
Observations	34,872	8,714	17,436	8,721	5,236	1,739	1,399	345
R-squared	0.92	0.61	0.81	0.80	0.72	0.68	0.77	0.67

Table 4: Hourly conventional energy marginal effect with heterogeneity by residual demand

The findings presented in table (4) reveal a negative correlation between fossil fuel generation and an additional 1GWh of RES (solar/wind). For instance, an additional 1GWh of renewable energy (solar/wind) leads to a reduction in conventional generation by approximately 470MWh for wind and 600MWh for solar, respectively. The reduction in conventional production remains lower than the additional renewable production (1GWh) even with the increase in residual demand[19]. This shows France's ability to export energy and is in line with the results in table (3). This export allows conventional power plants to undergo few shutdowns. As a result, the market price of energy is only marginally affected.

Regarding demand, the impact is notably positive. Any increase in demand, ceteris paribus, elevates conventional generation by approximately 460MWh, with marginal fluctuations in response to variations in residual demand. In Appendix 1.8, detailed results for each fossil energy source (gas, nuclear, fuel oil, and coal) mirror these same patterns, with gas and coal exhibiting a significant reduction compared to other energy sources. Here too, we can see that the increase in conventional generation is less than the increase in demand, even with the increase in residual demand. We can thus conclude that France starts up very few power plants and supplements excess demand with imports, as highlighted by the results in table (3).

These factors may explain why RES and demand have less impact on prices when residual demand increases. In the case of Texas, wind power and demand affect prices exponentially, whereas in France, the impact remains very minimal. The above factors provide an insight into the complex dynamics of the French electricity market, highlighting the importance of interconnections and the generation mix in shaping prices during periods of high residual demand.

IV. Conclusion

Renewable energies have a dual impact on market prices. Firstly, they lower market prices thanks to the merit order effect and their zero marginal cost. Secondly, they contribute to price dispersion due to the uncertainty associated with forecasting errors. Applying

[19]The impacts on price are similar with RES or demand error and intermittency introduction. See table A.12

the findings of Weber and Woerman (in press) research to the French context highlights several important points.

Initially, with the introduction of RES on the French market, our results show a negative correlation with price. For demand, the effect on price is positive.. Moreover, the study of renewable energy characteristics, notably intermittency and uncertainty, amplifies these price effects, except in the case of solar power, which remains distinct. Furthermore, our results highlight the impact of fluctuations in residual demand, a variability influenced by the instability of renewable energy generation. Unlike the situation in Texas, the influence of these demand variations on prices in France is not exponential, mainly due to the presence of interconnections and conventional mix. In all scenarios, demand and its oscillations are well managed.

These findings not only underscore the significant challenges posed by renewable energies to the French electricity system but also emphasize the potential of demand management as a valuable strategy in addressing these challenges. In future public policies, efforts to mitigate uncertainties associated with renewable generation and further increase its share in the electricity mix could be bolstered by focusing on enhancing the flexibility of demand, which is already predictable in the French context.

This study may be subject to limitations. In France, in addition to wind and solar power, other renewable energy sources such as hydroelectricity are also integrated into the electricity market. Due to the unique characteristics of hydropower, our study has not taken its impact into account. The integration of hydropower could reveal additional information that our study may have inadvertently omitted. In addition, the impact of capacity markets, which serve as mechanisms for balancing supply and demand, could exert a mitigating influence on price change on the French market in the event of RES generation errors (uncertainty) and increase in residual demand.

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A. Appendix

1.1. RES (Wind and solar) installed capacity

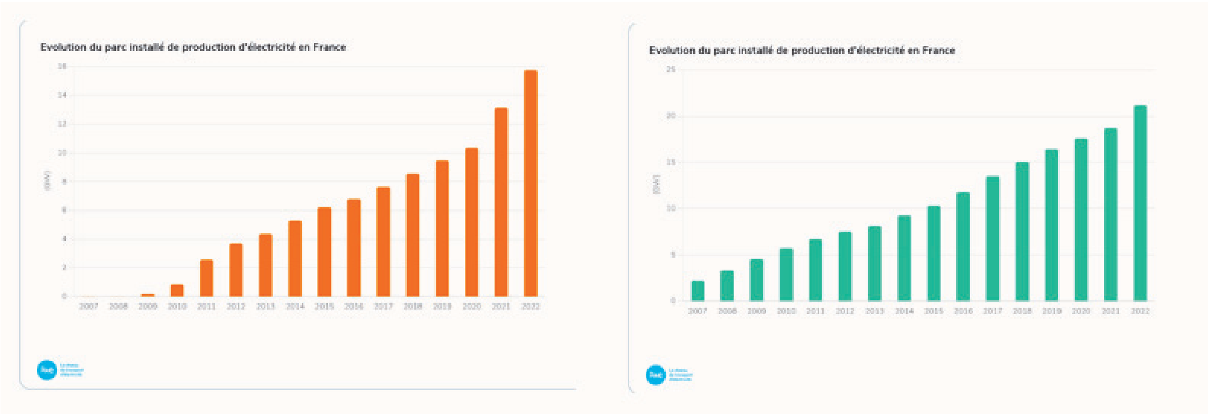
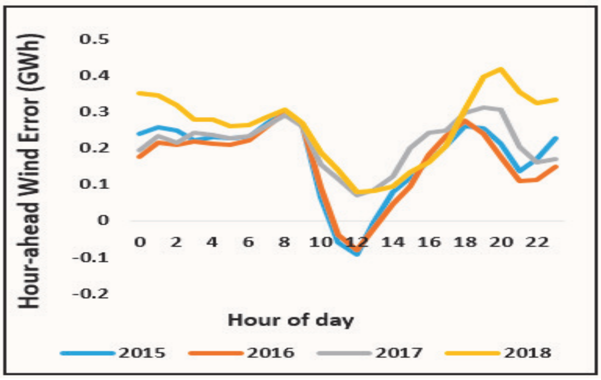
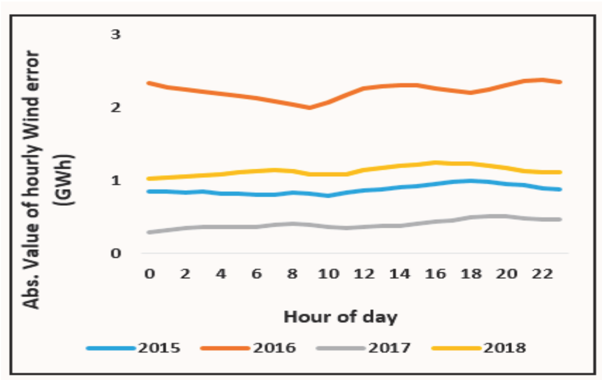


Figure A.1: **Installed wind and solar farm capacity**

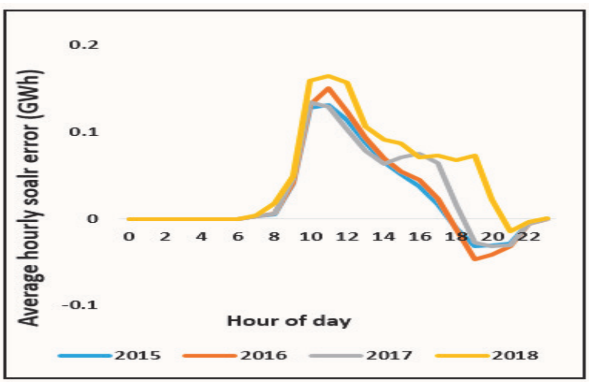
1.2. RES and demand errors



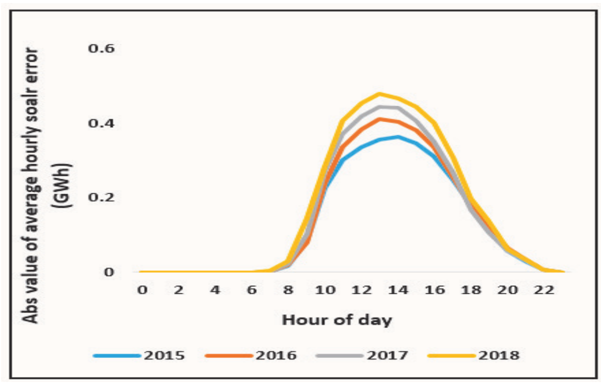
(a) **Wind Error**



(b) **Wind Error in abs. value**

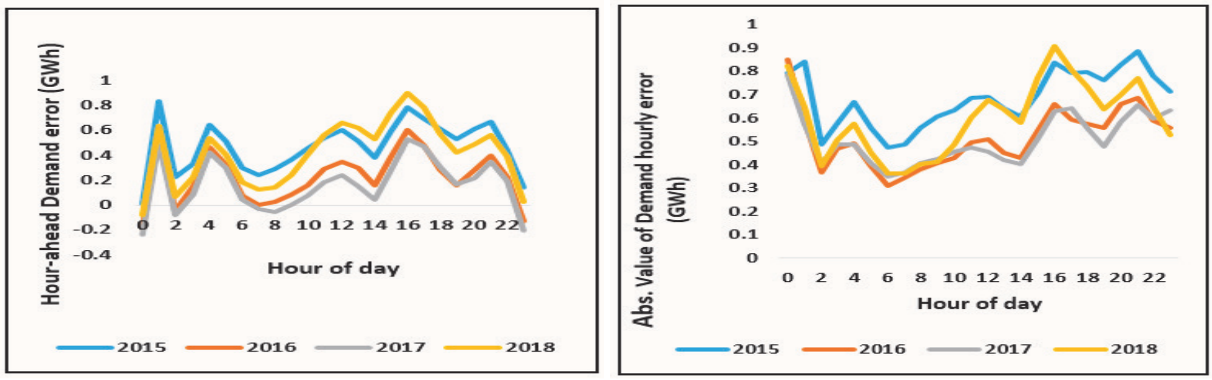


(c) **Solar Error**



(d) **Solar Error in abs. value**

Figure A.2: **RES Uncertainty**



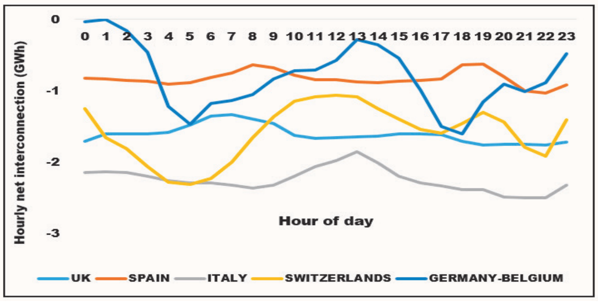
(a) **Demand Error** (b) **Demand Error in abs. value**

Figure A.3: **Demand Uncertainty**

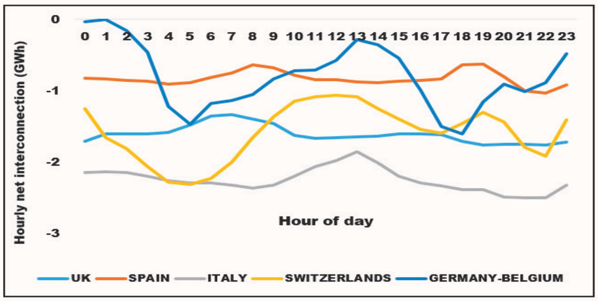
1.3. Explanation of over- and underestimation of uncertainty

The uncertainty observed in Figure (3) shows an underestimate (positive value) and an overestimate (negative value) of production. Overestimation occurs when the forecast is higher than actual production. The difference gives a negative value, as in the case of wind power. These values are generally explained by various phenomena, such as network constraints, unscheduled maintenance, etc. In France, according to Engie, RES, particularly wind power, are used as a means of flexibility to control the grid, due to their cost, in order to avoid the grid overload. They can also be shut down for reasons of biodiversity (bird detection, etc.) and neighborhood safety (noise emitted by wind turbines). There is also the phenomenon of negative prices, which can encourage renewable energy suppliers to reduce their production. As RES are remunerated outside the market by a guaranteed tariff, producers will produce at a loss if the market price is lower than this guaranteed price. This stoppage in production can also distort forecasts.

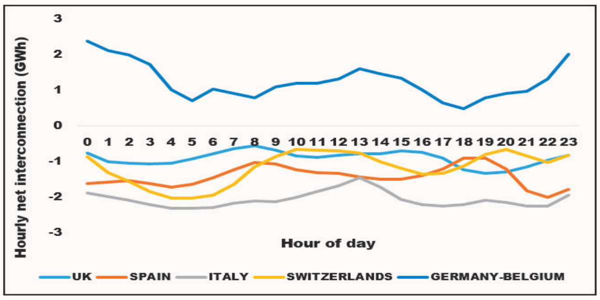
1.4. Interconnection trend over the studied period



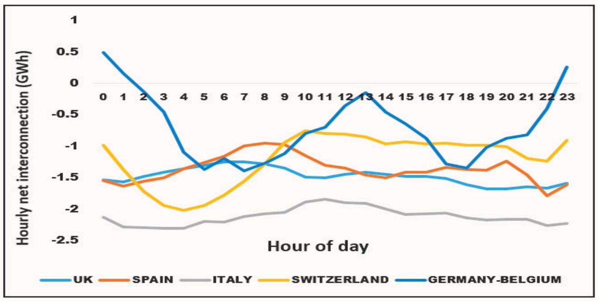
(a) **Hourly interconnections by country in 2015**



(b) **Hourly interconnections by country in 2016**



(c) **Hourly interconnections by country in 2017**



(d) **Hourly interconnections by country in 2018**

Figure A.4: **Hourly interconnections by country and year**

1.5. Full fixed effect impact of RES (Wind and Solar) and demand Marginal effect on prices

VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Wind generation (GWh)	-2.12***	-2.44***			-1.996***	-1.615***	-2.121***
	(0.07)	(0.09)			(0.0698)	(0.0675)	(0.137)
Solar generation (GWh)	-3.18***		-2.18***		-1.180***	-1.536***	-3.179***
	(0.35)		(0.47)		(0.259)	(0.0869)	(0.218)
Demand (GWh)	1.67***			1.72***	1.751***	1.676***	1.674***
	(0.05)			(0.05)	(0.0534)	(0.0531)	(0.0614)
Constant	-39.17***	49.52***	45.14***	-50.54***	-45.69***	-42.29***	-39.17***
	(2.38)	(0.23)	(0.47)	(2.53)	(2.801)	(2.838)	(3.159)
Observations	34,872	34,872	34,872	34,872	34,872	34,872	34,872
R-squared	0.60	0.38	0.33	0.56	0.617	0.721	0.600
Hour-of-day _HoD_	Yes	Yes	Yes	Yes	-	-	Yes
Month-of-year _MoY_	Yes	Yes	Yes	Yes	-	-	Yes
Year	Yes	Yes	Yes	Yes	Yes	-	Yes
HoD x MoY	-	-	-	-	Yes	-	-
HoD x MoY x Year	-	-	-	-	-	Yes	-
Clustered by HoD	Yes	Yes	Yes	Yes	Yes	Yes	-
Clustered by date	-	-	-	-	-	-	Yes

Table A.1: RES and demand Marginal effect on prices

1.6. Hourly Impact of RES and Demand on Interconnection by country over year

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
VARIABLES	All	< 25th %	25-75th %	> 75th %	75-90th %	90-95th %	95-99th %	>99th %
Wind generation (GWh)	-0.07***	-0.12***	-0.11***	-0.04***	-0.09***	-0.03	0.09***	0.23***
	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)	(0.03)	(0.03)	(0.03)
Solar generation (GWh)	0.42***	0.26***	0.33***	0.20	0.21	0.29	0.15	0.33***
	(0.06)	(0.04)	(0.04)	(0.14)	(0.17)	(0.23)	(0.10)	(0.09)
Demand (GWh)	0.07***	0.08***	0.12***	0.04***	0.06***	0.03	-0.02	-0.11***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.04)	(0.03)	(0.03)
Observations	34,871	8,714	17,435	8,721	5,236	1,739	1,399	345
R-squared	0.46	0.44	0.44	0.25	0.31	0.28	0.24	0.57

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

Table A.2: France and Germany Interconnection Marginal effect with heterogeneity by residual demand

VARIABLES	(1) All	(2) < 25th %	(3) 25-75th %	(4) > 75th %	(5) 75-90th %	(6) 90-95th %	(7) 95-99th %	(8) >99th %
Wind generation (GWh)	-0.08***	-0.01	-0.04***	-0.15***	-0.13***	-0.18***	-0.19***	-0.15***
	(0.01)	(0.00)	(0.00)	(0.01)	(0.01)	(0.02)	(0.02)	(0.04)
Solar generation (GWh)	0.05***	-0.04***	-0.00	0.11**	0.06*	0.24**	0.17	-0.43***
	(0.02)	(0.01)	(0.02)	(0.05)	(0.04)	(0.09)	(0.11)	(0.07)
Demand (GWh)	0.00	-0.07***	-0.02*	0.05***	0.04***	0.05**	0.06***	-0.02
	(0.01)	(0.01)	(0.01)	(0.00)	(0.01)	(0.02)	(0.02)	(0.04)
Observations	34,871	8,714	17,435	8,721	5,236	1,739	1,399	345
R-squared	0.19	0.44	0.20	0.37	0.39	0.41	0.33	0.52

Table A.3: France and Italy Interconnection Marginal effect with heterogeneity by residual demand

VARIABLES	(1) All	(2) < 25th %	(3) 25-75th %	(4) > 75th %	(5) 75-90th %	(6) 90-95th %	(7) 95-99th %	(8) >99th %
Wind generation (GWh)	-0.05***	0.01**	-0.36***	-0.08***	-0.11***	-0.02	0.00	-0.02
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.04)	(0.02)	(0.03)
Solar generation (GWh)	-0.29***	-0.19***	-0.09*	-0.28***	-0.40***	-0.13	0.03	0.10
	(0.03)	(0.03)	(0.05)	(0.06)	(0.07)	(0.13)	(0.06)	(0.07)
Demand (GWh)	0.10***	0.03***	0.30***	0.13***	0.12***	0.15***	0.14***	0.24***
	(0.00)	(0.01)	(0.02)	(0.00)	(0.01)	(0.03)	(0.02)	(0.02)
Observations	34,871	8,714	17,435	8,721	5,236	1,739	1,399	345
R-squared	0.31	0.32	0.45	0.30	0.28	0.32	0.49	0.62

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

Table A.4: France and Spain Interconnection Marginal effect with heterogeneity by residual demand

VARIABLES	(1) All	(2) < 25th %	(3) 25-75th %	(4) > 75th %	(5) 75-90th %	(6) 90-95th %	(7) 95-99th %	(8) >99th %
Wind generation (GWh)	-0.13***	-0.07***	-0.36***	-0.23***	-0.18***	-0.25***	-0.28***	-0.19***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)	(0.02)	(0.02)
Solar generation (GWh)	-0.04	0.11***	-0.09*	-0.13*	-0.17***	-0.08	-0.04	0.05
	(0.04)	(0.03)	(0.05)	(0.06)	(0.06)	(0.10)	(0.08)	(0.06)
Demand (GWh)	0.08***	0.04***	0.30***	0.12***	0.07***	0.11***	0.16***	0.06***
	(0.00)	(0.01)	(0.02)	(0.00)	(0.01)	(0.02)	(0.01)	(0.02)
Observations	34,871	8,714	17,435	8,721	5,236	1,739	1,399	345
R-squared	0.53	0.32	0.45	0.56	0.55	0.47	0.40	0.74

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

Table A.5: France and Switzerland Interconnection Marginal effect with heterogeneity by residual demand

VARIABLES	(1) All	(2) < 25th %	(3) 25-75th %	(4) > 75th %	(5) 75-90th %	(6) 90-95th %	(7) 95-99th %	(8) >99th %
Wind generation (GWh)	-0.07***	0.01***	-0.05***	-0.08***	-0.09***	-0.06***	-0.07***	-0.03
	(0.00)	(0.00)	(0.00)	(0.00)	(0.01)	(0.02)	(0.02)	(0.02)
Solar generation (GWh)	0.03	0.06***	0.06***	0.13***	0.16***	0.09	0.12**	0.34***
	(0.02)	(0.01)	(0.02)	(0.04)	(0.05)	(0.05)	(0.05)	(0.08)
Demand (GWh)	0.04***	-0.02***	0.04***	0.07***	0.06***	0.05**	0.08***	0.09***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.02)	(0.01)	(0.01)
Observations	34,871	8,714	17,435	8,721	5,236	1,739	1,399	345
R-squared	0.42	0.32	0.41	0.60	0.54	0.67	0.70	0.65

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

Table A.6: France and UK Interconnection Marginal effect with heterogeneity by residual demand

1.7. Comparison of demand and installed capacity

	Installed Capacity (GW)	**Hourly generation (GWh**	**Demand (GWh**
2015	121.05	96.84	91.5
2016	121.35	97.08	88.03
2017	123.39	98.71	94.19
2018	126.39	101.11	96.13

Table A.7

The table shows on the left installed capacity in France between 2015 and 2018. Based on the operating times of the various plants, we assume that, on average, the plants operate at 80% of their capacity. So, in the middle, we show the hourly production per GW, which we compare with the maximum demand registered over a year on the right.

The results show that France has a power plant capable of covering its demand. Note that these data do not take into account the various unforeseen events (maintenance, etc.) that can reduce hourly production.

In reality, the operating times of other energies, apart from nuclear, varies considerably, depending on market conditions. It should be keep in mind that operating time is the most important factor that can have impact on the operation of power plants, and therefore on the grid and the market.

1.8. Impact of RES and Demand on Conventional generation (gas, coal, nuclear and fuel oil)

VARIABLES	(1) All	(2) < 25th %	(3) 25-75th %	(4) > 75th %	(5) 75-90th %	(6) 90-95th %	(7) 95-99th %	(8) >99th %
Wind generation (GWh)	-0.22***	-0.14***	-0.23***	-0.21***	-0.23***	-0.20***	-0.11***	-0.06***
	(0.00)	(0.01)	(0.00)	(0.00)	(0.01)	(0.02)	(0.01)	(0.01)
Solar generation (GWh)	-0.20***	-0.21***	-0.14***	0.09***	0.12***	0.00	-0.02	-0.03
	(0.03)	(0.02)	(0.02)	(0.02)	(0.02)	(0.03)	(0.03)	(0.03)
Demand (GWh)	0.16***	0.14***	0.18***	0.17***	0.16***	0.16***	0.14***	0.09***
	(0.00)	(0.01)	(0.00)	(0.00)	(0.01)	(0.02)	(0.01)	(0.01)
Observations	34,872	8,714	17,436	8,721	5,236	1,739	1,399	345
R-squared	0.84	0.56	0.74	0.65	0.59	0.60	0.63	0.87

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

Table A.8: Marginal gas effect with heterogeneity by residual demand

VARIABLES	(1) All	(2) < 25th %	(3) 25-75th %	(4) > 75th %	(5) 75-90th %	(6) 90-95th %	(7) 95-99th %	(8) >99th %
Wind generation (GWh)	-0.15***	-0.49***	-0.19***	0.02**	0.02	-0.03	-0.12***	-0.25***
	(0.02)	(0.02)	(0.01)	(0.01)	(0.01)	(0.05)	(0.03)	(0.04)
Solar generation (GWh)	-0.35***	-0.64***	-0.31***	-0.49***	-0.43***	-0.60***	-0.63***	-0.46***
	(0.04)	(0.05)	(0.04)	(0.06)	(0.09)	(0.15)	(0.12)	(0.11)
Demand (GWh)	0.23***	0.57***	0.26***	0.10***	0.15***	0.12***	0.07***	0.06**
	(0.01)	(0.01)	(0.01)	(0.00)	(0.01)	(0.03)	(0.02)	(0.02)
Observations	34,872	8,714	17,436	8,721	5,236	1,739	1,399	345
R-squared	0.86	0.51	0.77	0.79	0.79	0.74	0.77	0.79

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

Table A.9: Marginal Nuclear effect with heterogeneity by residual demand

VARIABLES	(1) All	(2) < 25th %	(3) 25-75th %	(4) > 75th %	(5) 75-90th %	(6) 90-95th %	(7) 95-99th %	(8) >99th %
Wind generation (GWh)	-0.01***	-0.00***	-0.01***	-0.02***	-0.02***	-0.02**	-0.02***	-0.13***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.01)	(0.01)	(0.02)
Solar generation (GWh)	-0.02***	-0.00	-0.01***	0.02***	-0.00	-0.01	0.04***	0.00
	(0.00)	(0.00)	(0.00)	(0.00)	(0.01)	(0.02)	(0.01)	(0.04)
Demand (GWh)	0.02***	0.00***	0.01***	0.04***	0.01***	0.02***	0.07***	0.24***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.01)	(0.01)	(0.02)
Observations	34,872	8,714	17,436	8,721	5,236	1,739	1,399	345
R-squared	0.38	0.50	0.35	0.40	0.33	0.30	0.40	0.79

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

Table A.10: Marginal Fuel oil effect with heterogeneity by residual demand

VARIABLES	(1) All	(2) < 25th %	(3) 25-75th %	(4) > 75th %	(5) 75-90th %	(6) 90-95th %	(7) 95-99th %	(8) >99th %
Wind generation (GWh)	-0.47***	-0.05***	-0.09***	-0.08***	-0.09***	-0.10***	-0.05***	-0.07***
	(0.02)	(0.00)	(0.00)	(0.00)	(0.00)	(0.01)	(0.01)	(0.01)
Solar generation (GWh)	-0.60***	-0.06***	-0.04***	0.08***	0.09***	0.12***	-0.02	-0.10***
	(0.08)	(0.01)	(0.01)	(0.02)	(0.03)	(0.04)	(0.02)	(0.02)
Demand (GWh)	0.46***	0.04***	0.06***	0.06***	0.06***	0.07***	0.05***	0.02***
	(0.01)	(0.01)	(0.00)	(0.00)	(0.00)	(0.01)	(0.01)	(0.01)
Observations	34,872	8,714	17,436	8,721	5,236	1,739	1,399	345
R-squared	0.92	0.45	0.45	0.49	0.42	0.41	0.46	0.64

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

Table A.11: Marginal Coal effect with heterogeneity by residual demand

1.8.1 Marginal effect of RES or demand error and intermittency on conventional energy

VARIABLES	(1) All	(2) < 25th %	(3) <25-75th %	(4) > 75th %
Wind forecast in previous hour (GWh)	-0.49***	-0.81***	-0.56***	-0.24***
	(0.02)	(0.03)	(0.01)	(0.01)
Wind forecast hourly change (GWh)	-0.51***	-0.73***	-0.40***	-0.32*
	(0.10)	(0.20)	(0.11)	(0.16)
Wind error in previous hour (GWh)	-0.44***	-0.54***	-0.46***	-0.44***
	(0.02)	(0.03)	(0.02)	(0.01)
Wind error hourly change (GWh)	-0.38***	-0.45***	-0.31**	-0.29*
	(0.11)	(0.15)	(0.14)	(0.14)
Solar forecast in previous hour (GWh)	-0.57***	-1.02***	-0.46***	-0.23**
	(0.06)	(0.10)	(0.06)	(0.08)
Solar forecast hourly change (GWh)	-1.66***	-1.52***	-1.47***	-1.04***
	(0.25)	(0.37)	(0.24)	(0.18)
Solar error in previous hour (GWh)	-0.55***	-0.75***	-0.49***	-0.38***
	(0.08)	(0.08)	(0.08)	(0.06)
Solar error hourly change (GWh)	-0.59**	-0.71**	-0.30	-0.78**
	(0.28)	(0.30)	(0.23)	(0.36)
Demand forecast in previous hour (GWh)	0.47***	0.76***	0.52***	0.37***
	(0.01)	(0.02)	(0.01)	(0.00)
Demand forecast hourly change (GWh)	0.34***	0.78***	0.38***	0.24***
	(0.04)	(0.08)	(0.04)	(0.04)
Demand error in previous hour (GWh)	0.48***	0.72***	0.53***	0.37***
	(0.01)	(0.07)	(0.01)	(0.01)
Demand error hourly change (GWh)	0.23***	0.64**	0.31***	0.11
	(0.07)	(0.26)	(0.05)	(0.08)
Observations	34,872	8,714	17,436	8,717
R-squared	0.92	0.62	0.81	0.81

Table A.12: Full decomposition of marginal conventional energy impact on RES and demand

1.9. Daily (9am – 5pm) Marginal effect of RES and demand on price with heterogeneity by residual demand

VARIABLES	(1) All	(2) < 25th %	(3) 25-75th %	(4) > 75th %
Wind forecast in previous hour (GWh)	-2.10***	-2.03***	-2.17***	-1.93***
	(0.10)	(0.06)	(0.04)	(0.25)
Wind forecast hourly change (GWh)	-1.77**	1.31*	-1.99***	-1.98
	(0.69)	(0.66)	(0.53)	(1.66)
Wind error in previous hour (GWh)	-1.80***	-1.50***	-1.73***	-2.27***
	(0.07)	(0.07)	(0.03)	(0.18)
Wind error hourly change (GWh)	-0.15	0.90	-0.37	0.56
	(0.52)	(0.63)	(0.41)	(1.32)
Solar forecast in previous hour (GWh)	-2.69***	-2.62***	-2.11***	-1.62
	(0.54)	(0.43)	(0.36)	(1.52)
Solar forecast hourly change (GWh)	-6.58***	-3.17*	-6.07***	-6.89
	(1.68)	(1.41)	(1.41)	(4.07)
Solar error in previous hour (GWh)	-0.11	-1.62***	-0.66***	1.50**
	(0.16)	(0.24)	(0.16)	(0.51)
Solar error hourly change (GWh)	-0.27	-1.85*	-0.85	0.36
	(0.80)	(0.85)	(0.78)	(2.48)
Demand forecast in previous hour (GWh)	1.77***	2.10***	1.55***	2.15***
	(0.03)	(0.14)	(0.05)	(0.12)
Demand forecast hourly change (GWh)	2.52***	2.05**	2.35***	3.53**
	(0.52)	(0.74)	(0.32)	(1.31)
Demand error in previous hour (GWh)	1.74***	0.44	1.42***	2.17***
	(0.03)	(0.42)	(0.08)	(0.10)
Demand error hourly change (GWh)	1.72	1.46	1.68**	1.80
	(1.05)	(1.49)	(0.73)	(2.10)
Observations	13,077	2,220	7,122	3,733
R-squared	0.67	0.69	0.67	0.55

Table A.13: Full decomposition of price marginal effect (9am – 5pm) with heterogeneity by residual demand