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The Merit Order Effect of Wind and Photovoltaic Electricity Generation in Germany 2008-2012

by

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Executive Summary

Generation from renewable energy sources in Germany has experienced a considerable uptake in recent years. Mainly responsible for this development is the German Renewable Energy Sources Act (Erneuerbare Energien Gesetz, EEG), which establishes priority feed-in, purchase guarantee and fixed prices. The costs of this law are passed on to electricity consumers in the form of a surcharge. These consumers are split into a privileged and a non-privileged group. Charges for non-privileged consumers have risen sharply recently, leading to a debate about a reform of the Act.

A reform should take into account the merit order effect caused by renewable energy sources. On a liberalized electricity market, the feed-in of electricity generated by renewable energy sources lowers the wholesale price, since they offer electricity at close to zero marginal costs.

We estimate the merit order effect of both wind and photovoltaic (PV) electricity generation in Germany between 2008 and 2012. Our results indicate that for each additional GWh of renewables fed into the grid, the price of electricity on the day-ahead market is reduced by 1.10 to 1.30 €/MWh. The total merit order effect of wind and PV ranges from 5 €/MWh in 2010 to more than 11 €/MWh in 2012.

Keywords: Renewable energy, merit order effect, German Renewable Energy Sources Act, privileged consumers, distributional effects

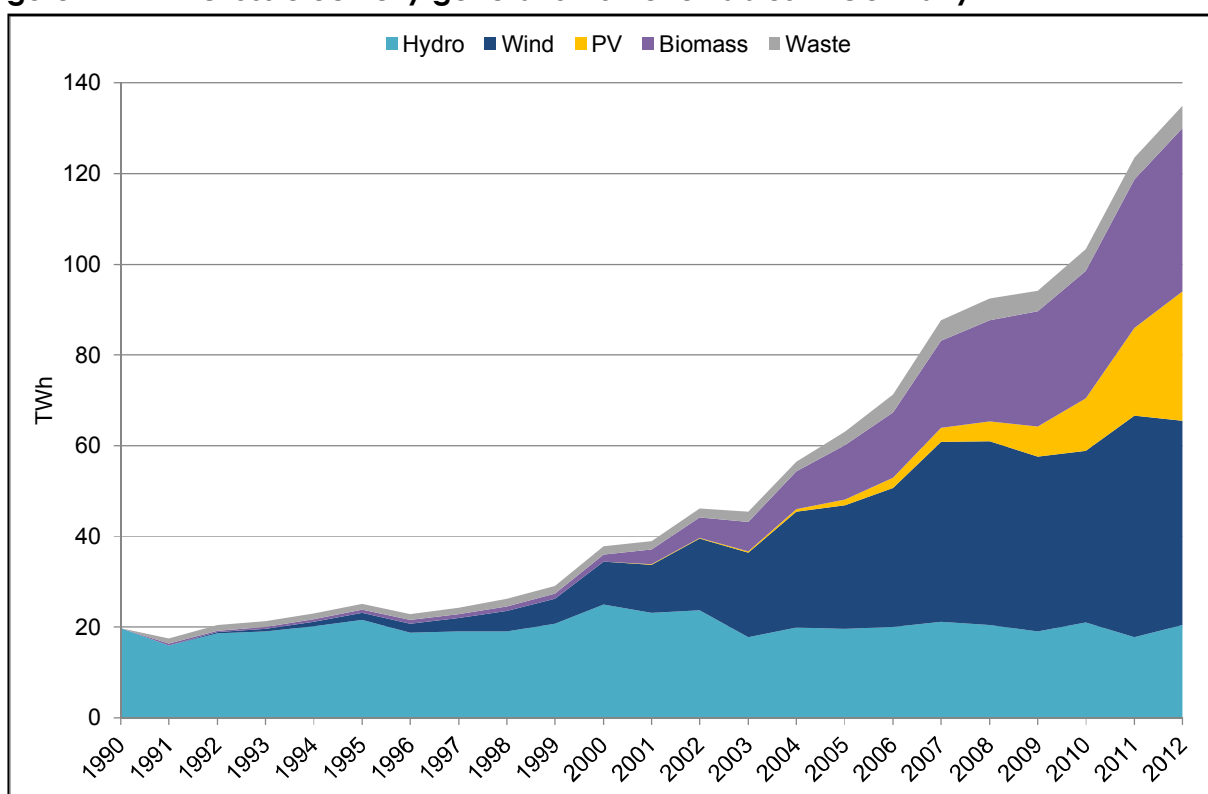
Contents

1	INTRODUCTION	5
2	PRICE DETERMINANTS ON THE GERMAN SPOT MARKET FOR ELECTRICITY	7
3	RECENT STUDIES OF THE MERIT ORDER EFFECT OF RENEWABLES	9
4	DATA	11
5	REGRESSION RESULTS	15
6	CONCLUSION	24
	REFERENCES	25
	DATA SOURCES	27
	APPENDIX	28

1 Introduction

Electricity generation from renewable energy sources in Germany has expanded rapidly over the past decades. Figure 1 shows that it rose from 20 TWh in 1990 to 135 TWh in 2012, of which wind provided 45 TWh and photovoltaics (PV) 29 TWh. Biomass was responsible for 36 TWh. One reason for this expansion is the key support instrument for renewables in Germany, the German Renewable Energy Sources Act (Erneuerbare Energien Gesetz, EEG). The EEG consists of priority feed-in, a purchase guarantee and a fixed feed-in tariff for electricity generated by renewable energy sources. The electricity from renewables fed into the grid via the EEG is mainly sold by network operators on the day-ahead (spot) market. The differential between the guaranteed price and the revenues achieved by renewables on the electricity market are paid for by power consumers.

Figure 1 Gross electricity generation of renewables in Germany



Source: AG Energiebilanzen 2013

To this end, power consumers are divided into privileged and non-privileged consumers. The privileged consumers mainly consist of energy intensive companies, who pay 0.05 ct/kWh for the EEG surcharge, while for non-privileged consumers (mainly households), the surcharge is calculated on a yearly basis based on the quantities of renewables fed into the grid, but also other parameters, such as revenues attainable on the spot market, the level of total final consumption, the scope of privileged consumers and forecasting errors of earlier years (see Öko-Institut 2012a for an analysis of the different components).

In October 2012 the transmission network operators published the surcharge for non-privileged consumers for 2013 at 5.23 ct/kWh, which is an increase of 1.68 ct/kWh on the surcharge of the previous year (3.59 ct/kWh) and considerably (100 times) higher than the surcharge for the privileged consumers. This led to discussions about the appropriateness of the privilege rules. On 28th of January 2013 environmental minister Peter Altmaier published his proposal for a reform of the EEG, which includes an increase of the surcharge for privileged consumers (BMU 2013).

Not least because renewables have a depressing effect on the wholesale price of electricity through the so-called merit order effect: The higher the feed-in of renewables, the lower the wholesale price (at least in the short run). Therefore, companies that buy electricity on the wholesale market (which is often the case) and are privileged under the EEG enjoy lower prices, which is likely to overcompensate for the amount they pay for the surcharge.

In this paper, we estimate the merit order effect of renewables in Germany between 2008 and 2012. Our analysis is based on a rich data set of hourly time series of spot market electricity prices and the corresponding feed-in of renewables and other energy sources for each hour. We apply regression analysis to model the specific merit order effect (per additional GWh of renewables) and the total merit order effects for each of the years between 2008 and 2012. We also explore merit order effects for different residual loads and derive implications for the future design of the EEG.

The paper is structured as follows. The next chapter describes how the price is determined on the German day-ahead (spot) electricity market and shows a stylized merit order curve. The following chapter reviews recent literature on the merit order effect. We discuss results and the merits and challenges of different modelling approaches. We then present the data in Chapter 4, conduct a first descriptive analysis and perform tests needed for the specification of our regression model. Chapter 5 presents regression results. We calculate the merit order effect of renewables, both on average and for individual years and provide some extensions, such as an approximation of the electricity price curve by modelling its slope at different residual loads. In the final chapter we discuss implications for a reform of the EEG.

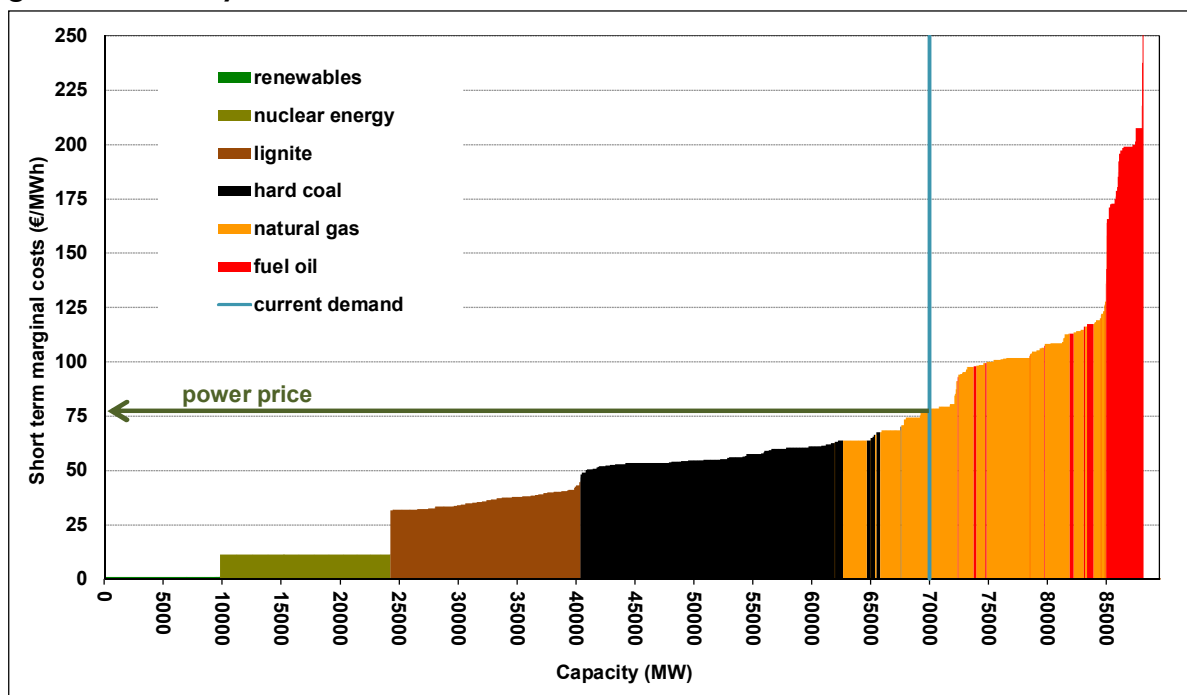
2 Price Determinants on the German Spot Market for Electricity

In liberalized power markets electricity prices and the deployment of power plants on the day-ahead (spot) market are determined on an exchange. The EPEX Spot, a merger of the German EEX and the French Powernext, is responsible for the electricity spot markets in Germany, Austria, France and Switzerland.

The electricity price on the spot market is determined by supply and demand. At 12 noon each day an auction each for the 24 hours of the following day takes place. Power producers offer their electricity at short-term marginal costs, which consist mainly of fuel costs and CO₂-costs. The offers are then lined up from lowest to highest resulting in the merit order curve. Figure 2 shows a stylized merit order curve for Germany. Renewables offer electricity at close to zero marginal costs, followed by nuclear energy, lignite, hard coal, gas and fuel oil plants.

The spot market price for each hour is then determined by the marginal plant that is needed to satisfy electricity demand in the respective hour. This price is then received by all power plants that serve the market during that hour. The difference between marginal costs and the electricity price is the profit for the plant owner. All power plants with marginal costs higher than the market price are not used for generation.

Figure 2 Stylized German merit order curve



Source: Öko-Institut 2013

As more renewable energy sources are added to the generation mix, the merit order curve is shifted to the right and lower prices on the day-ahead market result. Previous research has shown that the merit order effect of renewables is greater on the spot market than on the forward market (Öko-Institut 2012b). A close interaction between

the spot and the forward market exists. If this was not the case, arbitrage between the two markets would be possible (cf. Sensfuß 2011).

Since transmission lines exist between countries in Europe, the power demand on the German market is not only influenced by German demand, but also through imports and exports to and from neighbouring countries. Germany's electricity market forms one market zone with Austria and is linked automatically via market coupling organised by the power exchanges to France, the Netherlands, Denmark and Sweden.

Table 1 illustrates how large the price convergence of the German spot market with selected neighbouring markets already is. With the introduction of the Central Western European market coupling (including France) at the end of 2010 price convergence between the German and the French spot market increased from about 20% to 70% in 2011 and 64% in 2012. As a general trend it can be observed that price convergence is not yet as high with countries that have not yet introduced automatic market coupling with Germany (e.g. Poland and Switzerland).

Table 1 Price convergence of the German electricity spot market with selected neighbouring countries

Year	France	Switzerland	Denmark 1	Denmark 2	Norway 2	Poland
2008	10%	9%	7%	6%	4%	
2009	17%	12%	18%	16%	10%	12%
2010	25%	13%	64%	39%	25%	12%
2011	70%	15%	54%	59%	19%	12%
2012	64%	14%	40%	42%	14%	11%

Source: EPEX, NordpoolSpot, PolPX, own calculations

In essence, a common merit order curve for the linked markets exists, as long as prices are the same, i.e. enough transmission capacity is available. Since the electricity prices we use in this analysis already embody the effects of electricity imports and exports, we cannot isolate this effect. It could be expected that merit order effects are larger if the German market was taken in isolation. It would be an interesting endeavour to analyse the extent to which the merit order effect changes when import and export flows and transmission capacities are accounted for.

3 Recent Studies of the Merit Order Effect of Renewables

In their first monitoring report on the EEG (Renewable Energy Sources Act), the German Ministry for the Economy and the German Environmental Ministry give an overview of the results of studies carried out on the merit order effect in Germany to date (BMWi / BMU 2012, 40). The results range from 2 to 13 €/MWh and are generally higher in recent years, as more energy generated by renewable sources is fed into the grid.

Two broad methods to analyse the merit order effect of renewables have been employed. First, regression analysis of historical time series data and second, electricity market modelling. The former analyses historical price and generation data, while the latter compares different scenarios within an electricity market model.

There are merits and challenges concerning either of the methods. Using an electricity market model requires careful calibration and especially the definition of a reasonable counterfactual scenario. Regression analysis, on the other hand, can employ actual historical data and does not have to make assumptions about alternative developments. At the same time, only rather short-term merit order effects, based on the current electricity market and power generation structure are calculated. And issues such as the costs for new power plants or network development are not considered.

In their analysis of the merit order effect of renewables and cogeneration in Spain, Gelabert, Labandeira, and Linares (2011) use hourly data on electricity prices and the feed-in of renewables and other energy sources to determine the effect. They use daily average prices to reduce noise and run an OLS regression in first differences of the electricity price on renewables and other variables in different specifications. They conclude that an additional GWh of energy from renewables or cogeneration leads to a decrease in the spot electricity price of 1.9 €/MWh on average and note that the effect is greater for hours with high demand (as the merit order curve is steeper in those times).

Jónsson, Pinson, and Madsen (2010) have a slightly different focus, as they mainly want to model the spot price dynamics on the Danish electricity market. They use wind forecasts and employ non-parametric parameter estimates. They also find a significant price effect of wind, especially on the high demand end.

Von Roon and Huck (2010) analyse the effect of cogeneration and renewables on German spot market prices by regressing the spot market price of electricity on the residual load, in order to determine the average slope of the merit order curve of fossil fuels. They conclude that an extra GWh of renewables or cogeneration decreases the spot price by 2.4 €/MWh (on average), by replacing fossil technologies. Related to the average wind power generation in 2008 this is equivalent to an average total merit order effect of 11 €/MWh.

Since day-ahead wind forecasts are used as a basis by bidders in the spot market auctions, Neubarth, Woll, and Weber (2006) use those forecasts to determine the

effect of an additional GWh of wind on the spot market price and conclude that it is equal to 1.9 €/MWh. This is equivalent to an average total merit order effect of 7.6 €/MWh in 2006.

Although electricity market models take a different approach, researchers have generated results in the same range. Using an agent-based electricity market model Sensfuß (2011) and Sensfuß, Ragwitz, and Genoese (2008) calculate an average merit order effect for Germany of 1.7€/MWh in 2001 to 7.83 €/MWh in 2006 and from 5.82 €/MWh in 2007 to 6.09 €/MWh in 2009. In their model for Spain De Miera, Del Río González, and Vizcaíno (2008) determine a merit order effect between 5 and 12 €/MWh in 2005-2007.

Our contribution to the existing literature is to model the merit order effect for wind and photovoltaic separately (as well as jointly) and update the calculations of the merit order effect to June 2012. This is of particular interest, since the build-up of photovoltaic cells has picked up significantly between 2010 and 2012.

4 Data

We use hourly time series data published by the European Power Exchange (EPEX), the European Energy Exchange (EEX) and the European Network of Transmission System Operators for Electricity (entso-e) for our analysis. We have hourly data for EPEX day-ahead (spot) prices and information on the total load, and the contribution of different generation technologies during the respective hours. Numbers for PV are available from July 2010 onwards, since they started to be reported after the installed capacity of PV reached 10 GW. Therefore, we use data on the generation mix from 19/07/2010 onwards and conduct analysis on the merit order effect of wind alone that dates back to 2008. Our data series end on 30/06/2012. Table 2 shows the mean and standard deviation for the variables used in the analysis.

Table 2 Summary statistics for sample variables (hourly averages)

Hourly data		2008	2009	2010	2011	2012 (first half)	All
Price	€/MWh	65.76 (28.66)	38.85 (19.41)	44.48 (13.98)	51.12 (13.61)	42.74 (16.96)	49.25 (21.87)
Wind		4.61 (3.87)	4.31 (3.45)	4.09 (3.67)	5.06 (4.41)	5.68 (4.90)	4.65 (4.03)
PV				1.06 (1.82)	2.12 (3.25)	3.28 (4.89)	2.17 (3.59)
Load		56.42 (9.34)	52.48 (9.83)	55.77 (9.31)	55.35 (10.33)	54.13 (10.09)	54.91 (9.86)
Nuclear		15.95 (1.44)	14.45 (1.65)	15.11 (1.59)	11.63 (3.40)	10.31 (1.76)	13.85 (2.90)
Lignite		15.30 (1.40)	14.67 (1.99)	14.99 (1.67)	14.99 (1.57)	14.73 (2.02)	14.96 (1.73)
Hard coal		9.18 (3.79)	7.99 (3.51)	7.23 (3.26)	6.92 (3.09)	7.37 (3.54)	7.78 (3.53)
Gas		4.11 (2.21)	3.97 (2.17)	2.09 (1.31)	2.49 (1.13)	2.10 (1.18)	3.05 (1.94)
Pump storage			0.57 (0.50)	0.57 (0.50)	0.61 (0.55)	0.78 (0.69)	0.61 (0.55)
Hydro			0.33 (0.08)	0.33 (0.08)	0.39 (0.16)	0.55 (0.12)	0.38 (0.13)
Seasonal storage			0.08 (0.10)	0.08 (0.10)	0.12 (0.14)	0.20 (0.19)	0.11 (0.13)
Observations	No.	8784	8760	8760 PV: 3984	8760	4368	

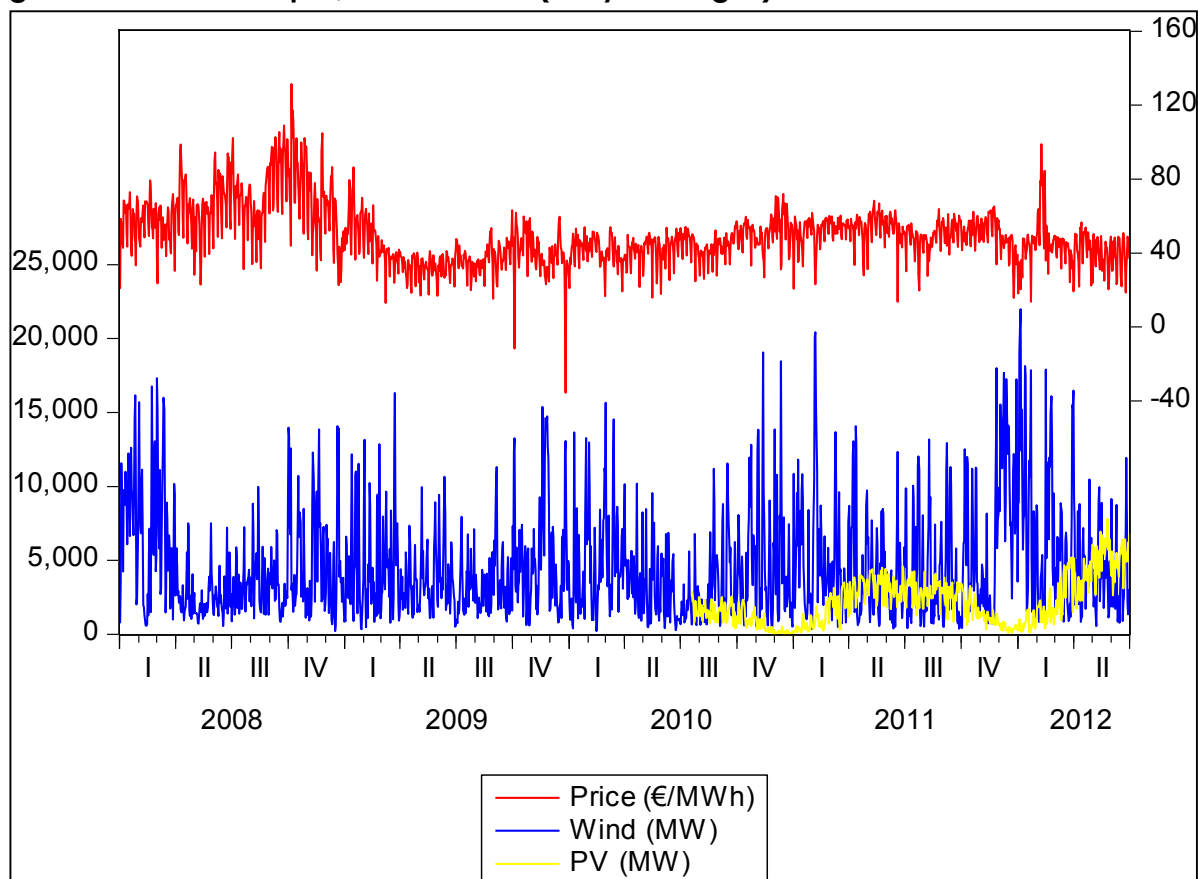
Source: EPEX, EEX, entso-e

One can observe that both the load and especially mean prices fell sharply between 2008 and 2009 as a result of the financial and economic crisis. It can also be observed that there exist base load technologies with relatively low volatility, such as nuclear or brown coal. PV, wind and gas, on the other hand, exhibit high volatilities.

Individual generation technologies do not add up to the total load. This is the case, since reporting of conventional generation is voluntary at the EEX. As a tendency

fuel specific generation data is available for the four big utilities (RWE, E.ON, EnBW and Vattenfall), but not for the generation of utilities owned by municipalities (Stadtwerke). For the baseload technologies, nuclear and lignite, the coverage is nearly complete, for hard coal the coverage is about 55% and for natural gas about 40%. However, generation from wind and PV is fully reported. Biomass, on the other hand, which is also supported by the EEG does not report at the EEX. Since biomass acts as a baseload technology, we do not expect hourly merit order effects, but rather a general reduction of the price level. The same is the case for existing run of river hydro power plants that are not supported by the EEG.

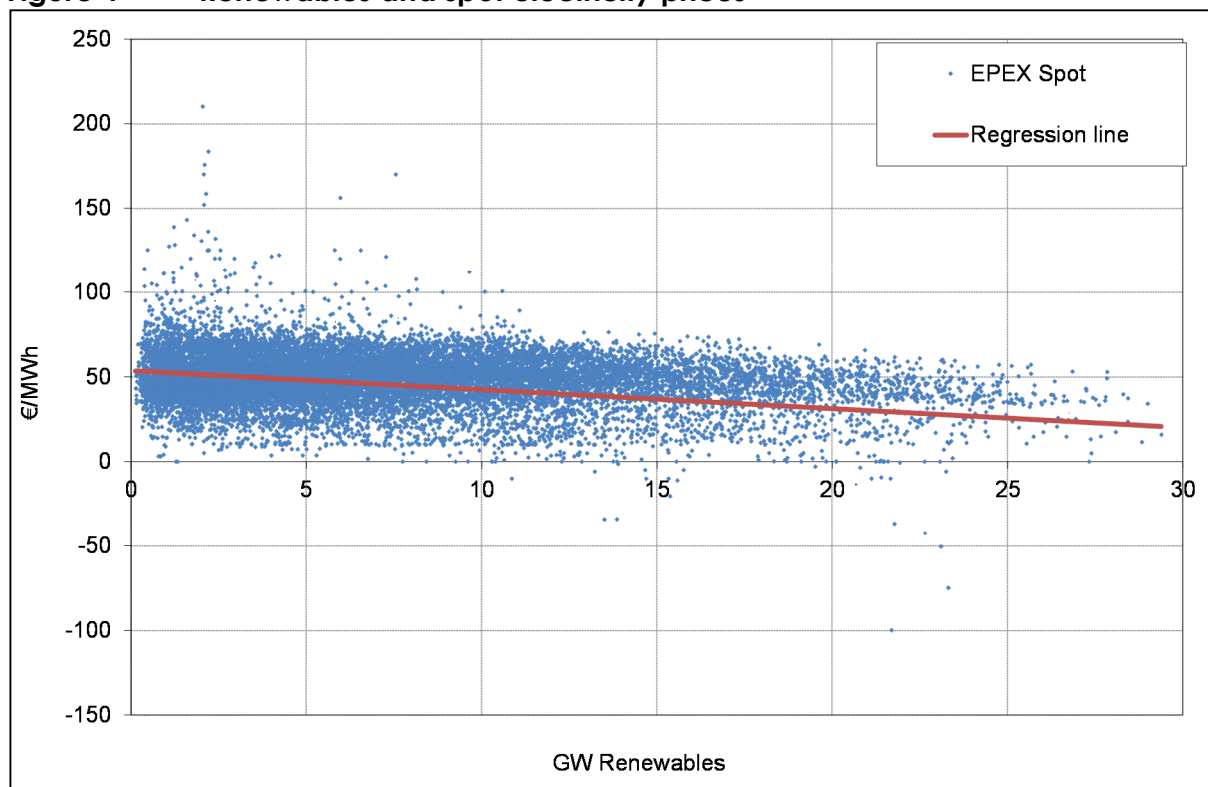
Figure 3 EPEX Spot, wind and PV (daily averages)



Source: EPEX, EEX

Figure 3 plots daily averages of generation from wind and PV over time, as well as the spot market electricity price. The increase of generation from the renewable sources, especially PV, is clearly visible. It can also be seen that electricity price volatility has reduced since 2009 and the level of prices is generally lower in recent years than in 2008.

A first indication of the merit order effect can be gained by plotting spot electricity prices against different levels of feed-in of renewables (wind + PV). Figure 4 plots this relationship between 2010 and 2012. Overlaid is the regression line determined in our analysis below, with a slope of -1.12 €/MWh, indicating that every additional GWh of renewables lowers the price of electricity by 1.12 €/MWh on average.

Figure 4 Renewables and spot electricity prices

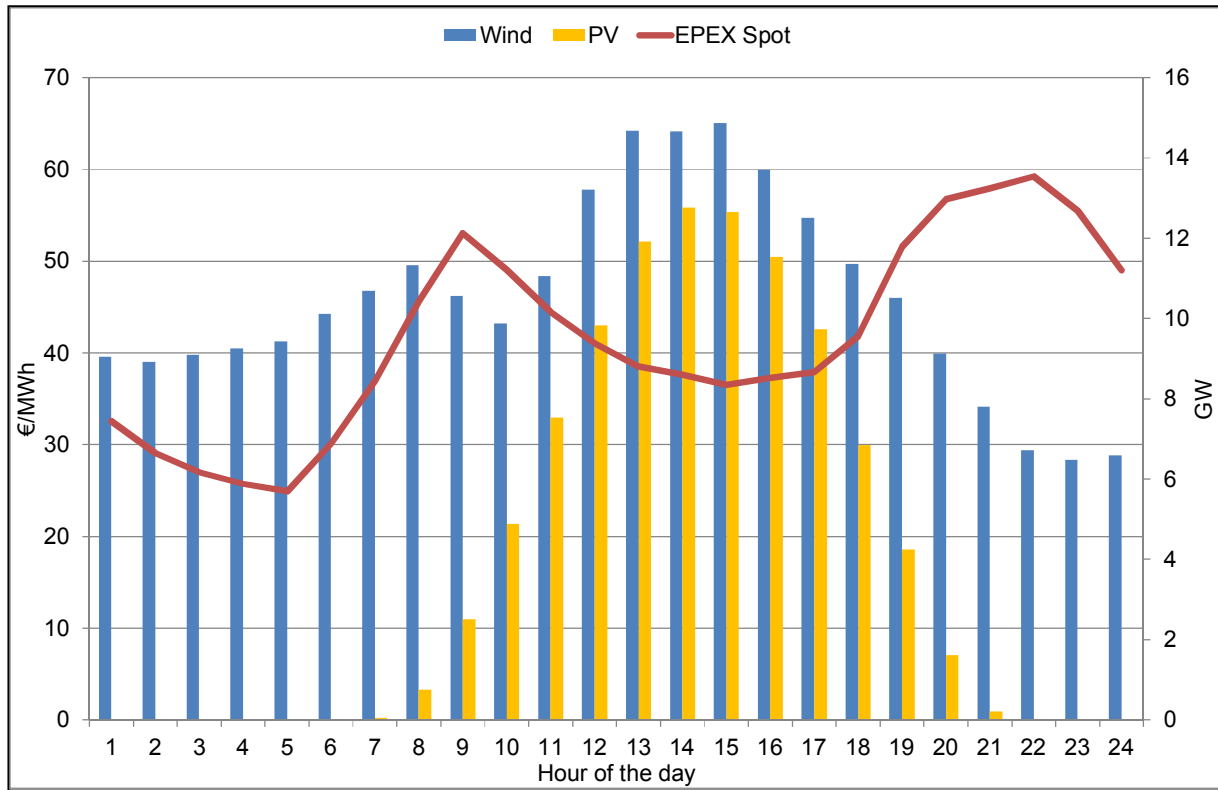
Source: EPEX, EEX, own calculations

Looking more closely at the conditions on an individual day with a high generation of both wind and PV (26/04/2012), Figure 5 displays the hourly EPEX spot price and the feed-in of wind and PV in each hour of that day. Clearly, the spot price rises with demand in the early hours of the day, but during the middle of the day is reduced by high wind and photovoltaics feed-in. This is the merit order effect of renewable energy sources during those hours. Our goal is to estimate by how much on average the spot price is reduced through additional wind and PV feed-in.

The question is whether we should use hourly or daily averaged data for our analysis. An argument against the use of hourly data is that the prices for all 24 hours of the following day are determined at the same point in time on the day before and hence with the same information set. Usually, a time series is characterised by updating, which means that information is updated from one observation to the next (cf. Huisman, Huurman and Mahieu 2007; Härdle and Trück 2010). This means that real updating on the electricity market only takes place every 24 hours. The information used to determine day-ahead prices, however, is different for each hour of the following day, even though this information is available at the same point in time on the day before. An advantage of using hourly data is that especially the feed-in of photovoltaic energy is very volatile during the day and that hourly effects are to be expected. If we averaged the data over the day, these effects would no longer be visible. Since one aim of this study is to provide a first estimate of PV merit order effects, we are employing hourly data for our analysis. A calculation using daily averages (in differences) (cf. Gelabert, Labandeira and Linares 2011) is provided in the Appendix as a sensitivity check.

We tested for unit roots in the time-series using the augmented Dickey-Fuller (ADF) test (Dickey and Fuller 1979) with automatic lag selection based on the Schwarz information criterion (SIC). The null hypothesis of a unit root could be rejected for all of the series used in the analysis.¹

Figure 5 EPEX Spot, wind and solar feed-in on 26/04/2012



Source: EPEX, EEX

¹ For the daily averages, however, unit roots were detected for both the price series and the PV series. That is why, for the sensitivity analysis, the regression was run in first differences.

5 Regression Results

We model the electricity price as dependent on a constant c , the feed-in of wind $wind$ and photovoltaics pv and total load $load$ as an indicator for total demand. As well as hourly, daily, monthly and yearly dummies.

Equation 1

$$Spot_t = c + b_1 wind_t + b_2 pv_t + b_3 load_t + \sum_{k=1}^{23} b_{k+3} dh_{kt} + \sum_{l=1}^6 b_{l+26} dd_{lt} + \sum_{m=1}^{11} b_{m+32} dm_{mt} + \sum_{n=1}^4 b_{n+43} dy_{nt} + u_t$$

We use OLS and estimate this model with different specifications: i) Wind as the only explanatory variable besides the constant and the dummies ii) wind and PV (a shorter time-series, since data for PV is only available from mid-2010) iii) aggregated renewables (wind + PV) iv) wind, PV and load as the explanatory variables. The results are displayed in Table 3.

Table 3 OLS Regression: Merit order effect of wind and PV

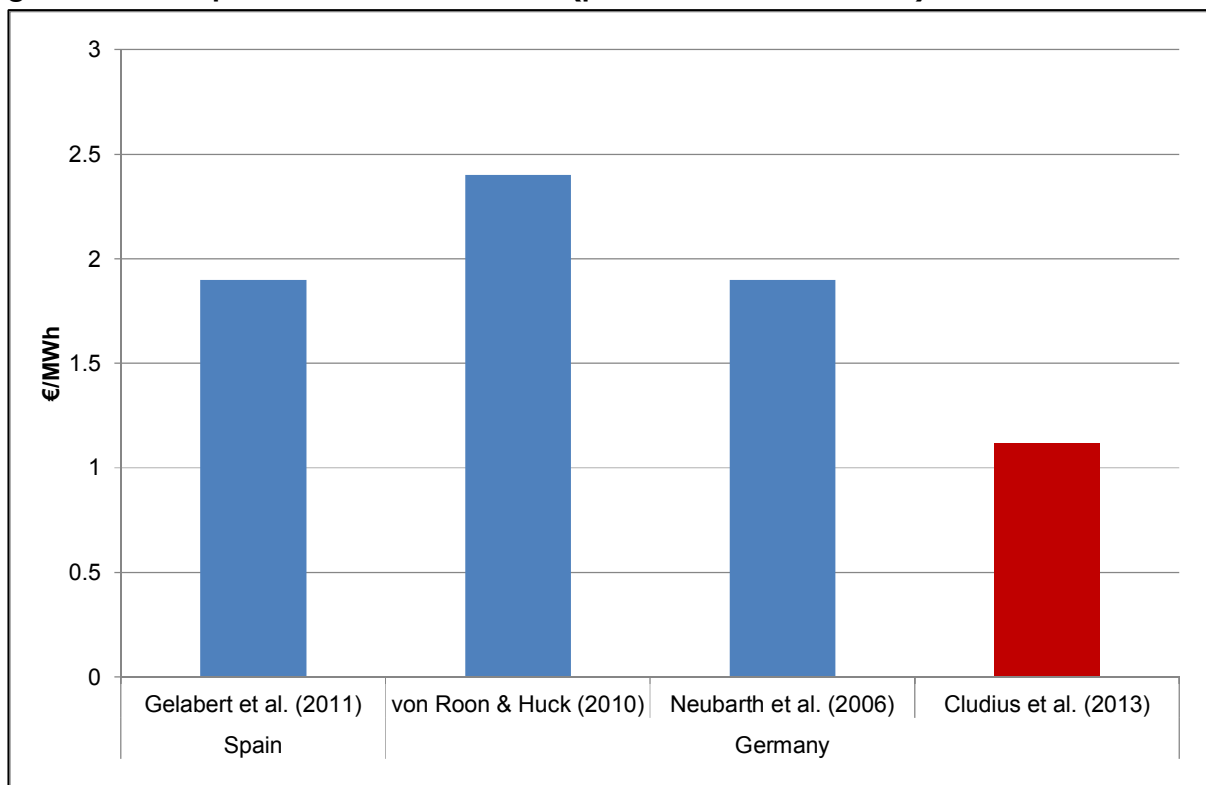
	Wind	Wind, PV	Total RE	+ Load
C	50.19*** (0.98)	58.60*** (1.12)	53.56*** (1.04)	-12.42*** (2.20)
Wind	-1.30*** (0.06)	-1.17*** (0.05)		-1.14*** (0.04)
PV		-1.10*** (0.07)		-1.22*** (0.06)
Total renewables (wind + PV)			-1.12*** (0.04)	
Load				1.25*** (0.04)
Hourly dummies	X	X	X	X
Daily dummies	X	X	X	X
Monthly dummies	X	X	X	X
Yearly dummies	X	X	X	X
Observations	39,432	17,112	17,112	17,112
Time frame	01/01/2008 - 30/06/2012	19/07/2010 - 30/06/2012	19/07/2010 - 30/06/2012	19/07/2010 - 30/06/2012
Adjusted R ²	0.60	0.65	0.64	0.77
DW-Statistic	0.33	0.34	0.38	0.38
Newey-West standard errors (robust to heteroskedasticity and autocorrelation) in parentheses *** significant at the 99% confidence level				

Source: EPEX, EEX, entso-e, own calculations

In essence, the variables of interest all model the average slope of the merit order curve of the residual load (conventional fuels). It is therefore not surprising that the coefficient for the merit order effect of wind, PV, and renewables as a whole are very similar and range from -1.10 to -1.30 €/MWh, especially because we are controlling for hour of the day, day of the week, month and year. The coefficient on load at 1.25 €/MWh for an additionally demanded GWh of electricity also reflects the average slope of the merit order curve. The constant implies that the price for electricity without renewables lies between 50 and 60 €/MWh. All coefficients are estimated precisely (as well as all of the coefficients on the dummies). The

explanatory power of the model increases as more independent variables are added. Since the Durbin-Watson test statistic (Durbin and Watson 1950) points to first order autocorrelation in the residuals, we estimate the model using Newey-West standard errors (Newey and West 1987) that are robust to heteroskedasticity and serial correlation. Figure 6 compares our result with those of previous studies. It is at the lower end of those earlier estimates, but of the same order of magnitude.

Figure 6 Specific merit order effect (per GWh of renewables)



Source: EPEX, EEX, entso-e, own calculations

We now turn to modelling the influence of the generation mix on the spot electricity price. In this case we include all of the generation technologies responsible for the generation of electricity in a particular hour. Therefore, we include wind, PV, nuclear, lignite, hard coal, gas, pump storage, seasonal storage and hydro in the equation, as well as the dummies.

Equation 2

$$\begin{aligned}
 \text{Spot}_t &= c + b_1 \text{wind}_t + b_2 \text{pv}_t \\
 &+ b_3 \text{nuclear}_t + b_4 \text{lignite}_t + b_5 \text{hard}_t + b_6 \text{gas}_t + b_7 \text{pump}_t + b_8 \text{seasonal}_t + b_9 \text{hydro}_t \\
 &+ \sum_{k=1}^{23} b_{k+9} \text{dh}_{kt} + \sum_{l=1}^6 b_{l+32} \text{dd}_{lt} + \sum_{m=1}^{11} b_{m+38} \text{dm}_{mt} + \sum_{n=1}^4 b_{n+49} \text{dy}_{nt} + u_t
 \end{aligned}$$

Table 4 details results of this regression. The coefficients describe the effect of a marginal demand increase of 1 GWh that is met by the respective technology. If, for

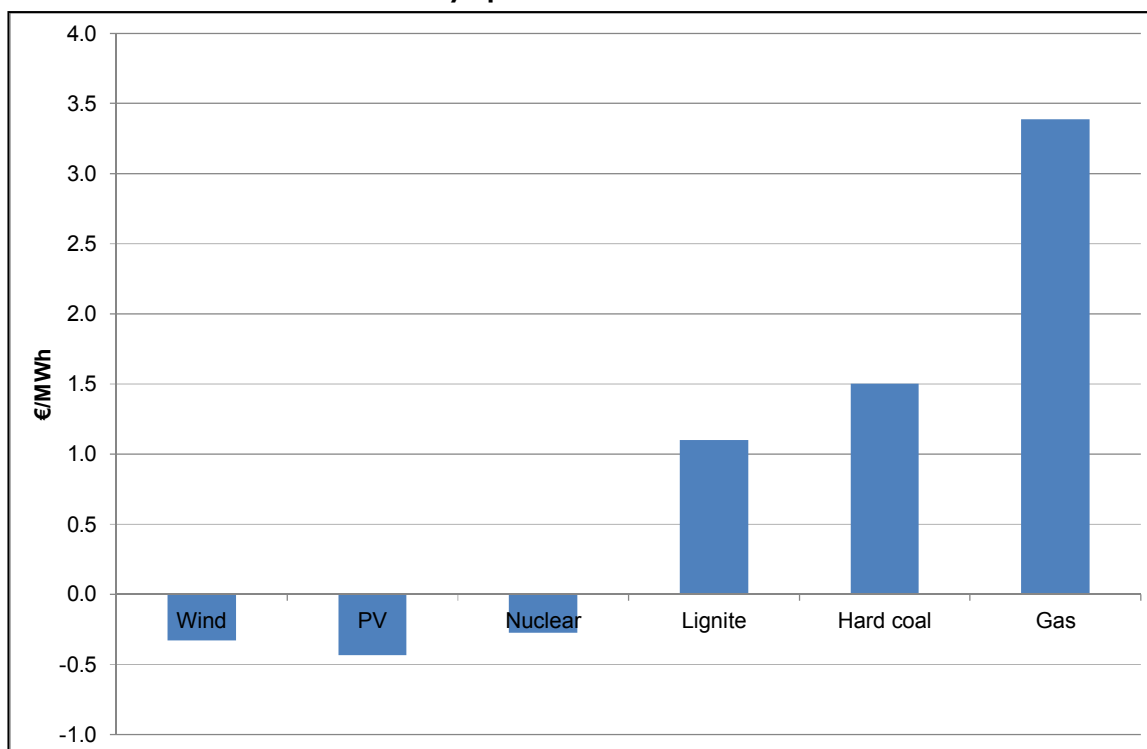
example the additional demand is met by a hard coal power plant, the price rises by 1.50 €/MWh. The increasing slope of the merit order curve becomes visible in the regression results. An additional demand of 1 GWh that is met by a natural gas plant, which is at the higher end of the merit order curve, increases the price by 3.40 €/MWh.

Table 4 OLS Regression: Merit order effect and the generation mix

	Wind, PV	Total RE
C	12.30*** (2.71)	12.46*** (2.67)
Wind	-0.33*** (0.04)	
PV	-0.43*** (0.05)	
Total RE		-0.35*** (0.04)
Nuclear	-0.27*** (0.09)	-0.28*** (0.09)
Lignite	1.10*** (0.15)	1.06*** (0.15)
Hard coal	1.50*** (0.10)	1.49*** (0.09)
Gas	3.39*** (0.29)	3.40*** (0.29)
Pump	3.75*** (0.24)	3.80*** (0.24)
Seasonal	8.19*** (1.20)	8.02*** (1.21)
Hydro	-1.30 (1.75)	-1.41 (1.74)
Dummies	X	X
Observations	17,112	17,112
Time frame	19/07/2010 - 30/06/2012	19/07/2010 - 30/06/2012
Adjusted R2	0.79	0.79
DW-Statistic	0.45	0.45
Newey-West standard errors (robust to heteroskedasticity and autocorrelation) in parentheses *** significant at the 99% confidence level		

Source: EPEX, EEX, own calculations

Figure 7 Effects of selected technologies satisfying a 1 GWh demand increase on the EPEX electricity spot market



Source: EPEX, EEX, own calculations

The coefficients on wind and PV are smaller in this specification, as this time we do not estimate what happens when they replace another technology, but when a demand increase is met by those technologies in the first place. Following Gelabert, Labandeira, and Linares (2011) we can, for a given level of demand, estimate the substitution effects between the technologies by subtracting the coefficients. For example, an additional demand of 1 GWh electricity is met by wind rather than a lignite plant is estimated to reduce prices by -1.43 €/MWh (-0.33-1.10). The large coefficients on pump and seasonal storage indicate that those technologies are associated with exceptionally high demand. Figure 7 shows a summary of the marginal effect of different technologies on the price if they are used to satisfy a marginal demand increase.

Up until now, we have estimated the specific merit order effects of renewables, i.e. what happens (on average) if an additional GWh of renewable energy is fed into the grid. This is equal to the regression coefficients in Equation 1. In a next step, we want to conduct this analysis for individual years between 2008-2012, in order to check whether the specific effect changes over time.

Furthermore, we estimate the total average effect in the respective years, by multiplying the specific effects with the average renewable energy that was fed into the grid in the respective year. We differentiate between wind and PV.

Table 5 details the specific effect of an additional GWh of wind in the respective years. It is determined in a regression of the spot electricity price on a constant, the feed-in of wind and the time dummies (specification i) above). The average hourly feed-in of wind in the respective years is also displayed. The last row details the average total effect by multiplying the specific effect with the average amount of wind fed into the grid each year. The average total merit order effect of wind energy ranges from 3.59 €/MWh in 2010 to 7.67 €/MWh in 2012.²

Table 5 **Specific and total merit order effect of wind electricity generation 2008-2012**

	2008	2009	2010	2011	2012 (first half)
Wind specific effect (€/MWh)	-1.53***	-1.53***	-0.88***	-1.00***	-1.35***
Average wind feed-in per hour (GW/h)	4.61	4.31	4.09	5.06	5.68
Wind total effect (€/MWh)	-7.05	-6.62	-3.59	-5.09	-7.67

Source: EPEX, EEX, own calculations

Since the time series on photovoltaic energy fed into the grid is only available from mid-2010 onwards, we repeat the analysis of specific and total effects for wind and PV for the years 2010 to 2012. The specific effects are the coefficients of a regression of the electricity price on a constant, wind and PV, as well as the time dummies (specification ii) above). The average total effect of photovoltaic electricity generation on the EPEX spot market price ranges from 1.55€/MWh in 2010 to

² 2012 results are calculated using data up until 30/06/2012 (see above), which should be a reasonable proxy for the whole year. We do, however, envisage updating the analysis until the end of 2012, as soon as the relevant data becomes available.

3.56€/MWh in 2012. Responsible for this development is the significant increase of photovoltaic energy that is fed into the German grid over the past years.

Table 6 Specific and total merit order effect of wind and PV 2010-2012

	2010 (second half)	2011	2012 (first half)
Wind specific effect (€/MWh)	-0.89***	-1.04***	-1.37***
Average wind feed-in per hour (GW/h)	4.09	5.06	5.68
Wind total effect (€/MWh)	-3.65	-5.27	-7.80
PV specific effect (€/MWh)	-1.47***	-0.93***	-1.09***
Average PV feed-in per hour (GW/h)	1.06	2.12	3.28
PV total effect (€/MWh)	-1.55	-1.96	-3.56
Total average merit order effect of wind and PV (€/MWh)	-5.20	-7.23	-11.36

Source: EPEX, EEX, own calculations

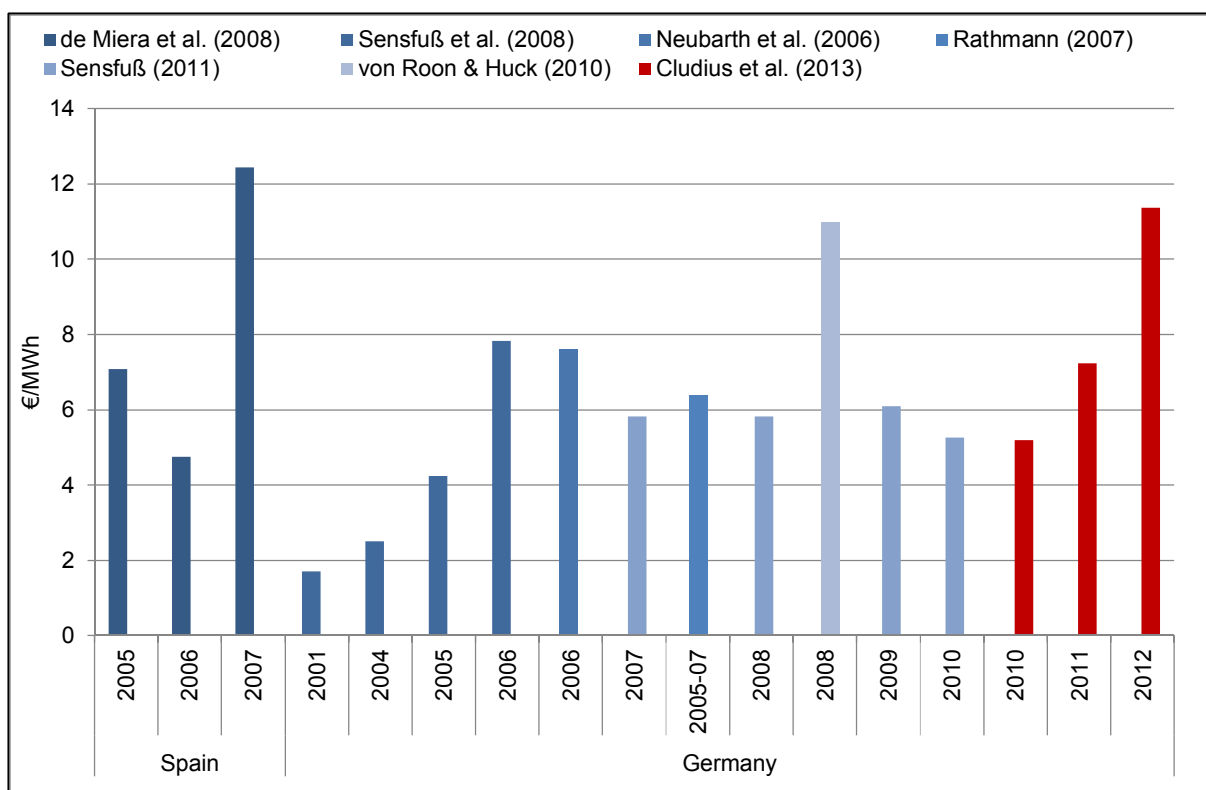
The total average merit order effect of renewables between 2010 and 2012 has therefore grown from 5.20 €/MWh in 2010 to 11.36 €/MWh in 2012. This effect is both dependent on the specific effect and the average amount of renewable energy fed into the grid.³

Higher specific effects occur in times of expensive fuel prices (2008), because this means that the marginal cost of electricity generation is higher and therefore the merit order curve steeper. In 2009 high specific effects were also observed, despite low demand as a result of the financial and economic crisis. This can be attributed to special effects - among others - related to regulatory provisions phased out at the end of the year. This phase-out led to negative power prices that occurred in hours with high renewable feed-in and low demand. In those hours the merit order curve was extremely steep at the left end (for an analysis of the special situation in 2009 refer to EWI 2010). In 2010 and 2011 the specific effect of renewables is smaller, since the price is determined in the middle of the merit order curve. Therefore, the specific effects, have exhibited some volatility between 2008 and 2012. They were especially high in 2008, due to high fuel costs, lower in 2010 to 2011, due to lower demand as a result of the financial and economic crisis and have picked up again in 2012.

The other determinant of the total merit order effect, the amount of the renewable energy fed into the grid has, however, followed a clear trend: upwards, as especially new photovoltaic cells were installed. Figure 8 compares our results of the average total merit order effect with those of previous studies for Germany and Spain. Results are in the same range with an upward trend in recent years.

³ One could additionally consider the production of biomass of about 28 TWh in 2010, 33 TWh in 2011 and 36 TWh in 2012 (AG Energiebilanzen 2013), amounting to an average hourly feed-in of 3.20 GW in 2010, 3.77 GW in 2011 and of 4.10 GW in 2012. An additional merit order effect of 3.58 €/MWh and 4.59 €/MWh in 2012 can be estimated, using the average specific factor of renewables (specification iii) of -1.12.

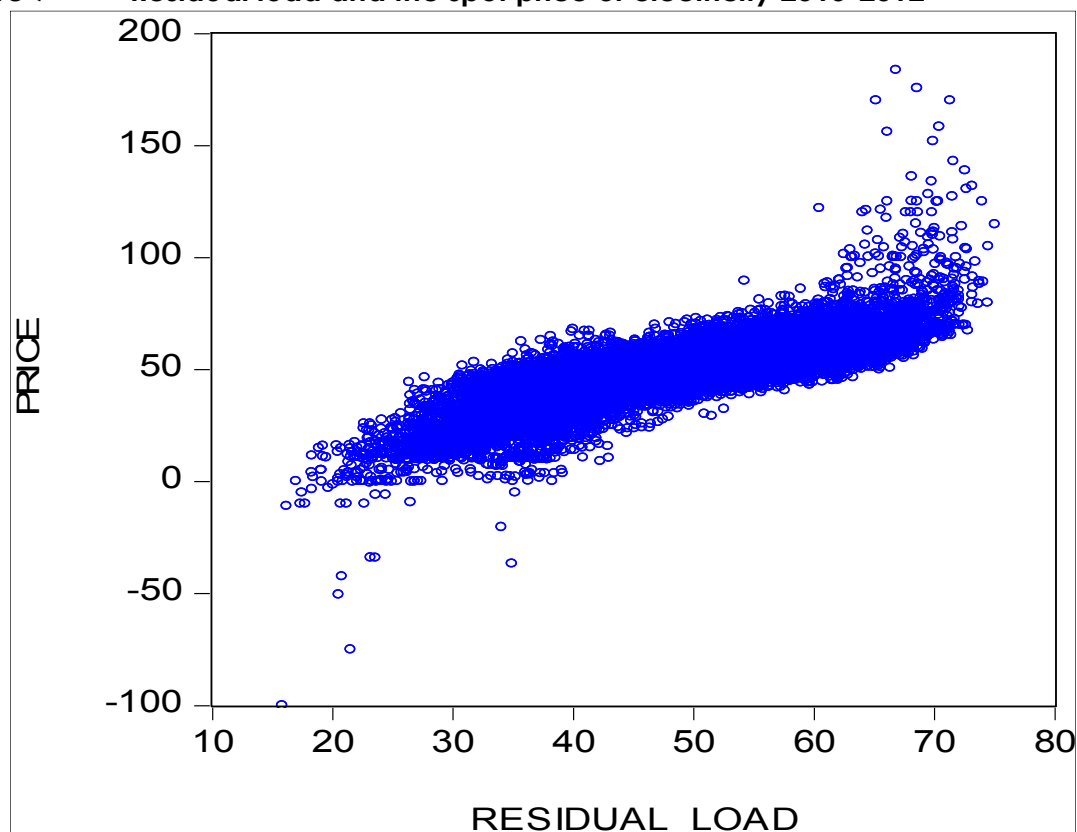
Figure 8 Comparing our results of the total average merit order effect of wind and PV to other studies



Source: EPEX, EEX, own calculations

The final part of our analysis is concerned with approximating the electricity price curve at different levels of residual load (to be met by conventional power plants). Should the installation of renewables continue to expand, the level of residual load is likely to be reduced in those hours in which renewables produce electricity (for example at noon for PV). Therefore, the following results are significant to predict merit order effects in the future. They also indicate the likely prices that will be achievable on the electricity spot market as more and more renewable energy sources are added to the generation mix.

Figure 9 plots the spot market price against the residual load. It shows that the more electricity is generated using fossil technologies, the higher the EPEX spot price becomes. At very low levels of fossil generation, the price of electricity can fall below €0, as was the case between 1:00 and 9:00 a.m. on 26 December 2009, where low demand coupled with a lot of wind, depressed prices to -120 and -200€/MWh. On the other hand, prices can climb to several hundred €/MWh, during times of high demand and low renewable feed-in. Generally, the plot confirms that higher prices are usually associated with a higher share of fossil fuels in the generation mix.

Figure 9 Residual load and the spot price of electricity 2010-2012

Source: EPEX, EEX, entso-e

We determine the slope of the merit order curve for different residual loads by regressing the EPEX spot price on a constant and the residual load (defined as total load – fluctuating renewables). We omit time dummies in this regression, as those would pick up some of the differences in load and make it harder to approximate the slope of the electricity price curve for different residual loads.

Equation 3

$$Spot_t = c + b_1 residual_t + u_t$$

All coefficients are estimated highly precisely (Newey-West standard errors are again used). Table 7 shows the estimated coefficients and confirms the expectation that the merit order curve is relatively steep at the left end, then reaches a plateau between 40 to 60 GW and becomes steeper again at 70 GW. At residual loads below 40 GW renewables start to substitute baseload power plants such as lignite and nuclear. If low residual loads occur for a few hours only, these plants are generally not shut down completely but are operated with partial load. This has different reasons such as ramp rates, start-up costs and the provision of system services. Figure 9 illustrates that, as a result, the spot market has produced negative power prices at low residual loads (for a detailed discussion refer to EWI 2010). Compared to the stylized merit order curve shown in Figure 2, the analysis based on actual historical data is different at the left hand side of the electricity price curve, where the slope is much steeper than in the stylized model. This is the case, because

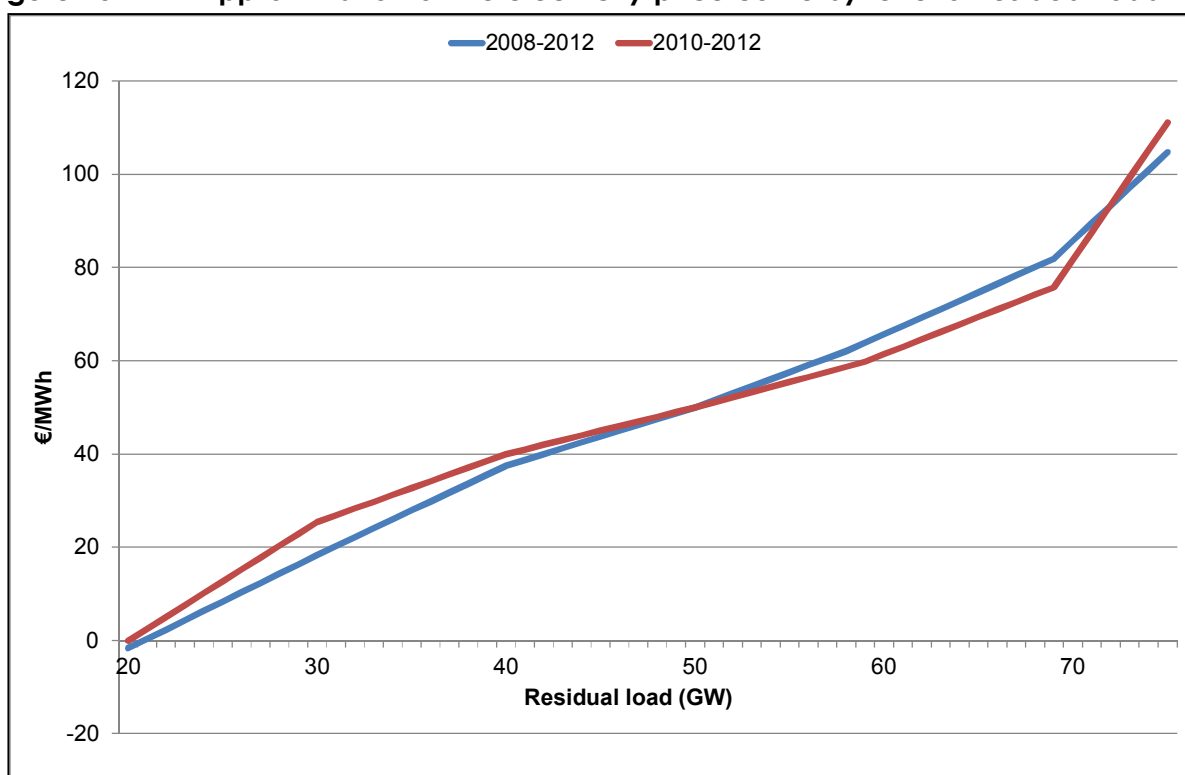
the stylized curve does not take into account the factors discussed above, which can lead to negative prices.

Table 7 Approximation of the slope of the merit order curve at different residual loads

Residual load (GW)	2008-2012	2010-2012
< 30 GW	1.99	2.55
30 – 40 GW	1.92	1.46
40 – 50 GW	1.25	1.00
50 – 60 GW	1.51	1.09
60 – 70 GW	1.80	1.60
70 – 80 GW	3.80	5.89

Source: EPEX, EEX, own calculations

Figure 10 Approximation of the electricity price curve by level of residual load



Source: EPEX, EEX, entso-e, own calculations

Figure 10 shows this approximation graphically. The approximated merit order curve is anchored at 50 GW/ 50 €/MWh, the centre of the scatterplot. Our results indicate that the more renewables come to the market the lower will be overall prices that can be achieved on this market. At the same time, the value of the electricity produced by renewables is low, when the residual load is low. This means that the value of renewable energies decreases in those hours in which a large share of total demand can be met by renewable energy sources. Until now, the EEG has only limited incentives to optimise the layout of biomass, wind or PV installations in a way that they produce electricity at times with higher prices. One way to do so could be PV plants that are aligned to the east and west and can harvest power when plants aligned to the south cannot. These results are also relevant for the impact

assessments that will be necessary within the framework of the discussion of an improved market design (for a discussion of a possible market design see Matthes et al. 2012).

6 Conclusion

We have estimated the merit order effect of wind and photovoltaic electricity generation in Germany between 2008 and 2012. The average specific effect (reduction of the spot market price per additional GWh of renewable energy) lies between 1.10 and 1.30 €/MWh. These effects vary across years, as they depend on fossil fuel prices, the overall level of demand and other factors. The average total effect of wind and PV (specific effect times average renewable energy feed-in) has risen from 5.20 €/MWh in 2010 to 11.36 €/MWh in 2012. These effects that are visible on the day-ahead market also have implications for other electricity contracts (i.e. the forward market).

These findings are especially interesting in the context of the German Renewable Energy Sources Act (EEG) which levies a surcharge on electricity consumers for the support of renewable energy sources. It seems that the merit order effect overcompensates the group of privileged consumers for their contribution to the surcharge. The burden on the non-privileged consumers could be reduced if the surcharge for the privileged consumers took into account the merit order effect of renewables. Our results point to a potential contribution by privileged consumers of around 1 ct/kWh (rather than 0.05 ct/kWh they are charged at the time of writing).

Further analysis should be conducted on the long-run merit order effects. We have attempted to highlight some of the issues by estimating the slope of the merit order curve at different residual loads. Our results indicate that the more renewables come to the market the lower will be overall prices that can be achieved on this market. This is an important prerequisite to be used in discussions about a reform of the EEG and the general market design. As an interesting topic for future work, an analysis of the impact on the merit order effect of different levels of import and export to neighbouring countries would also be worth investigating.

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Data sources

EPEX Spot. European Power Exchange. Market data. Auction results. Germany/Austria. EPEX Spot. Paris.

EPEX Spot. European Power Exchange. Market data. Auction results. France. EPEX Spot. Paris.

EPEX Spot. European Power Exchange. Market data. Auction results. Switzerland. EPEX Spot. Paris.

European Energy Exchange (EEX): Transparency in Energy Markets. Voluntary Commitment of the Market Participants. Ex-post data. Previous day production. Leipzig.

European Energy Exchange (EEX): Transparency in Energy Markets. Statutory Publication Requirements of the Transmission System Operators. Actual wind power generation. Leipzig.

European Energy Exchange (EEX): Transparency in Energy Markets. Statutory Publication Requirements of the Transmission System Operators. Actual solar power generation. Leipzig.

European Network of Transmission System Operators for Electricity (ENTSO-E): Resources. Data Portal. Country Packages, Production, Consumption, Exchange. Brussels. (<https://www.entsoe.eu/db-query/country-packages/production-consumption-exchange-package/>)

Nordpool Spot: Hourly Elspot Prices. Lysaker Norway

PolPX Spot: Historical Data. Market: DAM. Particular contracts. IRDN. Auction 2. PolishPowerExchange. Warsaw.

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Appendix

As a sensitivity analysis, we present results for daily averages in first differences (cf. Gelabert, Labandeira and Linares 2011). The estimated merit order effects differ only slightly from the ones estimated in levels on an hourly basis. As expected, PV effects are not estimated as precisely, as averaging mutes effects that occur during different hours of the day.

Table 8 OLS Regression: Merit order effect of wind and PV (daily averages)

	Wind	Wind, PV	+ Load	+ Mix
C	15.46*** (0.75)	12.74*** (0.73)	2.20 (1.54)	4.57*** (1.59)
ΔWind	-1.19*** (0.08)	-1.12*** (0.08)	-1.10*** (0.07)	-0.55*** (0.12)
ΔPV		-1.20*** (0.27)	-0.98*** (0.24)	-0.37 (0.29)
ΔLoad			0.87*** (0.11)	
ΔNuclear				-0.26 (0.59)
ΔLignite				0.95** (0.39)
ΔHard coal				0.92*** (0.32)
ΔGas				2.57*** (0.60)
ΔPump				1.35 (1.72)
ΔSeasonal				7.51* (4.13)
ΔHydro				1.21 (3.79)
Daily dummies	X	X	X	X
Monthly dummies	X	X	X	X
Yearly dummies	X	X	X	X
Observations	1,642	712	712	712
Time frame	01/01/2008 - 30/06/2012	19/07/2010 - 30/06/2012	19/07/2010 - 30/06/2012	19/07/2010 - 30/06/2012
Adjusted R ²	0.59	0.67	0.73	0.72
DW-Statistic	2.45	2.63	2.62	2.70
Newey-West standard errors (robust to heteroskedasticity and autocorrelation) in parentheses *** significant at the 99% confidence level				

Source: EPEX, EEX, entso-e, own calculations

Table 9 Specific and total merit order effect of wind 2008-12 (daily averages)

	2008	2009	2010	2011	2012
Wind specific effect (€/MWh)	-1.62***	-1.33***	-0.92***	-1.00***	-1.22***
Average wind feed-in per hour (GW/h)	4.61	4.31	4.09	5.06	5.68
Wind total effect (€/MWh)	-7.47	-5.75	-3.77	-5.06	-6.94

Source: EPEX, EEX, entso-e, own calculations

Table 10 Specific and total merit order effect of wind and PV 2010-12 (daily averages)

	2010	2011	2012
Wind specific effect (€/MWh)	-1.04***	-1.06***	-1.29***
Average wind feed-in per hour (GW/h)	4.09	5.06	5.68
Wind total effect (€/MWh)	-4.25	-5.38	-7.34
PV specific effect (€/MWh)	-0.87	-1.24***	-1.33**
Average PV feed-in per hour (GW/h)	1.06	2.12	3.28
PV total effect (€/MWh)	-0.91	-2.63	-4.37
Total average merit order effect of wind and PV (€/MWh)	-5.16	-8.01	-11.72

Source: EPEX, EEX, entso-e, own calculations