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Assessment of RES technology market values and the merit-order effect – an econometric multi-country analysis

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Abstract
This study presents an assessment of both the merit-order effect and the market values of electricity generated from variable renewable energy sources, namely wind and solar photovoltaics. The historical price development in several European countries – that cover 73% of the renewable energy source share in Europe’s regional electricity markets – has been taken into account. To gain insights into the impact of renewable electricity on prices, market values and the merit-order effect were calculated using a multivariate regression analysis and ex-post calculations. All the countries analyzed show a consistent, negative impact of renewable electricity on electricity spot market prices and a decreasing market value of renewable energy source, possibly attributable to increased shares. The coefficients are economically and statistically significant. This study provides insights into a large geographical spread of European electricity markets, enables a comparison between countries, and therefore has valuable implications for policy makers.

Keywords
Merit-order effect, market value of renewable electricity, European electricity markets, variable renewables

Introduction
This study presents an assessment of both the merit-order effect and the market values of electricity generated from variable renewable energy sources (RES), namely wind and solar photovoltaics (PV). The historical price development in several European countries – covering 73% of the RES share in Europe’s regional electricity markets – has
been taken into account. To our knowledge, this is the first study of its kind with such a large geographical scope that enables a Europe-wide comparison of the discussed effects on electricity spot markets and derives policy conclusions for an integrated electricity market.

The state-of-the-art in econometric analyses of electricity prices and the merit-order effect are outlined within an extensive literature review that covers several European electricity markets and also some examples from the US (ERCOT). The analysis includes a calculation of the market values based on historical data of variable RES' generation profiles and the corresponding spot market prices. In the discussion section, these outcomes are interpreted and contrasted with findings from the literature.

The study underlying this paper was conducted within the framework of the Intelligent Energy Europe (IEE) project DIA-CORE (DIA-CORE is a collaborative project of several European research institutions, policy consultants and one industry representative, establishing a policy dialogue on the assessment and convergence of RES policy in EU Member States. This initiative was possible thanks to the financial and intellectual support offered in the European Commission’s IEE Programme, operated by the Executive Agency for Small and Medium Enterprises. For more details on the DIA-CORE project, see www.diacore.eu.).

Literature review

The literature analyzing the empirical effects of renewable generation on the electricity spot price and the associated implications for the merit order and market value is very diverse, covering a range of methodologies and countries. To our knowledge, however, a Europe-wide study of these effects that encompasses as many countries as is the case here has not been executed so far. This literature review gives a broad overview of the empirical approaches used to analyze the merit order and market value effects of renewables over the last few years.

The German electricity market has experienced exceptional RES growth over the past decade and has been analyzed frequently. Pham and Lemoine,1 for example, apply a GARCH framework, and model the effect of wind power and of PV, separately, on the German electricity spot price in the period 2009 to 2012. They use a maximum likelihood estimation and discover a price-depressing effect of increased renewables’ feed-in. Cludius et al.2 also focus on Germany and look at the merit-order effect of wind and PV. Using ordinary least squares (OLS) regressions in different specifications, they find that each additional GWh of renewables fed into the grid decreases the price of electricity on the day-ahead market by 1.1 to 1.3€/MWh. The derived merit-order effect is 5€/MWh in 2010 and rises to over 11€/MWh in 2012 according to their calculations. When applying a univariate regression model, Weber et al.3 find similar effects for Germany in the period between 2004 and 2005. They estimate a drop in the day-ahead price of electricity by 1.89€/MWh for each additional GWh of wind power.

Another study that looks at the German and Austrian power sectors simultaneously was conducted by Würzburg et al.4 They apply a multivariate regression approach for the years 2010 to 2012, and also find a substantial merit-order effect of renewables (wind power and PV taken as a joint explanatory variable). The authors estimate a decrease of around one euro per additional GWh of renewable electricity and thus calculate an average merit-order effect of 7.6€/MWh based on these results.
Another country that has been analyzed by several authors is Spain. A study by Gelabert et al.\textsuperscript{5} looking at day-ahead electricity prices between 2005 and 2009 finds that “a marginal increase of 1 GWh of electricity production using renewables and cogeneration is associated with a reduction of almost 2€ per MWh in electricity prices (around 4% of the average price for the analyzed period).” Gil et al.\textsuperscript{6} analyze the effect of integrating large-scale wind power into the Spanish electricity market in the years 2007 to 2010. They apply a conditional probability approach and find that the price of electricity would have been around 9.7 €/MWh or 18% higher without wind production. Using an artificial intelligence-based technique (M5P algorithm) to determine the influence of wind power technology on the spot market, Azofra et al.\textsuperscript{7} also analyze historical data for Spain in the year 2012. They find that “wind power depressed the spot prices between 7.42 and 10.94€/MWh for a wind power production of 90% and 110% of the real one, respectively.”

Two other studies analyze developments on the Danish electricity market. Østergaard\textsuperscript{8} analyzes data for the year 2005 and finds that electricity spot prices would have been higher in Denmark without any wind power generation – namely by 1€/MWh in 2004, 4€/MWh in 2005 and 2.5€/MWh in 2006. Jönsson et al.\textsuperscript{9} apply a non-parametric regression model and look at the effect of day-ahead wind power forecasts on electricity spot prices between 2006 and 2007. The variation and price effects here are especially high because of the Danish electricity market’s specific characteristics of a relatively small size with high wind penetration. In times of high wind feed-in, a downward effect of 55-50€/MWh was estimated. This describes an overall effect which is induced by “large shares” of wind in total electricity generation and not normalized to e.g. 1 GWh of additional wind power generated. All in all, Jönsson et al.\textsuperscript{9} say that about 40% of the variation in Danish electricity prices can be assigned to wind power.

The Netherlands, Italy and Ireland are other European countries where market values and/or the merit-order effect of variable RES have been assessed. In Ireland, for instance, O’Mahoney and Denny\textsuperscript{10} analyzed the merit-order effect of wind generation on the Irish electricity market. Applying an OLS multiple regression model, they find that wind power induced a coefficient on wind of –0.0099 for the year 2009. Scaling this up to the market outcomes in that year implies that prices would have been 12% higher without wind generation. The total value of wind generation to the market dispatch shifted €141 million from non-RES consumers to producers. Nieuwenhout and Brand\textsuperscript{11} study the impact of wind power on electricity prices in the Netherlands. This empirical study primarily compares different wind generation intervals according to historical weather data in the years 2006–2009. They find that average day-ahead prices on the Dutch electricity market were around 5% higher during no-wind intervals in comparison to the rest of the analyzed period. A more recent study of the Italian electricity market – another relevant European market in terms of installed variable RES capacities – was conducted by Clò et al.\textsuperscript{12} Applying a multivariate linear regression model for the years 2005 to 2013, they find an impact of variable RES (PV and wind power) on the Italian electricity spot prices. Analyzing the two technologies separately, the authors conclude that “an increase of 1 GWh in the hourly average of daily production from solar and wind sources has, on average, reduced wholesale electricity prices by, respectively, 2.3 €/MWh and 4.2 €/MWh and has amplified their volatility.”\textsuperscript{12} This study is interesting because it analyzes data covering almost a decade and also takes variability into account.

Finally, to complete the overall literature review and to open up the geographical scope, some literature from the United States is presented. Woo et al.\textsuperscript{13} use a stationary AR-process
to model the effect of wind generation on balancing energy prices and variance in Texas for the years 2007 to 2010. The four-zone Electricity Reliability Council of Texas (ERCOT) works with 15-min balancing energy market prices, which allow an extremely high-resolution study of the market. The authors find that “a 1 GW increase in wind generation (during 15 min) decreased Texas balancing electricity prices between 13 and 44 US$/MWh.” Nicholson et al. also analyze the ERCOT market, with a focus on balancing energy. The authors use an ARMAX model and find wind generation decreases the balancing energy prices by 0.67 to 16.4 US$/MWh per additional GW of wind power (depending on the year, time of day and area in the Texas network). A direct comparison to previous findings is not possible, because the markets differ, prices are in a quarter hourly resolution, and the effect is assessed on balancing energy prices not spot prices. Nevertheless, the impact of variable RES on all tiers of the electricity market is clear when looking at this strand of literature.

The overall conclusion that can be drawn from this literature review is that variable renewables have a visible effect on electricity prices, and can induce a merit-order effect. Moreover, market values of RES are largely influenced by their share in overall electricity generation and the respective time of day in which variable RES feed-in takes place. Nevertheless, it is also important to consider that wind and solar power lead to substantial variation in electricity prices. It is also not entirely correct to assume that these technologies operate at zero marginal costs – implying that the effects that have been observed so far could have been overestimated to a certain extent. Overall, however, the downward effect of variable RES on electricity spot prices seems to be unambiguous.

**Empirical approach**

The approach followed in our analysis is oriented along the lines of the papers by Würzburg et al. and Gelabert et al. The independent or outcome variable is the electricity price, measured as the hourly spot price on the country’s respective electricity exchange platform. We then assess, as explained before, how this price changes in hours with different levels of RES infeed.

**Data**

The data underlying the following regressions stem from various sources. Specifically, spot prices from different electricity trade platforms, load data from ENTSO-E, Nordpool and other country-specific sources were gathered as well as cross-border flows from ENTSO-E and wind and PV-infeed from other national sources. Furthermore, the input data for the EMMA model, prepared from ERA weather data to calculate RES infeed, were used to calculate values for earlier years (2008–2010) where no data from RES electricity providers were available. Eurostat Data served as a source, especially concerning installed capacity and gas prices (http://ec.europa.eu/eurostat/data/database). As data availability is limited, it was not possible to provide a full assessment for all European Member States. On the one hand, RES penetration in some countries is still relatively negligible, whereas other countries with high RES penetration lacked the data necessary for the analysis. Nevertheless, roughly 73% of all installed variable RES capacity is covered by the following study (68.8% of PV and 75.1% of wind power).
Data are in hourly resolution. To deal with leap years, the respective 29th of February was introduced as a regular date. Daylight saving time poses a problem as two values occur at the same time at one point, i.e. a 25-h day. To deal with this problem, the first of the two values was then deleted.

We are interested in how electricity spot prices are influenced by different levels of variable renewables (wind and PV). The price used is always the day-ahead price, which serves as a basis for purchasing and selling decisions on the day-ahead market. The literature further argues that this price has a more significant impact in terms of traded volumes when compared to the intra-day price.

Hourly RES infeed is our main dependent variable of interest. We want to observe how electricity prices are changed by different levels of renewables fed into the grid. As the dependent variable is the day-ahead price, ideally, RES infeed should be represented as a day-ahead forecast variable as well. In most cases, however, only actual infeed data could be obtained.

One of the most important determinants of electricity spot prices is the hourly load as this represents the demand that has to be met in the respective hour. Prices are usually higher during periods of high demand. This can change if these periods coincide with high levels of RES infeed. Renewables can strongly influence prices because they have almost zero marginal costs. Ideally, load and RES infeed should be represented as a forecast variable, but only actual load data could be obtained in most cases.

Cross-border flows: If available, this variable was also introduced. Cross-border flows improve the explanatory power of the model as they show how the supplied electricity was distributed, whether electricity was exported to a neighboring country or additional electricity had to be imported due to high demand. A net effect was calculated, i.e. inflows were subtracted from outflows to best approximate the actual levels of demand in the respective Member State at the given point in time. Unfortunately, such data were only available for Germany. This limits the analysis, especially for interconnected countries such as Denmark.

Dummy variables were also included in the regression to account for seasonality (monthly dummies) and fluctuations during the week (weekly dummies).

**Merit-order effect**

The influence of variable renewables on electricity spot prices is modeled by a multivariate regression with different specifications. As the electricity price is determined by demand to a large extent, the load, also measured in an hourly resolution, is introduced as a main control variable. As the electricity generated does not remain exclusively in the respective country, cross-border flows of electricity improve the accuracy of the estimated relationship, if available.

Since different seasons of the year exhibit significantly different levels of demand, monthly dummies are introduced to reflect this pattern, which can be especially relevant in countries where electricity use is strongly weather-dependent, e.g. in France, where a substantial share of heating comes from electric heaters, so that demand in winter is a lot higher than in the summer. For the same reason, weekly dummies are used to account for different levels of electricity demand due to the structure of a given week. As the day-ahead electricity price is a variable that depends strongly on the price that occurred a day earlier, 24-h lags of the electricity price were also introduced as a control factor.
Main Regression: \( P_h = \beta_0 + \beta_1 LOAD_h + \beta_2 RE_h + \beta_3 ExIm_h + \beta_4 lagp_h + \beta_5 dummies + \varepsilon_h \)

The Durbin Watson test indicated positive autocorrelation among the residuals, such that robust (heteroscedasticity consistent) standard errors were computed. A second variation to account for this factor was performed by differencing the regression. This regression could only be executed if the dependent variables were also forecasts, i.e. if load and infeed were available as a 24-h ahead estimation. Only the difference to the preceding (i.e. 24 h behind) value is estimated by implementing this regression specification.

First, differencing, of the variables yields very similar results for the coefficient estimates. Taking the year 2010 in Germany as an example, the regression coefficient on wind infeed is –0.00098 compared to –0.00097 for explanatory variables in levels. As the regression making use of variables in levels has more explanatory power (adjusted R2 of 0.804 compared to 0.607), we keep the form as specified above.

Robustness checks and variations

Following Swinand et al., one variation of the regression was to approximate load as a non-linear variable to account for different levels of price elasticity at different levels of demand.

Non-linear load: \( \Delta P_d = \beta_0 + \beta_1 \Delta LOAD_d + \beta_2 \Delta LOAD^2_d + \beta_3 \Delta RE_d + \beta_4 \Delta ExIm_d + \beta_5 dummies + \varepsilon_d \)

Allowing load or infeed of RES to take on a non-linear shape by including a squared term changes the regression results only marginally. The squared term for load or wind/solar PV is neither statistically nor economically significant, and it does not improve the model’s explanatory power.

Residual load: \( \Delta P_d = \beta_0 + \beta_1 \Delta residualLOAD_d + \beta_3 \Delta ExIm_d + \beta_4 dummies + \varepsilon_d \)

Implementing residual load (as the load served by the remaining technologies – subtracting the hourly generation of solar PV and wind power) yields a significant positive value. Specifically, a coefficient of 0.0009431 implies that an increase in residual load by one percent of the total load increases the electricity price by €0.525. Or, phrased differently, a 1% decrease in the load provided by variable renewable technologies increases the electricity price by €0.525. Implementing a non-linear form of the variable does not add to the model fit for the residual load either. Overall, however, the result of this different specification does add to the robustness of our results since it substantiates our previous findings.

Absolute values

Absolute effects are calculated by taking the average hourly load of the respective Member State and scaling it up

\[
\text{Hourly load (MW\text{h})} \times 24 \left( \frac{\text{hours}}{\text{day}} \right) \times 365 \left( \frac{\text{days}}{\text{year}} \right) \times \beta_2 RE_{\text{wind}} = \text{average annual savings}
\]

The change in the price induced by an increase of an additional percent wind/solar power in the average hourly load, i.e. the coefficient on wind infeed (\( \beta_2 RE_{\text{wind}} \)), multiplied by said share of average hourly load is taken as the factor to calculate these costs.
Market values

The market value of variable renewable electricity is of interest for the present analysis as it determines how the different technologies will be remunerated for their generation, and to which extent generators will be able to recover their costs on the electricity spot market. The most common approach to calculating the market values of RES is to measure their respective price on the spot market. In this document, we apply the following formula:

\[
P_{z, m, t} = \frac{\sum_{z, m, t} (p_{z, m, t} \times qW_{z, m, t})}{qW_{z, m, t}}
\]

Using the historical data collected, market values of RES were calculated in the countries of interest for the respective available years. First of all, taking the example of wind infeed, the actual generation (measured in MWh) by wind power plants is multiplied by the respective spot price that occurred in the hour of their infeed (t). Then, this product is divided by the total quantity (MWh) of wind electricity generated throughout the respective period which yields the average price for one MWh of wind generated in the period of interest (usually one specific year). If the market is split into different pricing zones, an average is taken for the prices in the different zones. If possible in these cases, wind infeed is then weighted to account for the different quantities produced in the respective zones (z). This was not always possible as the data were not always available in this resolution.

To estimate a market value of RES that allows cross-country comparison, the values were put into perspective by presenting them as a share of the total load in the country. The market value for PV was calculated analogously. For this definition of the market value of variable renewables, the day-ahead spot price is the only price used – as is the case in most other studies (see e.g. Würzburg et al.\textsuperscript{4}), due to the fact that this price represents the majority of the traded volumes.

Results

Table 1 presents a comparison of regression outcomes for three European Member States. These countries were chosen explicitly as they represent three different geographical areas – i.e. southern, northern and central Europe. More insights into a wider spectrum of countries at a macro-level are given in the overall comparison of the merit-order effect, which is included graphically in section 4.2 of this paper.

It is clearly visible that all the explanatory variables are statistically significant, and that the model applied seems to be a good “one size fits all” approach. It yields an adjusted $R^2$ of up to 0.81. Table 2 shows regression results for additional countries analyzed in earlier years. The results are also depicted graphically in section 4.2 for all the countries analyzed.

More recent years are characterized by high levels of RES deployment and substantial feed-in of variable RES into the grid in a number of Member States. Therefore, the results are discussed in detail for the most recent years in our sample of countries. Table 3 shows selected results for Germany and Spain (countries with substantial wind power and solar PV deployment) as well as Denmark, which generates a substantial share of its electricity from wind power.

One can see that the adjusted $R^2$ differs between the different countries. Looking into a single Member States’ electricity market in detail would have allowed modeling more specifically the characteristics of the respective electricity market. However, for an overall comparison between European countries, and considering the limited data availability, this
approach yields the most comparable and robust results. In the discussion, these results will be contrasted with the literature which, as described beforehand, consists exclusively of country-specific studies (in Europe).

The coefficients on wind and solar PV infeed are economically and statistically significant. Their economic interpretation will be discussed in the following section. Cross-border flows, only available for Germany, also show significant effects – increased outflows of electricity, indicating potential oversupply on the German electricity market, and decreased electricity spot prices. 1 MWh of exported electricity decreases the spot price by \(0.0013\text{€/MWh}\) – an outflow of 1% of the average hourly load thus implies a spot price decrease of \(0.39\text{€/MWh}\). All the remaining explanatory variables also perform well in all the analyses done for the different countries. The introduction of variables is further explained in the Appendix 1, using the example of Germany. The following section presents three country case studies to give insights into different European spot markets, and to allow interpretation of the regression outcomes and the calculated market values.

**Country case studies**

**Denmark.** In Denmark, a negative but non-significant correlation can be observed between spot prices and wind infeed in the analyzed year of 2013. Hourly wind infeed varies between 12 and 4310 MWh, with an average of 1266.9 MWh in 2013. The average hourly load in Denmark is 3824 MWh, with peak values of up to 6538 MWh and minima of 2241 MWh.

![Figure 1. Electricity market variables for Denmark (analyzed year: 2013).](image-url)
Spot prices peak at 107€/MWh and can become zero or slightly negative (–0.07€/MWh). The annual mean electricity spot price was 39.9€/MWh in 2013.

Looking at the regression results for Denmark in the year 2013, one can observe an effect that is statistically and economically significant: Wind power fed into the grid in 2013 led to decreased day-ahead prices for electricity. An increase of wind infeed representing 1% of the average hourly load would lead the spot price to fall by 0.18€/MWh on average (This has been calculated as described beforehand: The coefficient describes the price decrease that occurs due to one additional MWh of wind power fed into the grid. Multiplying this by 1% of the average hourly load yields the monetary effect of a 1% increase in wind power in the hourly load.). As wind infeed in Denmark sometimes reaches values of over 100% of the average load, the impact on prices can be quite significant. The strong variability of the electricity price induces further economic effects. Large price spreads lead to higher income of electricity storage and demand-side applications (e.g. batteries, power to heat (P2H) applications). If these effects persist over a longer period of time, this sets incentives for increased investments in storage technology. This is a co-effect of the price variability which is partly attributable to high levels of variable RES infeed. In turn, this has several implications: Variable RES could be complemented by storage technology or demand-side applications, and price spikes would be smoothed out (In the longer term, this would again affect the profitability of the storage systems as they depend on the price spreads to be able to store electricity profitably. Long- and short-term storage have to be distinguished. Long-term storage (e.g. pumped hydro) benefits from larger price spreads on the electricity spot market. Short-term storage (e.g. battery) is linked to household prices. While the latter is uneconomic at the moment, technological learning is rapidly increasing and has important future implications for incorporating variable electricity at household level.17). Furthermore, the grid could be extended to better incorporate the fluctuating supply. Depending on the amount of variable RES fed in, at certain points in time, curtailing excess supply is the most economic option.18

The other regression coefficients for Denmark can be interpreted as follows: the day-ahead price that occurred 24h before has a positive influence on the spot price. Namely, if this price were one euro higher, the price of the following day is 27 cents higher on average.

Load also has a positive influence on the day-ahead price. If demand increases by 1%, the price would increase by 30 cents on average.

The standardized market value of wind power in the year 2013 is roughly 0.8, at a wind load share of almost 35%. Full load hours in 2013 were 2665 h/a – this figure is typical for a normal wind year, which was also confirmed by official sources, e.g. Kjaer (Danish Energy Agency).19 The historical data analyzed for this study do not show especially high or low demand for the year 2013. Therefore, as weather and load did not behave uncharacteristically, one can assume that our measure of the market value of wind power is largely attributable to wind power’s own increased share of electricity generation in Denmark. While the market value decreased, it still remained relatively high considering the high share of variable RES integrated into the Danish electricity market. This shows that a flexible system (like the Danish one) is able to incorporate a large volume of renewable generation without substantial decreases in its own market value. This will be discussed later on in more detail.

Germany. In Germany, the year 2012 is used to exemplify the electricity market. In this year, spot prices ranged between a maximum of 210€/MWh and a minimum of –221€/MWh, i.e. they exhibited a very large spread. The implications of this price variability are the same as
described for Denmark. The average annual spot price in 2012 was 44.8 €/MWh. The annual average of hourly wind infeed was 3832 MWh in Germany in 2012, although maxima of up to 19,497 MWh occurred at times. Hourly PV infeed peaked at 20,985 MWh and exhibited an annual average of 3061 MWh in 2012. The hourly load in Germany ranged between 14,975 and 57,767 MWh and has an annual average of 39,170 MWh.

Regression results for Germany in the year 2012 show a statistically and economically significant effect of wind power feed-in on day-ahead electricity prices. According to the findings, a price reduction of around 0.53 €/MWh would occur if 1% of average hourly load were generated from wind power. The coefficient for PV in 2012 is lower, indicating a decrease of around 0.06 €/MWh. The value increases if forecast variables for wind and PV are introduced. The coefficients are –0.0003 for solar PV and –0.0017 for wind power. For a 1% increase of the total hourly load, this implies a decrease in the electricity spot price by 0.12 or 0.68 €/MWh, respectively. These coefficients suggest that the price decrease estimated in Germany and the other countries could have been even more substantial, as the regression using actual values yields results at a higher significance level and a higher $R^2$. However, we use our results as input into the multi-country comparison.

The standardized market value of wind power in Germany in 2012 amounts to 0.89, whereas that of PV is 1.06. In 2012, the capacity factor of wind and solar, i.e. the utilization of wind and PV systems, was comparatively low – this could be an indication that the market value of both technologies was higher than usual in this particular year, as a high capacity factor usually leads to lower market values.
Spain. A negative and significant correlation between Spanish spot prices and wind infeed can be observed for the year 2013. In 2013, spot prices on the electricity market in Spain varied between 0 and 112€/MWh, with visible drops, especially in spring (see Figure 3). Values between 70 and 16,672 MW were fed in on an hourly basis by wind power in 2013, with a yearly average of 6196 MW per hour. Hourly PV infeed was more constant throughout the year, ranging between zero and 3781.7 MW. The load in Spain is also relatively constant throughout the year, at a mean of 28,140 MW per hour, and ranging from maxima of up to 39,633 to minima of down to 17,096 MWh at times.

In 2013, wind infeed had a negative effect on electricity spot prices according to the regression results for Spain. One percent additional wind power as a share of the average hourly load would have lowered spot prices on average by 0.8€/MWh in 2013. A similar effect can be observed for PV. An increase of hourly infeed by one GWh would have induced prices to fall by roughly 0.8€/MWh. In 2013, savings from an additional percent of wind would have amounted to €197.5 million and about the same amount for an increase of PV infeed. To scale up this effect and present an example, in 2013, savings induced by an additional GWh of hourly infeed would have amounted to €700 million for wind, and similar savings could be expected for an additional GWh of hourly PV infeed.

In 2013, the standardized market value of PV in Spain was 1.05, and 0.9 for wind power. This outcome does not seem to be driven by irregularities that occurred during the year, but to mainly reflect how the share of wind and solar power infeed contributes to their respective market value.

Figure 3. Electricity market variables for Spain (analyzed year: 2013).
Overview of EU member states

Figure 4 illustrates the results of our econometric approach for the geographical scope covered by our analysis. In this figure, price effects are related to the share of variable RES in the respective country’s electricity market: an increase in variable RES generation in the dimension of a 1% share of the average load of that country was used as a unit of reference for the price change. This approach is the most suitable for an overall comparison

![Merit-order effect for wind power and solar photovoltaics – comparison of price changes induced by feed-in of variable RES (2008–2014).](image)

**Figure 4.** Merit-order effect for wind power and solar photovoltaics – comparison of price changes induced by feed-in of variable RES (2008–2014).
between Member States as they do differ in size (RES targets are also set in relative terms for this reason). Apart from a few outliers, there is a clear trend that a higher load share of variable RES leads to lower electricity prices, and can thus induce a merit-order effect. This trend is even more apparent in more recent years, whereas earlier years show more dispersion, possibly due to other unobserved effects that also influence electricity spot prices.

Discussion

The literature on the merit-order effect and historical market values of variable renewables, as discussed above, features diverse approaches and spans a large bandwidth of outcomes. In the following, results from the literature are compared more specifically with the three case study regions assessed here. In the literature, an effect was mostly calculated for an additional GWh of variable RES per hour. To be able to compare our findings for Denmark, Spain and Germany with those from the literature, we also scaled up our outcomes to this measure.

Scaling up our results led to outcomes similar to the literature for Germany, i.e. 1.49€/MWh (2012) compared to around 2€/MWh for wind and solar PV together (2010–2012).4 For Spain, Gelabert et al.5 estimated a downward effect of around 2€/MWh on average for the years 2005 to 2009. For 2012, downward effects of wind power on electricity spot prices of over 10€/MWh have been found in the literature.7 Our finding of a decrease by 5.68€/MWh for one additional GWh of RES (if the coefficients for wind and solar PV are combined) is lower, but a direct comparison is not possible as a different measure was applied in Azofra et al.7 The same problem exists for Denmark, as the approaches applied in the literature are quite different to ours and not directly comparable. Results from the literature describe a Danish market with or without wind power and a paper from 2010 claims that 40% in price variation is attributed to wind power.9 Our result shows an average price decrease of 4.7€/MWh if one additional GWh were generated by wind power – the actual hourly price effect is also subject to large fluctuations due to the high level of wind penetration in the Danish market.

To summarize, our results are robust to different specifications, yield significant coefficients and do not differ substantially from findings in the literature. The multi-country approach seems to be quite suitable for an analysis of the whole of Europe, although the drawbacks mentioned earlier must be considered. The main lessons learned from the multi-country analysis are that, first of all, effects differ over countries, showing that different electricity markets are more or less able to incorporate large shares of RES. In Spain, for instance, the merit-order effect is relatively high. This effect is also visible in the relatively low market value for wind power and PV (compared to other European countries). In Denmark, on the other hand, average effects are not as substantial and the market value for wind power is also quite high considering the large share of total electricity demand it meets. This could be due to more flexible demand-side management that incorporates large shares of renewable electricity into the heating system if necessary.20 In Germany, when looking at generation profiles, it can be assumed that a balanced mix of renewables leads to a more stable infeed pattern of renewable electricity. This could prevent the extreme fluctuations that occur if only one technology is predominant, and could also be a possibility to prevent extreme impacts of fluctuating renewables on electricity prices. Looking at the different strategies applied to incorporate large shares of renewables into different electricity
markets yields interesting insights for other Member States that have not yet expanded their RES share to such an extent.

**Conclusions**

This study shows that a downward trend of electricity spot prices was induced by feeding in renewables in all the European Member States analyzed. At the same time, the market values of renewables decreased with their increasing share in total electricity demand. Focusing on three case study countries, these effects were discussed in more detail and contrasted with other regression specifications, as well as with historical market values of renewables. This confirmed the effect. Taking into account the drawbacks of a “macro” approach in comparison to country-specific analyses such as those discussed in the literature review, our study provides an integrated picture of Europe’s electricity markets and outcomes for Member States that have not been analyzed to this extent before. In terms of further research, it would be interesting to study the effects and determinants of increased price variability in more detail, as well as cross-country impacts between strongly interconnected regions. It would also be interesting and important to include fossil fuel prices as well as the CO₂ price into the different analyses, to enable a more complete understanding of the respective electricity markets.

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### Appendix 1

**Explaining the baseline estimation using the German Electricity Market**

Based on the example of Germany in the year 2008, in the following, it is briefly shown how the determinants chosen for the baseline regression model were introduced into the model and how they changed the regression fit and the adjusted R2. One can observe that, while the explanatory power of the model increases with all additional control or explanatory variables, introducing PV in the fifth model specification does not further increase the R2. This is due to the fact that PV capacity was comparably low in Germany in 2008 – an effect that is

<table>
<thead>
<tr>
<th>Variable</th>
<th>Germany</th>
<th>Denmark</th>
<th>Spain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>0.00045846</td>
<td>0.0080714</td>
<td>0.0020531</td>
</tr>
<tr>
<td></td>
<td>(0.000016985)</td>
<td>(0.00016509)</td>
<td>(0.00002713)</td>
</tr>
<tr>
<td>Cross-border flows</td>
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</tr>
<tr>
<td></td>
<td>(0.00036044)</td>
<td></td>
<td></td>
</tr>
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<td>-0.0047187</td>
<td>-0.0028472</td>
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<td>(0.000025069)</td>
<td>(0.00010867)</td>
<td>(0.00003482)</td>
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<td>PV infeed</td>
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<td>-0.0028387</td>
</tr>
<tr>
<td></td>
<td>(0.000039878)</td>
<td></td>
<td>(0.00009386)</td>
</tr>
<tr>
<td>24 h lagged spot price</td>
<td>0.46986</td>
<td>0.27302</td>
<td>0.31939</td>
</tr>
<tr>
<td></td>
<td>(0.0071222)</td>
<td>(0.010785)</td>
<td>(0.006631)</td>
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<tr>
<td>Monthly dummies</td>
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<td>✓</td>
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<tr>
<td>Weekly dummies</td>
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<td>✓</td>
</tr>
<tr>
<td>Year</td>
<td>2012</td>
<td>2013</td>
<td>2013</td>
</tr>
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<td>8330</td>
<td>8736</td>
</tr>
<tr>
<td>Adjusted R2</td>
<td>0.625</td>
<td>0.693</td>
<td>0.818</td>
</tr>
</tbody>
</table>

Multivariate regression estimation of hourly changes in electricity prices.
also visible for other Member States during that year. In more recent years, the economic significance of solar power has increased.

In the model specification (1), it can be seen that weekly and seasonal variation explain around 15% of price changes. The load – unsurprisingly – determines the main share of the electricity price and has a positive coefficient: Increased demand causes electricity prices to rise in line with basic market reasoning: If demand increases and supply remains unchanged, a shortage occurs, leading to a higher equilibrium price.

Table 2. Different model specifications to estimate the effect of RES feed-in on day-ahead prices in Germany.

<table>
<thead>
<tr>
<th></th>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
<th>Model 4</th>
<th>Model 5</th>
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<td>0.0019253</td>
<td>0.002111</td>
<td>0.0020983</td>
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<tr>
<td></td>
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<td>(0.00002208)</td>
<td>(0.000019873)</td>
<td>(0.000020337)</td>
<td></td>
</tr>
<tr>
<td>Wind infeed</td>
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<td>-0.0020057</td>
<td>-0.0020042</td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>(0.000040617)</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>24 h lagged spot price</td>
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<td>0.22424</td>
<td>0.22128</td>
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<td></td>
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<tr>
<td></td>
<td>(0.0073928)</td>
<td>(0.0066027)</td>
<td>(0.0066929)</td>
<td></td>
<td></td>
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<tr>
<td>Monthly dummies</td>
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<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weekly dummies</td>
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<td>✓</td>
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</tr>
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<td>0.741</td>
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</table>

OLS estimation of hourly changes in electricity prices (Germany).
As electricity spot prices are non stationary, the lagged value (24 h behind) was also introduced as a control variable. The lagged price is also highly significant and an increase of one euro seems to induce the day-ahead price of the same hour in the following day to be €0.27 higher on average.
The fit of the model improves further when introducing wind infeed as a determinant of electricity prices. PV infeed, at least in the year 2008 for Germany, does not improve the fit, but it does yield a significant coefficient.

Table 3. Regression outcomes of the effect of infeed of variable RES on the day-ahead spot price (base year: 2008).

<table>
<thead>
<tr>
<th></th>
<th>Germany</th>
<th>Belgium</th>
<th>France</th>
<th>Netherlands</th>
<th>UK</th>
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<tbody>
<tr>
<td>Load</td>
<td>0.0020983</td>
<td>0.015268</td>
<td>0.0025147</td>
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</tr>
<tr>
<td></td>
<td>(0.000020337)</td>
<td>(0.00019212)</td>
<td>(0.000024843)</td>
<td>(0.000009812)</td>
<td>(0.0000257170)</td>
</tr>
<tr>
<td>Wind infeed</td>
<td>-0.0020042</td>
<td>-0.051258</td>
<td>-0.0024276</td>
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</tr>
<tr>
<td></td>
<td>(0.000040607)</td>
<td>(0.0035567)</td>
<td>(0.00030201)</td>
<td>(0.00006732)</td>
<td>(0.000251999)</td>
</tr>
<tr>
<td>24 h lagged spot price</td>
<td>0.22128</td>
<td>0.23987</td>
<td>0.27386</td>
<td>7.2565</td>
<td>0.44611</td>
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<tr>
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<td>(0.0066929)</td>
<td>(0.0077914)</td>
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<tr>
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<tr>
<td>Weekly dummies</td>
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<td>✓</td>
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<td>✓</td>
</tr>
<tr>
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<td>8736</td>
<td>8699</td>
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<tr>
<td>Adjusted R2</td>
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<td>0.703</td>
<td>0.817</td>
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<td>0.81</td>
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</table>

OLS-Estimation of hourly changes in electricity prices (incl. 24 h price lag).