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Hourly Price Elasticity Pattern of Electricity Demand in the German Day-ahead Market

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Abstract

System security in electricity markets relies crucially on the interaction between demand and supply over time. However, research on electricity markets has been mainly focusing on the supply side arguing that demand is rather inelastic. Assuming perfectly inelastic demand might lead to delusive statements regarding the price formation in electricity markets. In this article we quantify the short-run price elasticity of electricity demand in the German day-ahead market and show that demand is adjusting to price movements in the short-run. We are able to solve the simultaneity problem of demand and supply for the German market by incorporating variable renewable electricity generation for the estimation of electricity prices in our econometric approach. We find a daily pattern for demand elasticity on the German day-ahead market where price-induced demand response occurs in early morning and late afternoon hours. Consequently, price elasticity is lowest at night times and during the day. Our measured price elasticity peaks at a value of approximately -0.006 implying that a one percent increase in price reduces demand by 0.006 percent.

Keywords: Electricity markets, Hourly price elasticity of demand, Empirical demand analysis

JEL classification: C26, L94, Q21, Q41

1. Introduction

The price elasticity of demand is important to understand the functioning of electricity markets. From an industrial organization perspective, there is a big difference between markets with a price inelastic demand compared to the markets showing rather elastic demand. In electricity markets this is especially important

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since there is an ongoing debate whether it is possible to match demand and supply at all times. An inelastic price elasticity of demand assumption would imply that the burden of balancing electricity consumption and generation at all times rests with the supply side.

The empirical literature estimating long-run and short-run price elasticity of demand in electricity markets is extensive. For the short-run, peer-reviewed studies have estimated the elasticity for different sectors and time intervals. Table 1 shows that estimates of price elasticity vary from -0.02 to -0.3 depending on the chosen approach, the country-specific data and the sector. Taylor et al. (2005), for instance, find that short-run elasticity ranges from -0.05 to -0.26 for the industrial sector in North Carolina by using annual data. He et al. (2011) confirm this finding whereas Bardazzi et al. (2014) measure a slightly higher elasticity in terms of magnitude for the Italian industry sector. For the residential sector, numerous studies have been performed as well (i.e. Ziramba (2008), Dergiades and Tsoulfidis (2008) and Hosoe and Akiyama (2009)). However, little attention has been devoted to the wholesale market. So far, this market has only been investigated by Genc (2014) and Lijesen (2007). Whereas Genc (2014) applies a bottom-up Cournot modeling framework, Lijesen (2007) uses a regression approach in order to quantify the price elasticity during peak hours. Genc and Lijesen conclude from their chosen approaches that the hourly price elasticity is rather small (-0.14 and -0.001). They argue that this low elasticity, measured on an hourly basis, is less likely to occur and hourly consumption shifts are in practice not easily performed.

In this article we extend the existing literature by studying the German electricity market while recognizing that demand elasticity can vary during the day. We observe that the past and ongoing debate on short-run elasticity focuses on average price elasticity for different sectors and to some degree neglects the importance of timing in electricity markets. Because the utility from electricity consumption varies throughout the day, the price level should follow a pattern reflecting this hourly utility of market participants. Finding this pattern helps to understand how markets participants respond to electricity prices. Using data on load, prices, wind generation, and prices for the German day-ahead market, we quantify the magnitude of the demand elasticity and describe the pattern for its variation throughout the day.

Furthermore, our estimated price elasticity of demand reflects the electricity market in a more generalized form, since we do not only account for a specific sector but measure the elasticity with respect to the consumption of all end consumers. We are able to determine the degree of demand flexibility within the day-ahead market by assuming demand functions to be different depending on the time of the day. In our estimations, we assume the utility of electricity consumption to be different throughout the day and varying on an hourly basis. Thereby, we can gain insights on the contribution of demand reactions to overall system

Source	Type of model	Type of data	Elasticity	Sector	Region
Garcia-Cerrutti (2000)	Dynamic random variables model	Annual	-0.79 to 0.01, mean -0.17	Residential	California
Al-Faris (2002)	Dynamic cointegration and Error Correction Model	Annual, 1970-1997	-0.04 / -0.18		Oman
Bjørner and Jensen (2002)	Log-linear fixed effects	Panel, 1983-1996	-0.44		
Boisvert et al. (2004)	Generalized Leontief		Peak: -0.05	TOU	
Holtedahl and Joutz (2004)	Cointegration and Error Correction Model	Annual, 1955-1996	-0.15	Residential	Taiwan
Reiss and White (2005)	Reduced form approach	Annual, 1993 and 1997	0 to -0.4	Residential	California
Taylor et al. (2005)	Generalized McFadden with nonlinear OLS and Seemingly Unrelated Regression	1994-2001	-0.26 to -0.05	Industry	Duke Energy, North Carolina
Bushnell and Mansur (2005)	lagged residential prices Error Correction Model	Annual, 1969-2000	-0.1 -0.263	Residential Residential	San Diego Australia
Bernstein et al. (2006)	dynamic demand model with lagged variables and fixed effects	Panel, 1977-2004	-0.24 to -0.21	Residential, Commercial	US
Rapanos and Polemis (2006)		1977-1999			Greece
Halicioglu (2007)	Bounds testing approach to cointegration within ARDL model	1965-1999	-0.31		Turkey
Lijesen (2007)	reduced form regression linear, loglinear	1968-2005	-0.0014 -0.0043	Wholesale	Netherlands
Dergiades and Tsoulfidis (2008)	Bounds testing approach to cointegration within ARDL model	1965-2006	-1.06	Residential	US
Ziramba (2008)	Bounds testing approach to cointegration within ARDL model	1978-2005	-0.02	Residential	South Africa
Hosoe and Akiyama (2009)	OLS/Translog cost function	1976-2006	0.09 to 0.3	Residential	Japan
He et al. (2011)	General equilibrium analysis	2007	-0.017 to -0.019, -0.293 to -0.311, -0.0624 to -0.0634	Industry, residential, agriculture	China
Bardazzi et al. (2014)	Two-stage translog model	Panel, 2000-2005	-0.561 to -0.299	Industry	Italy
Genc (2014)	Cournot competition model	Hourly 2007, 2008	-0.144 to -0.013 - 0.019 to -0.083	Wholesale	Ontario

Table 1: Literature review of estimated short-run elasticity

security. By using variable wind generation as an instrument variable, we apply a two-stage regression approach to solve the simultaneity problem of demand and supply.¹

Our results show that the short-run price elasticity of demand in the German day-ahead market is not perfectly inelastic. Even though our obtained short-run price elasticity of demand is generally low, consumers still react to price movements. We stress that a price elasticity of demand for the day-ahead market is not explicitly showing the contribution of each consumer group. However, measuring the price elasticity of demand can give a more meaningful understanding of the contribution of demand reactions to system security. Furthermore, the daily pattern of our estimate of price elasticity reveals some prominent peaks in the morning and evening, where the price elasticity of demand is highest. As expected, these hours show overall high price levels providing incentives to consumers for a reduction of their consumption. In the morning and evening hours, price elasticity varies between -0.004 and -0.006. Thus, we infer that demand reductions in these hours are to some extent beneficial for consumers. On the contrary, we measure a lower price elasticity of demand at night times and during the day. A lower elasticity indicates less willingness of consumers to adjust the consumption due to high or low electricity prices. This can be due to the fact that economic activity in general is higher during daytime. We also infer that demand may be shifted from peak hours (morning and late afternoon) to off-peak hours (night) where consumers make use of lower price levels.

The remainder of the paper is organized as follows. Section 2 deepens the understanding on the German market by thoroughly explaining the structure of the retail and wholesale market. Section 3 presents the applied econometric approach. Section 4 describes the data being used. It further presents and discusses the estimation results. Section 5 concludes.

2. Market Structure

In this article, we focus our analysis on the day-ahead auction of the EPEX Spot for Germany and shed light onto the level of price elasticity of demand for German electricity consumers with respect to the day-ahead price.² The day-ahead auction clears demand and supply one day before electricity is physically delivered and can be considered as the most important reference price for electricity just before electricity is generated and consumed. We therefore choose to measure the price elasticity of electricity demand with respect to the day-ahead price.

¹The approach is similar to Bönnte et al. (2015).

²For completeness, the day-ahead market comprises the German and Austrian region, but we only measure the elasticity with respect to German end user consumption.

However, before the day-ahead auction takes place, power market participants have already engaged in all kinds of contracts by bilateral trade, futures trading or over-the-counter (OTC) trading. Within the day-ahead auction market participants have the possibility to adjust their positions before electricity is generated and consumed on the next day. Since our analysis focuses on the day-ahead price it is crucial to understand two important aspects about the day-ahead auction. First, the traded volume at the EPEX Spot does not equal the total market demand of all end consumers of electricity. Second, the demand curve observed in the day-ahead market can not be related to the total demand curve of electricity consumers. The importance of these two aspects can be better understood by explaining the functioning of the day-ahead market.

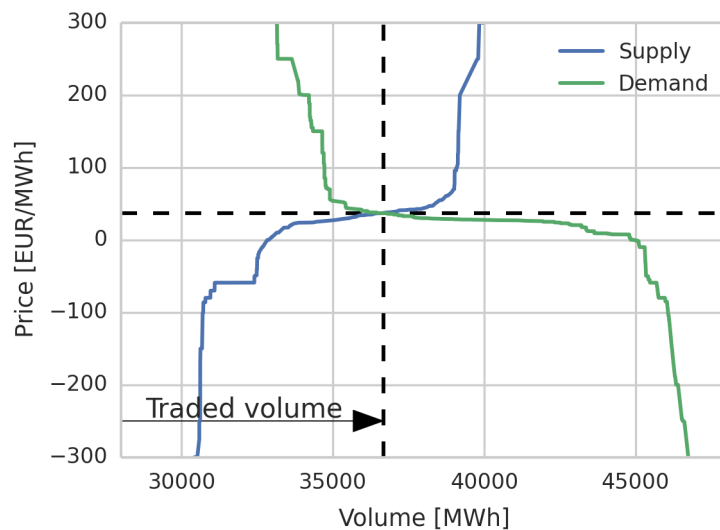


Figure 1: Supply and demand curves for one hourly product (14:00 - 15:00) on 07.05.2014 (EPEX Spot, 2015)

Since participants trading day-ahead volumes might have open positions prior to day-ahead trading or planned to generate the electricity by using their generation assets, we conclude that the day-ahead market serves primarily as a platform to adjust trading positions before the electricity is actually generated and delivered. Figure 1 presents an exemplary hour with realized day-ahead market demand and supply curves from the EPEX Spot.

At first glance it seems that demand of participants in the day-ahead auction is very price elastic, since it inhibits an almost horizontal line at a price of 36 EUR/MWh. This interesting observation can be misleading because it leads to the conclusion that end consumers are very price elastic with respect to demand. However, the day-ahead demand curve in Figure 1 only represents the trading of positions by

participants and therefore the seemingly flexible demand does not come as a surprise. To sum up, we observe in the day-ahead auction trading between generators, retailers and large consumers that act on the supply and demand side (von Roon et al., 2015). In order to disentangle these effects, it is worth mentioning how these bids and offers emerge. Offers on the supply side are submitted by

- generators not having sold their generation capacity and trying to sell their generation
- retailers and large consumers that have a long position (from OTC or future trading) and try to sell their excess electricity

Participants demanding electricity are

- generators having sold their production but are seeking to replace their generation
- retailers and large consumers that have a short position and seek to satisfy their demand

From intuition one would suggest that only generators submit offers on the supply side. But because trading does not start with the day-ahead market, offers and bids of generators can be found on both the supply and demand side (Stigler and Bachhiesl, 2015). This becomes even clearer, when we take a look at Figure 1 and divide the submitted bids into bids submitted below and above the market clearing price. Below the market clearing price are bids of generators that are going to produce electricity. On the supply side, these are generators that have successfully offered their spare generation capacity for sale. On the demand side, these are generators that tried to acquire electricity at lower costs compared to their own generation costs in the day-ahead market, but were not successful. Because they could not buy the electricity in the day-ahead market, these generators will be generating electricity with their own assets. This means all bids that have been submitted below the market clearing price (on the demand and supply side) belong to generators who will generate electricity in the respective hour. Thus, the traded volume in the day-ahead market only reflects the volume of positions that has been successfully traded by a part of participants who will be generating electricity. It does not reflect the total amount that will be generated and consumed in the respective hour.

By drawing the connection between the demand of the whole electricity market and the day-ahead price, we are able to estimate the price elasticity of demand of all electricity consumers with respect to the day-ahead price.

In our analysis we measure the effect of the day-ahead price on the overall electricity demand for all consumers in Germany. While we can use the price in the day-ahead market as an important variable for

our analysis, the volume of the day-ahead market does not reflect the total electricity demand of all end consumers. This demand can only be observed by taking additional sources into account, such as grid load which is published by transmission system operators.

3. Theoretical Framework

3.1. Demand and Supply in Electricity Markets

In order to specify our econometric model, knowledge about the supply and demand functions in electricity markets is pivotal. In a first step, we focus on the components of these functions to facilitate a general understanding of the causal relationships. We then construct an econometric model in Section 3.2 that incorporates all important demand and supply factors necessary for the estimation.

The demand for quantities (i.e. electricity) can be regarded as a function of various inputs. The relation can be written as

$$q_{el} = f(p_{el}, HDD, time-of-the-day) \quad (1)$$

, where q_{el} is the quantity consumed, p_{el} is the price for electricity, HDD are heating degree days capturing the seasonality within the data. To determine the heating degree days we use outside temperature data. The obtainable temperature variations translate into the need for heating, measured in HDD ; if outside temperature is low, heating processes consume more electricity compared to warmer weather conditions.³ Furthermore, temperature has an effect on consumer habits, such that higher temperature levels affect outside activities in a positive manner (Bessec and Fouquau, 2008).

Furthermore, electricity consumption depends on the time of usage. This is mainly driven by the shape of the consumer's utility function over the day. During the day, utility of electricity consumption is assumed to be highest, since economic activity is highest when e.g. industrial and commercial processes are running and electric appliances in offices are active. At night, consumption drops since utilization rates of production processes as well as household consumption decrease. Both effects translate into different electricity consumption patterns over the day. In Germany, the pattern commonly shows demand peaks in the morning when activity in households and industry increases. Throughout the day the consumption levels tend to remain on a high level which is mainly driven by industrial demand and usage of electrical appliances at work. In the early evening hours, the combined consumption pattern shows a second peak when people return home and start using electrical appliances while many industrial processes may also still be active.

³The data in Section 4 reveals that this relation is true for Germany, however it may not be applicable to other countries.

There are also additional variables determining the level of demand, such as economic activity. But most of these variables hardly vary on an hourly or day-to-day basis and are not directly observable. Therefore we abstract from including additional variables for the demand side.

The supply of quantities (i.e. electricity) can also be regarded as a function of multiple inputs:

$$s_{el} = f(p_{el}, p_{fuel}, r) \quad (2)$$

, where s_{el} is the quantity produced, p_{fuel} is a vector of fuel prices and r is the production of variable renewable energy.

In electricity markets, the structure of the supply side is commonly represented by the merit order curve. It represents the marginal generation costs of all conventional (fossil) power plants. The shape of the curve mainly depends on the technologies being used for power generation and their respective fuel prices p_{fuel} .⁴

However, variable renewable energy generation is becoming more and more important to the overall market in recent years. Since renewable energy technologies do not rely on fossil fuel inputs to generate electricity, their fuel costs are close to be zero. What is unique about the generation from variable renewable energies is its stochastic nature that is driven by wind speeds and solar radiation. By using wind generation as instrument variable in Section 3.2, we account for volatile time and weather-dependent wind generation that helps us to capture price movements in our estimation.

3.2. Econometric Approach

Prior to estimating the price elasticity of demand, we expand on factors affecting demand or supply on electricity markets. The chosen factors are essential for specifying the econometric model. Influential factors with their directional influences on demand and supply are depicted in Figure 2.

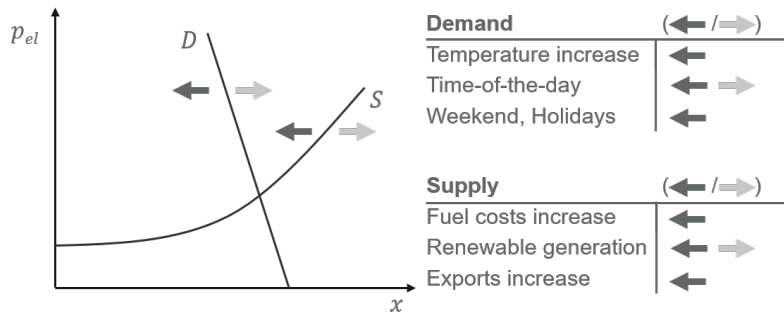


Figure 2: Factors influencing demand and supply on electricity markets

⁴Common power plant types and fuels are hydro power, nuclear, lignite, coal, gas and oil.

It is 'commonly' assumed that temperature increases lead to demand decreases within the temperate zone.⁵ Whereas week-ends and holidays reduce electricity demand due to lower demand of the industry and partially of households, the time of the day, can have both a demand-reducing or increasing effect.⁶

On the supply side, increasing fossil fuel costs have an increasing price effect (c.f. also Figure 2). As a consequence conventional power plants will be less likely to supply the electricity market with high volumes. Furthermore, generation of fluctuating variable renewables shifts the supply curve to the right, as the generation takes place at zero short-run marginal costs. When electricity is exported, production exceeded demand and thus the supply curve is shifted to the left.

In our paper, we account for factors shifting supply and demand by applying a two-stage regression approach to hourly data. Due to the fact that the electricity price is determined by demand and supply and therefore endogenously⁷ specified within the market, we use hourly expected wind generation as a variable to proxy electricity prices in the first stage.⁸ Wind generation as a variable fulfills the two conditions (1) $cov[w, p_{el}] \neq 0$ and (2) $cov[w, \mu] = 0$, where w is wind generation, p_{el} the electricity price and μ the error term.

The first condition is needed in order to provide unbiased electricity price estimates. In our context the chosen instrument w correlates with the electricity price (c.f. Figure 4b). From the second condition it follows that w and μ are not correlated. Because wind can be regarded as a stochastic variable especially throughout the day and load inhibits strong daily patterns, both can be regarded as independent (c.f. Figure 4a). With these two conditions fulfilled we are now able to postulate the first and second stage equations. The first stage can be written as

$$p_{h,t}^{el} = \gamma_{0,h} + \gamma_{1,h} \cdot w_{h,t} + \epsilon_{h,t} \quad (3)$$

and the second stage as

$$q_{h,t}^{el} = \beta_{0,h} + \beta_{1,h} \cdot p_{h,t}^{el} + \beta_2 \cdot HDD_t + \beta_3 \cdot MON_t + \beta_4 \cdot FRI_t + \mu_{h,t}. \quad (4)$$

We estimate price coefficients $\beta_{1,h}$ and dummy coefficients $\beta_{0,h}$ on an hourly basis h . We do this, because

⁵Especially in rather cold climates, such as Germany. In southern European countries the effect will be different due to higher outside temperatures and therefore higher air conditioning usage.

⁶As explained in more detail in section 3.1.

⁷Durbin and Wu-Hausman test statistics show highly significant p-values. The null hypothesis tests for all variables in scope being exogenous. With p-values for both test of both equal to 0,000 we reject the null of exogeneity implying that prices and demand are endogenous.

⁸Solar radiation is intentionally left out as an additional variable since its correlation to demand is comparatively high leading to a potential bias in our results. The correlation can be explained since demand is usually high around middle day when the sun is likely to shine.

we expect the utility of electricity consumption to be different in each hour of the day. Here, $\beta_{0,h}$ captures the price independent change of utility from electricity consumption throughout the day. Since we expect a different demand pattern for working days and week-ends, we eliminate week-ends and holidays from the data. Furthermore, we add dummies for Monday (MON) and Friday (FRI)⁹ to capture noise at the beginning of the week and as well as before the week-end.

4. Empirical Application

4.1. Data

Our data set consists of hourly data for 2015. We include hourly data for load, day-ahead-prices and the forecast of production from variable renewables for Germany. In addition, HDD are calculated based on hourly temperatures that we obtain from the NASA Goddard Institute for Space Studies (GISS). Summary statistics are provided in Table 2. The empirical analysis focuses on the estimation of the variation of price elasticity throughout the day on an hourly basis.

Variable	Mean	Std. Dev.	Min.	Max.	Source
Load [MWh]	61688	9428	38926	77496	ENTSO-E
Wind Generation [MWh]	8574	6864	153	32529	EEX Transparency
Day-ahead price [EUR/MWh]	35.6	11.5	-41.74	99.77	EPEX Spot
Temperature [°C]	10.4	7.9	-6.3	34.6	NASA MERRA
Heating degree days [K]	10.1	6.9	0	26.3	NASA MERRA

Table 2: Descriptive statistics (for weekdays, without public holidays and Christmas time)

The hourly load profile for Germany was taken from ENTSO-E. According to ENTSO-E, load is the power consumed by the network including network losses but excluding consumption of pumped storage and generating auxiliaries.¹⁰ The load data includes all energy that is sold by German power plants to consumers.¹¹ Load therefore is the best indicator on the level of demand in the German market area since almost all energy sold has to be transferred through the grid to consumers. Figure 3a shows average hourly values for weekdays in the German market area in a box plot. The plot shows significant differences in the level for night hours (00:00-6:00, 19:00-00:00) compared to daytime. Also load peaks in the morning (9:00-12:00) and evening hours (16:00-18:00). Especially in the evening, variation in load levels is higher

⁹For Mondays the dummy is positive for the time between 0:00 and 9:00. For Fridays the time frame is from 17:00 to 23:00.

¹⁰ENTSO-E collects the information from the four German transmission system operators (TSO) and claims that the data covers at least 91% of the total supply. These quantities may also be reflected in the day-ahead price which we can not account for.

¹¹To a small amount load may also include energy that is sold from neighboring countries to the German market. These trade flows impact the domestic electricity price and load. However, we expect this impact to be rather small.

than at other times. The average load level is 62 GW and the maximum peak load is 77 GW in the early evening hours.

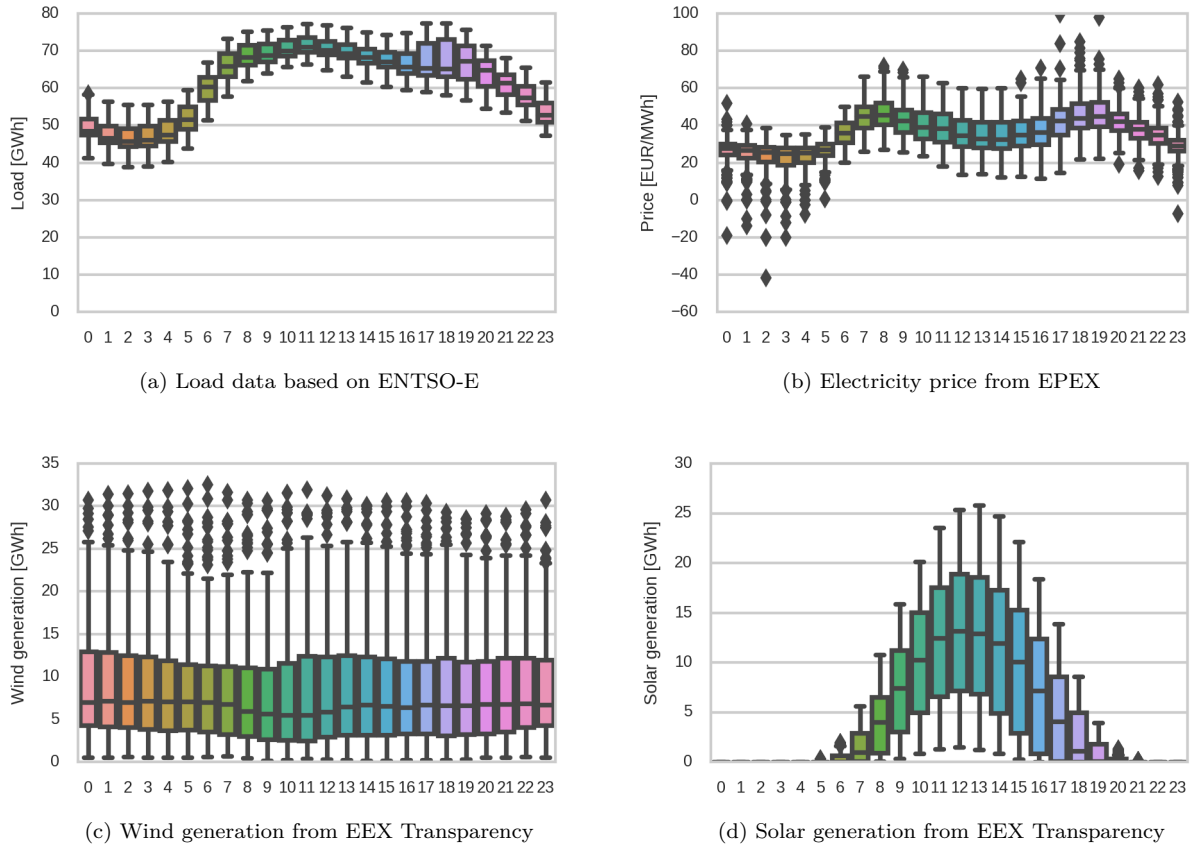


Figure 3: Averaged hourly wind generation data from EEX Transparency for 2015

We obtain the hourly price for electricity from the European Power Exchange (EPEX) which is the trading platform for Germany. Although not all electricity is sold through the day-ahead-auction, the price reflects the value of electricity in the respective hours and contains all available information on demand and supply at that specific point in time (cf. Section 2). Figure 3b shows a box plot for the hourly electricity price for each hour of the day. The average hourly electricity price is at 36 Euro per MWh over the 24 hours time interval and for weekdays (without public holidays and Christmas time). The electricity price pattern is similar to the load pattern emphasizing the fact that higher demand levels tend to increase prices in the day-ahead market. Especially during peak times in the morning and evening one can observe higher standard deviations and peaking prices. Standard deviation over all hours is around 12 Euro per MWh.

Electricity generation from wind and solar power is taken from forecasts published on the transparency

platform by the European Energy Exchange (EEX). These forecasts result from multiple TSO data submissions to the EEX. Since they are submitted one day before physical delivery, they contain all information that is relevant for participants in the day-ahead market.¹² Figure 3c and 3d show box plots for electricity generation from wind and solar power. Due to weather dependent generation volatility, we observe a larger amount of volatility in the hourly data. Wind generation varies steadily throughout the day with a small increase during the day. Solar generation shows its typical daily pattern with no generation at night and peak generation values for midday.

The level of demand does not only depend on the electricity price which in return is partially influenced by generation from wind. We add weather as an additional parameter to our investigation of electricity demand. In particular, the level of temperature is a main driver for the seasonal variation of demand. We compute a Germany wide average temperature based on the reanalysis MERRA dataset provided by NASA (NASA, 2016). The hourly values are then averaged in order to obtain a consistent value for Germany. Based on the averaged hourly temperature we derive HDD, that are relevant for the seasonal variation of demand in electricity markets.¹³ This accounts for the seasonal variation in demand over the year.

We also considered including fuel and CO₂ costs as the major generation costs for electricity generation but since the variation in costs is small over the year 2015, we exclude them from a further analysis.

Furthermore, Figure 4 depicts the data and the respective correlations for each hour interval of the day. In Figure 4a, the correlations between solar generation, wind generation and load are depicted. We observe that the correlation between solar generation and load is higher in absolute values than the correlation between wind generation and load. However, wind and solar generation are correlated opposite in sign with load being positively correlated with wind generation and solar generation negatively correlated with load. With regard to the instrumental variable method, we apply, it is important to stress that the correlation between wind generation and load is low.

Figure 4b shows the correlation between wind generation and electricity price as well as the correlation between solar generation and electricity price. Both, wind and solar generation are negatively correlated with the electricity price, however their patterns are different throughout the day. The correlation between wind generation and electricity price weakens over the day until 17:00 where the correlation is lowest with an absolute value of -0.45. From 17:00 on the correlation between wind generation and price increases again. The pattern for the correlation between solar generation and electricity price is reversed whereas the

¹²We also considered taking the actual generation from renewables but reckon that the ex-ante forecasts are reflecting the causal relationship in a better way since decisions made on the day-ahead market are based on forecast values.

¹³We calculate HDDs based on a reference temperature of 20 °C.

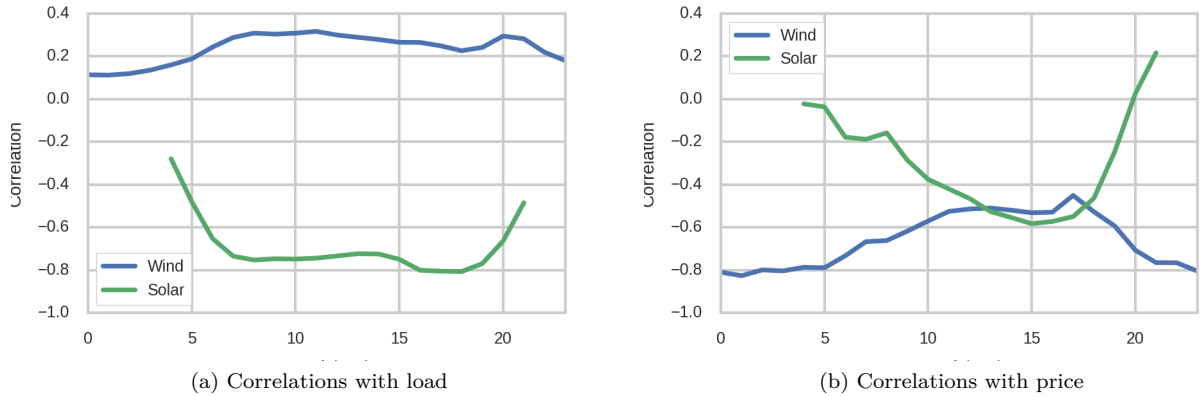


Figure 4: Correlations with load and prices in 2015

increasing correlation until 17:00 is mainly driven by an increasing solar radiation.

4.2. Estimation results

By applying the econometric framework, we are able to estimate the level of price elasticity of demand for the German day-ahead market on an hourly basis.

The results of the estimation can be found in Table 3. When taking a look at the price coefficients in Table 3a, we can see that all price coefficients are negative in sign and are significant at least at the 1% level. We note that coefficients during morning hours (9:00-12:00) are less significant and lower in absolute values. The hourly dummy coefficients capture the varying level of utility throughout the day. During the day, hourly coefficients are higher than at other times. In the evening, we can observe a peak in the level of utility, especially between 16:00 - 20:00 (c.f. Figure 5). Beside the hourly coefficients, we also account for the influence of temperature and weekdays on electricity demand. All coefficients are significant at the 0.1% level and can be explained in their sign. HDD have a positive sign and thus increase electricity demand. Mondays and Fridays are negative in sign, indicating that demand is generally lower at the start of the week and at the end than at other working days.

Since the focus of our work is on the hourly price elasticity of demand, we estimate the elasticity based on the results from the basic regression. The results are displayed in Figure 6 and the numerical values can be found in Table 4.

As observed before, all coefficients are negative in sign and significant at a strict 1% level. With the elasticity estimates at hand, we are able to plot a distinctive pattern for the hourly price elasticity of demand for the German day-ahead market. The unique shape of the hourly price elasticity of demand pattern is depicted below in Figure 6.

Hour	Price	Dummy
0	-0.0526*** (-4.02)	.
1	-0.0533*** (-4.21)	-0.0349** (-2.74)
2	-0.0489*** (-4.27)	-0.0565*** (-4.69)
3	-0.0600*** (-4.92)	-0.0463*** (-3.81)
4	-0.0718*** (-5.60)	-0.0138 (-1.10)
5	-0.8380*** (-5.88)	0.0630*** (4.53)
6	-0.0911*** (-4.84)	0.2282*** (11.00)
7	-0.0854*** (4.28)	0.3513*** (13.44)
8	-0.056*** (-3.58)	0.3700*** (17.07)
9	-0.0366** (-2.97)	0.3505*** (20.64)
10	-0.0360** (-2.75)	0.3725*** (22.07)
11	-0.0421** (-2.90)	0.3984*** (22.29)
12	-0.0472** (-2.95)	0.3885*** (21.56)
13	-0.0578** (-3.16)	0.3830*** (19.61)
14	-0.0679*** (-3.40)	0.3684*** (17.79)
15	-0.0822*** (-3.76)	0.3632*** (15.71)
16	-0.1073*** (-3.60)	0.3710*** (11.52)
17	-0.1407** (-2.96)	0.4317*** (7.46)
18	-0.0951** (-2.81)	0.3923*** (8.81)
19	-0.0832*** (-3.34)	0.3650*** (10.91)
20	-0.0910*** (-4.81)	0.3146*** (13.39)
21	-0.0694*** (-5.14)	0.2315*** (14.00)
22	-0.0583*** (-4.58)	0.1605*** (10.56)
23	-0.0545*** (-4.12)	0.0709*** (5.09)

(a) Dummy and price coefficients

	Coefficient
Heating degree days	0.0800*** (70.03)
Monday dummy	-0.0519*** (-25.10)
Friday dummy	-0.0335*** (-11.18)
Constant	0.7539*** (78.95)
Observations	5856
R^2	0.911
Adjusted R^2	0.910

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

(b) Regression coefficients

Table 3: Regression results

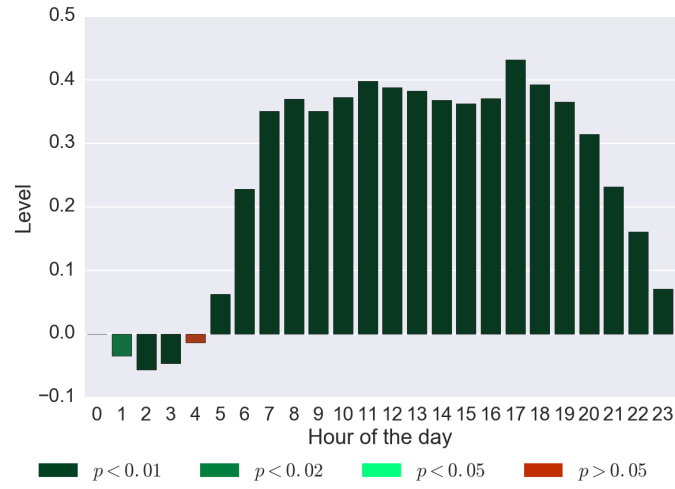


Figure 5: Hourly dummies for the electricity demand for Germany

Hour	Elasticity
0	-0.0021*** (-3.99)
1	-0.0020*** (-4.17)
2	-0.0018*** (-4.23)
3	-0.0021*** (-4.88)
4	-0.0025*** (-5.55)
5	-0.0031*** (-5.83)
6	-0.0040*** (-4.80)
7	-0.0042*** (-4.25)
8	-0.0027*** (-3.56)
9	-0.0016** (-2.96)
10	-0.0015** (-2.74)
11	-0.0017** (-2.88)
12	-0.0017** (-2.94)
13	-0.0021** (-3.14)
14	-0.0025*** (-3.37)
15	-0.0031*** (-3.72)
16	-0.0043*** (-3.57)
17	-0.0064** (-2.93)
18	-0.0047** (-2.79)
19	-0.0042*** (-3.31)
20	-0.0043*** (-4.77)
21	-0.0031*** (-5.10)
22	-0.0026*** (-4.54)
23	-0.0022*** (-4.09)

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 4: Hourly price elasticity of electricity demand for Germany

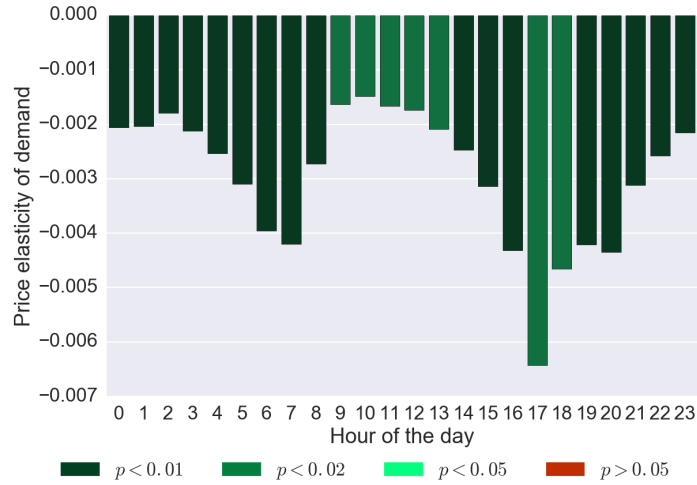


Figure 6: Hourly price elasticity of electricity demand for Germany

The elasticity is the lowest during night times (22:00 - 6:00). During these hours electricity demand and utility from electricity consumption is generally lower (as we can also observe from Table 3a). The graph shows two prominent peaks of price elasticity of demand in the morning and in the evening. At these times working hours start and end. Possible reasons for a high elasticity of demand at those times is the shifting or delaying of consumption. When prices are low in the morning, some processes may be able to start the operation earlier and thereby circumventing a time with a higher electricity price level. The same might be true for the evening, when the workday ends. Here working hours may be extended to lower price levels at other times. Throughout the day, the price elasticity of demand remains relatively low and is less significant. At those hours, economic activity is high and the option to shift or delay electricity consumption might not be feasible for consumers. In other words, consumers are bound to consume electricity which results in high electricity consumption regardless of the price level.

5. Conclusion

Using data on German load, price, generation of wind and temperature, we estimate the hourly pattern of price elasticity of demand for the German day-ahead market. By doing this, we are able to determine the degree of short-run flexibility within this market. To the best of our knowledge, a market-wide hourly analysis of the price elasticity of demand has not been conducted so far. Based on our two-stage regression approach which uses wind generation as an instrument to proxy the electricity price, we find that hourly price elasticity of demand is elastic, especially during the morning and evening. Values for price elasticity range from approximately -0.002 to -0.006 depending on the investigated hour. The hourly price elasticity pattern

reveals that elasticity is lowest in the night hours and around mid day. Low values for price elasticity during night time (22:00 - 06:00) indicate that consumers are less likely to react to price increases with demand decreases. We argue that this is the case since some industrial demand has already been shifted to off-peak hours with lower price levels. Low values for price elasticity around middle day may however be explained by high economic activity. The inherent need for electricity on both, the industrial and household side, trigger high consumption levels that usually come with high electricity price levels not allowing consumers to shift their demand in these peak demand hours. Price elasticity of demand is the highest in the early morning (06:00 - 08:00) and late afternoon (16:00 - 20:00) hours, with levels between -0.004 and -0.006 (approximated).

The empirical results indicate a high level of variation of price elasticity of demand throughout the day in the German day-ahead market. However, the magnitude of demand shifting has to be put into perspective. Although the hourly elasticity is low from a first glance, hourly elasticities and therefore load shifting accumulates over the year. The found elasticity pattern helps to understand when demand shifting occurs, which we link to the consumer's time dependent utility functions. We find that especially during peak times in the morning and evening, price elasticity of demand is highest and may contribute to a secure electricity system by decreasing demand in critical situations, when, for instance, electricity prices are high.

We further observe that not only in the German electricity market the deployment of fluctuating renewable energies is growing. Our research sheds some light on how flexible the German electricity market has already been in the past, given the underlying renewable generation of the German day-ahead market. It may also give policy makers a starting point for evaluating the short term flexibility of the German electricity market and the need of capacity markets. Future demand flexibility should therefore be re-assessed to improve the political decision making process regarding electricity markets. In addition to the analysis of the day-ahead market, we reckon that further research on flexibility should focus on the interaction of the day-ahead, intraday and balancing power markets to complement our analysis. Whereas this additional research on the interaction of linked markets adds further insights on the flexibility of demand reactions, we argue that at least in the short run, the day-ahead market remains the most important market where demand and supply are balanced out.

Literature

- Al-Faris, A. R. F. (2002). The demand for electricity in the GCC countries. *Energy Policy*, 30(2):117–124.
- Bardazzi, R., Oropallo, F., and Paziienza, M. G. (2014). Do manufacturing firms react to energy prices? Evidence from Italy. Technical report, Università degli Studi di Firenze, Dipartimento di Scienze per l'Economia e l'Impresa.
- Bernstein, M. A., Griffin, J. M., and Infrastructure, S. (2006). *Regional differences in the price-elasticity of demand for energy*. National Renewable Energy Laboratory.
- Bessec, M. and Fouquau, J. (2008). The non-linear link between electricity consumption and temperature in Europe: A threshold panel approach. *Energy Economics*, 30:2705–2721.
- Bjørner, T. B. and Jensen, H. H. (2002). Energy taxes, voluntary agreements and investment subsidies—a micro-panel analysis of the effect on Danish industrial companies' energy demand. *Resource and Energy Economics*, 24(3):229–249.
- Boisvert, R., Cappers, P., Neenan, B., and Scott, B. (2004). Industrial and commercial customer response to real time electricity prices. *December*, available online at <http://eetd.lbl.gov/ea/EMS/drlm-pubs.html>.
- Bönte, W., Nielen, S., Valitov, N., and Engelmeyer, T. (2015). Price elasticity of demand in the epeX spot market for electricity—new empirical evidence. *Economics Letters*, 135:5–8.
- Bushnell, J. B. and Mansur, E. T. (2005). Consumption Under Noisy Price Signals: A Study of Electricity Retail Rate Deregulation in San Diego*. *The Journal of Industrial Economics*, 53(4):493–513.
- Dergiades, T. and Tsoulfidis, L. (2008). Estimating residential demand for electricity in the United States, 1965–2006. *Energy Economics*, 30(5):2722–2730.
- EPEX Spot (2015). European power exchange.
- Garcia-Cerrutti, L. M. (2000). Estimating elasticities of residential energy demand from panel county data using dynamic random variables models with heteroskedastic and correlated error terms. *Resource and Energy Economics*, 22(4):355–366.
- Genc, T. (2014). Market Power Indices and Wholesale Price Elasticity of Electricity Demand. Technical report.
- Halicioglu, F. (2007). Residential electricity demand dynamics in Turkey. *Energy Economics*, 29(2):199–210.
- He, Y., Yang, L., He, H., Luo, T., and Wang, Y. (2011). Electricity demand price elasticity in China based on computable general equilibrium model analysis. *Energy*, 36(2):1115–1123.
- Holtedahl, P. and Joutz, F. L. (2004). Residential electricity demand in Taiwan. *Energy Economics*, 26(2):201–224.
- Hosoe, N. and Akiyama, S.-i. (2009). Regional electric power demand elasticities of Japan's industrial and commercial sectors. *Energy Policy*, 37(11):4313–4319.
- Lijesen, M. G. (2007). The real-time price elasticity of electricity. *Energy Economics*, 29(2):249–258.
- NASA (2016). GMAO MERRA: Modern Era Retrospective-Analysis for Research and Applications. <http://gmao.gsfc.nasa.gov/merra/>.
- Rapanos, V. T. and Polemis, M. L. (2006). The structure of residential energy demand in Greece. *Energy Policy*, 34(17):3137–3143.
- Reiss, P. C. and White, M. W. (2005). Household Electricity Demand, Revisited. *The Review of Economic Studies*, 72(3):853–883.
- Stigler, H. and Bachhiesl, U. (2015). Zur ökonomischen fundierung des energy-only-marktes. *9. Internationale Energiewirtschaftstagung an der TU Wien*.
- Taylor, T. N., Schwarz, P. M., and Cochell, J. E. (2005). 24/7 hourly response to electricity real-time pricing with up to eight summers of experience. *Journal of regulatory economics*, 27(3):235–262.
- von Roon, S., Eberl, B., and Hinterstocker, M. (2015). Limitierte gebote im day-ahead handel als maß für liquidität und preisauflschlag im intraday-markt. *9. Internationale Energiewirtschaftstagung an der TU Wien*.
- Ziramba, E. (2008). The demand for residential electricity in South Africa. *Energy Policy*, 36(9):3460–3466.