Renewable Energy 57 (2013) 94–100

Contents lists available at SciVerse ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

# The impact of renewable energy on electricity prices in the Netherlands

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ARTICLE INFO

Article history:
Received 31 October 2012
Accepted 18 January 2013
Available online 21 February 2013

Keywords:
Electricity prices
Merit order
Renewable energy
Wind speed
Sunshine
Water temperature

ABSTRACT

Electricity markets may become more sensitive to weather conditions because of a higher penetration of renewable energy sources and climatic changes. We investigate whether weather conditions had a growing influence on the average daily day-ahead price in the Dutch electricity market in the period 2006–2011, a period when renewable energy production increased. We account for weather conditions in both the Netherlands and Germany, as these two markets are closely connected. We find that the average wind speed in Germany negatively affects Dutch electricity prices. This effect is fairly constant despite the significant increase in German wind energy capacity. The impact of wind speed in the Netherlands on Dutch electricity prices slightly increased. We do not find a robust effect of the intensity of sunshine on electricity prices. The Dutch electricity price remains to a large extent related to the marginal costs of conventional gas-fired power plants. Although renewable energy sources have an increasing share in the generation portfolio, their impact on the electricity price in the Dutch electricity market is modest.

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## 1. Introduction

Electricity markets have changed substantially in the last couple of years, partly as a result of policies promoting sustainable ways of generation [1,2]. Electricity producers have to participate in the European emissions trading scheme, raising the opportunity cost of using carbon fuels [3]. In addition, subsidy schemes and tax incentives, amongst others, have given a boost to the installation of windmills, solar cells and Combined Heat & Power installations (CHP) [4]. Growth in wind and solar capacity makes electricity generation more sensitive to climate conditions [5–8]. If the wind blows or the sun shines, the supply curve moves to the right as these forms of electricity generation are characterised by very low marginal costs. As a result, the electricity price may become more directly connected to weather conditions and less to the marginal costs of fossil-fuel plants [9–11]. In addition, the growth of CHP capacity also raises the potential impact of outdoor temperature on electricity supply as these plants are mainly dispatched to produce heat. As such, climate factors might come to play a more important role in the electricity market. For example, higher temperatures can result in more cooling problems for thermal power plants, for instance if they become restricted in using river water for cooling purposes [12,13]. Higher temperatures also mean a growing demand for cooling by residential users [14]. As such, it is important to investigate how climate connects with electricity prices.

Although electricity demand and supply may become more climate sensitive, it is not clear whether this will also hold for the electricity price. This will depend on the shape of both the supply and demand curve. The flatter these curves, the smaller the price effect of changes in supply and demand, i.e. the higher the price elasticity. In Fig. 1, we show the day-ahead electricity price in euros per MWh in the Netherlands (APX market) for the period 2006–2011. This figure suggests that the price elasticity in the Dutch electricity market has increased. Prices were very volatile a number of years ago, but they became more moderate in recent years. Given this pattern, one may doubt whether the increasing share of renewable energy sources in electricity supply (see also Ref. [15]), has resulted in a larger impact on electricity prices as well. This is the focal point of this paper, in which we investigate whether the impact of climate factors on the daily average day-ahead Dutch electricity price has changed during the period 2006–2011. As the Dutch electricity market is closely linked to the German one, we also take German climate conditions into account. To illustrate this link: the magnitude of the cross-border transport capacity between the Netherlands and Germany is about 3 GW, which is the equivalent of 15% of Dutch peak demand [34].

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http://dx.doi.org/10.1016/j.renene.2013.01.025

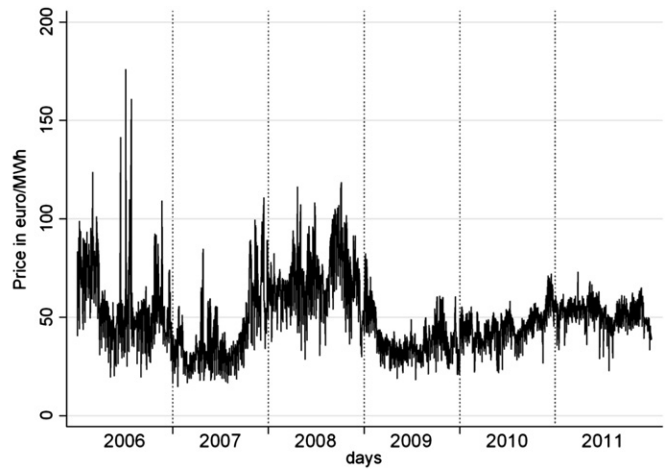


**Fig. 1.** The day-ahead electricity price (APX) in The Netherlands, 2006–2011 (daily averages). Source: Bloomberg.

Our research relates to the debate on the capability of electricity-only markets to provide sufficient incentives for investments in generation capacity when there is an increasing role of renewable energy [1,12,16,17]. If electricity prices become more sensitive to weather conditions, they may show higher volatility. During favourable weather conditions, high levels of production from wind and solar installations may press the electricity price close to zero, while during less favourable conditions, prices might surge to levels reflecting supply scarcity. In addition, the average price level over time could turn out to be insufficient to give investors in generation capacity a 'proper' return on their investments, in particular in peak generation capacity [18]. The result could be the foreclosure of conventional power plants before an encompassing and reliable renewable energy infrastructure and the accompanying institutions are in place [19].

The structure of the remainder of this paper is as follows. In Section 2 we discuss our empirical model and the data. Section 3 describes the results of the time series analysis, while Section 4 concludes.

## 2. Model and data

In order to estimate the impact of specific factors on prices, we need to control for all factors which affect movements of the demand or the supply curve [20]. To this extent, we include the major factors playing a role in setting the day-ahead electricity price in the Dutch market ($P$). Model *(1)* gives the reduced-form equation in which we use instrumental variables capturing demand and supply conditions (see Ref. [21] for a long–run equilibrium model). This equation will be estimated using daily data derived from a number of sources, which will be mentioned below. In our model, we include both economic and climate factors. The main economic factors affecting the electricity price are the overall tightness in the market ($D$), the intensity of competition ($C$) and the marginal costs of production ($F$). The main climate factors which are taken into account are the speed of wind, both in the Netherlands and Germany ($W^{NL}$ and $W^{GER}$), daylight (DL; being the same in the two countries as they are on the same latitude), the intensity of sunshine in the two countries ($S^{NL}$ and $S^{GER}$) and the temperature of river water in the Netherlands (RTR). We include day-of-the-week dummies to control for weekly patterns. Note that seasonal patterns already are captured by the daylight variable. We estimate the model in logs as the impact of the explanatory variables on the electricity prices is likely to be non-linear [6,8]. However, the variables RTR, $S^{NL}$ and $S^{GER}$ cannot be expressed in logs as their value is zero for most (RTR) or for some days. As such, we get the following equation:

$$\begin{aligned}\mathrm{Log}\left(P\right) = {} & ß_0 + ß_1\log\left(D\right) + ß_2\log\left(C\right) + ß_3\log\left(F\right) + ß_4\mathrm{RTR} \\ & + ß_5\log\left(W^{NL}\right) + ß_6\log\left(W^{GER}\right) + ß_7\log\left(\mathrm{DL}\right) + ß_8 S^{NL} \\ & + ß_9 S^{GER} + ß_{10}\mathrm{Dummy\ Sunday}\ldots \\ & + ß_{15}\mathrm{Dummy\ Friday} + \varepsilon \end{aligned} \tag{1}$$

Below we elaborate on each of the explanatory variables.

### 2.1. Tightness of the market

The tightness of the market is an important factor as the demand for electricity is highly volatile while generation capacity is inflexible in the short run. A higher demand for electricity implies that the demand curve shifts to the right along the merit order, enabling the marginal firm to charge a price above its marginal costs until the marginal costs of the last unit not dispatched [22]. In addition, the more capacity used, the weaker the ability of the remaining capacity to respond to further demand increases. We measure this effect by the daily average level of the residual demand, which is the demand

**Table 1**
Average annual values of main economic variables, 2006–2011.

| | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|
| APX (Euro/MWh) | 57 | 39.9 | 70.1 | 39.2 | 45.4 | 52.1 |
| Demand (GW/day) | 241.6 | 232.1 | 219.5 | 200.3 | 218.0 | 210.0 |
| - Production | 174.2 | 183.5 | 177.7 | 187.2 | 197.2 | 172.2 |
| - Import | 70.3 | 59.8 | 60.0 | 47.1 | 45.5 | 56.6 |
| - Export | 2.9 | 11.3 | 18.2 | 34.1 | 24.7 | 18.8 |
| RSI (index) | 1.3 | 1.3 | 1.2 | 1.2 | 1.3 | 1.4 |
| Gas price (Euro/MWh) | 20.3 | 14.5 | 24.9 | 12.3 | 17.4 | 22.6 |

Sources: APX and gas price: Bloomberg; other variables: NMa.
Note: Demand refers to the residual demand of the centralised generation units, which is equal to the production by these units plus total imports minus total exports.

excluding the demand met by decentralised generation. Using data collected by the Dutch Competition Authority [23], we calculate this residual demand as the aggregated production of the domestically centralised generators plus imports minus exports. In the period under review, the residual demand in the Netherlands is characterized by a lot of volatility: the highest level of demand is about twice as high as the lowest level of demand. In addition, Table 1 shows that there is a relatively strong decline in 2009, which is caused by the economic downturn after the outbreak of the financial crisis that resulted in a decline in the overall demand for electricity [24]. To some extent, the decline in residual demand is caused by an increase in decentralised production: on annual basis, the production by decentralised units increased from 31.7 TWh in 2006 to 42.2 TWh in 2011, while the production by the centralised units remained about the same [25]. A lower overall demand and a higher supply by decentralised production units both have a negative impact on power prices.

### 2.2. Intensity of competition

The intensity of competition in the electricity industry strongly depends on the magnitude of demand on the one hand and the flexibility of supply on the other [26]. A frequently used measure for competition in the electricity market is the Residual Supply Index (RSI), which was first introduced by Sheffrin [27] for the Californian electricity market (see also [28,29]). The basic formula for the *RSI* of firm $i$ is:

$$\mathrm{RSI}_i = \frac{\sum_{j=1}^{n} \mathrm{CAP}_j - \mathrm{CAP}_i}{\mathrm{TD}} \tag{2}$$

where CAP denotes capacity, TD total demand, and $i$ and $j$ are firm indices. Note that $\mathrm{RSI}_i$ measures the aggregate supply capacity remaining in the market after subtracting firm $i$'s capacity, relative to total demand. If the $\mathrm{RSI}_i$ is below 1, firm $i$ is needed to meet demand, which makes it a pivotal player. The advantage of RSI over other structural indicators is that it accounts for the relative position of firms compared to other producers while including total demand [30]. The lower RSI, the more market power a firm is supposed to have. Hence, we expect a negative relationship between RSI and the day-ahead electricity price. We measure total capacity as the sum of domestic generation capacity and the import capacity. The relevant demand is based on the net load of the Dutch system, which is equal to actual domestic generation plus imports minus exports (see Section 2.1). We establish that RSI gradually increased since 2008, implying that market power in the Dutch market is decreasing (see Table 1).

### 2.3. Marginal costs

We use (daily day-ahead) natural gas prices as a measure for the marginal costs of production, as gas-fired power plants determine a significant part of the merit order in the Dutch market [23]. An increase in the gas price means that the supply curve moves upwards. Hence, we expect that the gas price has a positive impact on the electricity price. In the period 2006–2011, the daily day-ahead gas price on the Dutch gas market (TTF) fluctuated between € 5 and € 50 per MWh. At the beginning of the period, it stood at € 28 and dropped to less than € 10 in spring 2007. It rose to more than € 30 in the autumn of 2008 and then again dropped below € 10 in spring 2009. Since then, it has gradually increased to the € 20–25 range.

### 2.4. Wind energy

Wind-powered electricity generation has grown strongly in many countries as it is increasingly becoming economically attractive. This holds in particular for Germany, where it has almost doubled to about 25 GW in 2012, but much less so for the Netherlands [31]. Since the marginal costs of wind powered generators are low, more wind powered production may lead to lower market prices, which is called the merit-order effect of wind power [32]. If the wind blows, the merit order shifts to the right, resulting in a lower electricity price. We expect that the increase in wind-generation capacity has resulted in more influence of wind on the electricity price. Although firms use wind-speed forecasts to schedule their wind-power production for the day-ahead market (e.g. Ref. [33]), we use data on actual hourly wind speed, taking into account technical restrictions in the power production by windmills. We define wind energy ($W$) to be equal to the cube of wind speed, as physics laws hold that kinetic energy is ½ times mass times the square of speed and that mass per second is proportional to speed. In addition, since wind turbines start producing electricity at wind speeds of approximately 1.6 m/s (equal to Beaufort wind force 2) and have to be shut down at wind speeds of approximately 24.5 m/s (equal to Beaufort wind force 10) to prevent damage to the turbines, we correct the wind energy to be 0 in those instances. As model *(1)* is on daily basis, we include the daily averages of the hourly wind energy.

Because the Dutch market is closely linked to the German market, where a large number of windmills have been installed, we include wind energy of both the Netherlands ($W^{\mathrm{NL}}$) and Germany ($W^{\mathrm{GER}}$). The data on wind energy in the Netherlands is based on the average wind energy measured in a number of locations. We use data published by the Dutch meteorological institute (KNMI) for a number of locations in coastal regions where most windmills are sited, namely Valkenburg, De Kooy, Lelystad, Leeuwarden, Lauwersoog and Wilhelminadorp. For Germany we use wind speed data published by German meteorological institute (DWD) referring to five different locations (Berlin, Kiel, Hannover, Düsseldorf and München), as windmills are not concentrated in specific regions in Germany but spread over the country. German wind energy ($W^{\mathrm{GER}}$) is the average of these five locations.

In order to test to which extent wind energy ($W$) adequately captures the effect of wind production, we also estimate model *(1)*

**Table 2**
Descriptive statistics.

| | Mean | Std. dev. | Min. | Max. |
|---|---|---|---|---|
| Log(APX) | 3.86 | 0.34 | 2.69 | 5.17 |
| Log(demand) | 5.39 | 0.13 | 4.93 | 6.17 |
| Log(RSI) | 0.22 | 0.19 | −0.24 | 1.04 |
| Log(Gas price) | 2.87 | 0.35 | 1.50 | 3.90 |
| RTR* | 0.04 | 0.23 | 0 | 2.80 |
| Log($\mathrm{Wind}^{\mathrm{NL}}$) | 4.58 | 1.32 | −3.77 | 7.91 |
| Log($\mathrm{Wind}^{\mathrm{GER}}$) | 3.70 | 1.17 | 0.42 | 7.22 |
| Daylight | 737 | 184 | 463 | 1006 |
| $\mathrm{Sun}^{\mathrm{NL}}$ | 0.38 | 0.27 | 0 | 0.93 |
| $\mathrm{Sun}^{\mathrm{GER}}$ | 0.35 | 0.25 | 0 | 0.95 |

Note: RTR = the river-temperature restriction is measured as the number of degrees (in Celsius) above the threshold temperature of 23 °C.

**Table 3**
Correlation matrix.

| | APX | Demand | RSI | Gas price | RTR | $Wind^{NL}$ | $Wind^{GER}$ | Day- light | $Sun^{NL}$ | $Sun^{GER}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| APX | 1 | | | | | | | | | |
| Demand | 0.048 | 1 | | | | | | | | |
| RSI | −0.40 | −0.48 | 1 | | | | | | | |
| Gas price | 0.069 | 0.21 | 0.04 | 1 | | | | | | |
| RTR | 0.10 | 0.05 | 0.03 | 0.03 | 1 | | | | | |
| $Wind^{NL}$ | −0.14 | −0.15 | 0.07 | −0.01 | −0.08 | 1 | | | | |
| $Wind^{GER}$ | −0.18 | −0.09 | 0.07 | −0.04 | −0.07 | 0.78 | 1 | | | |
| Daylight | −0.18 | −0.27 | 0.28 | −0.13 | 0.19 | −0.13 | −0.16 | 1 | | |
| $Sun^{NL}$ | −0.02 | −0.14 | 0.07 | −0.05 | 0.09 | −0.23 | −0.29 | 0.33 | 1 | |
| $Sun^{GER}$ | −0.03 | −0.11 | 0.10 | −0.06 | 0.15 | −0.27 | −0.36 | 0.43 | 0.70 | 1 |

Note: all variables are measures in logs, excluding RTR (River temperature restriction) and sun intensity ($Sun^{NL}$ and $Sun^{GER}$).

by using actual data on wind production in Germany, published by the German TSOs (Amprion, 50Hertz, TenneT and Transnet). If wind energy, which is calculated on the basis of actual wind speed data, is closely related to actual wind production, as happens to be the case, we may use the former in our regression analysis.

### 2.5. Daylight and sun intensity

Another environmental factor which may have become more important for the electricity market is the duration of daylight. This factor affects both demand and supply. Electricity consumption in the Netherlands is for a substantial part meant for lighting; hence, the longer the days, the lower demand, which has a price-reducing effect. Day length also affects supply. The longer the days, the more electricity solar cells produce. This means that the supply curve moves to the right, reducing prices. Because of the growth in solar cell capacity installed, in particular in Germany (from about 3 GW to almost 25 GW; [34]) but not in the Netherlands, we expect that the negative impact of daylight on prices has increased. We include daylight in our analysis by the daily number of minutes of daylight, which is the same in the two countries as they are on the same latitude.

In addition, we include a variable measuring the intensity of sunshine in order to control for the fact that summer days can be cloudy while winter days can be sunny. We measure this weather condition by the number of hours of sunshine as a percentage of total number of hours of daylight, averaged for a number of weather stations in The Netherlands (Valkenburg, De Kooy, De Bilt, Lelystad, Leeuwarden, Lauwersoog, Wilhelminadorp and Maastricht) as well as for Germany (Berlin, Kiel, Hannover, Düsseldorf and München). The data, derived from the websites of the Dutch and German meteorological institutes (KNMI and DWD, respectively) show that the intensity of sunshine has a seasonal pattern and fluctuates from day to day.

In order to test to which extent the variable intensity of sun shine (S) adequately captures the effect of solar energy, we also estimate model *(1)* by using actual data on solar production in Germany, published by the German TSOs (Amprion, 50Hertz, TenneT and Transnet, respectively) on their respective websites. As data on solar production is only available for the year 2011, this test is done for that year only. If the effect of the intensity of sun shine is closely related to the effect of solar production, as happens to be the case, we may use the former in our regression analysis.

### 2.6. Temperature of river water

Environmental restrictions on thermal power plants using river water for cooling purposes may impact on electricity prices as well. If the water temperature exceeds a certain threshold (in the Netherlands 23 °C), power plants are forced to reduce their production for environmental reasons. Hence, higher temperatures of river water means that the supply curve shifts to the left. For the German wholesale market, McDermott and Nilsen [13] find that electricity price rises by approximately 0.2% for every degree that the river temperature exceeds the regulatory threshold. We take account of this effect through a variable that measures the number of degrees the actual river temperature exceeds the threshold temperature. The data on the river temperature, which are obtained from Rijkswaterstaat, refer to the temperature of the river Lek close to Hagesteijn.

## 3. Results

### 3.1. Statistics

We estimate the day-ahead price in the Dutch market on the basis of daily data over the period 2006–2011 with model *(1)*. We use daily instead of hourly data as most of our explanatory variables are only available on a daily basis. In order to control for endogeneity, we include the lags of the explanatory variables ‘demand’ and ‘gas price’. We include day dummies to capture weakly patterns in demand. Table 2 has the descriptives of the variables, while Table 3 gives the correlation matrix. The temperature of river water was at maximum 2.8 °C above the environmental threshold. Table 2 also shows that the Netherlands, on average, is windier than Germany, and has slightly higher sun intensity. Before using the data in the regression analysis, we apply statistical tests on stationarity, autocorrelation and the presence of ARCH effects (not reported here but available upon request). Tests on unit roots with the Elliott-Rotherberg Stock test suggest that the data are stationary. Hence, the model is estimated in levels. We also include two AR variables to control for autocorrelation and we add a variance equation to control for clustered volatility. In order to examine whether the impact of the explanatory variables changes over time, we estimate the model for three subsequent periods: 2006–2007, 2008–2009 and 2010–2011. Note that as our model is estimated in logs, the coefficients can be read as elasticities, enabling us to compare the size of coefficients for the different variables within one period as well as to compare the coefficients between the periods.

### 3.2. Findings

We find that the economic factors have an impact on the electricity price, with the variables all showing the expected signs (see Table 4). Both demand and gas price have a positive effect on electricity prices. In particular, the gas price appears to be a key factor behind electricity prices, with an elasticity of about .6, which exceeds the impact of changes in demand. The market structure, captured by RSI, had a relatively large influence on electricity prices in 2006–2007, but this effect declined to a much lower level, indicating that the electricity market has become more competitive

**Table 4**
Effects of explanatory variables on the log of the average daily APX price, 2006/2007, 2008/2009 and 2010/2011.

| Explanatory variables | 2006–2007 | 2008–2009 | 2010–2011 |
|---|---|---|---|
| Log(demand(−1)) | 0.47 (0.03)*** | 0.45 (0.02)*** | 0.39 (0.02)*** |
| Log(RSI) | −0.65 (0.07)*** | −0.16 (0.03)*** | −0.18 (0.02)*** |
| Log(gas price(−1)) | 0.58 (0.04)*** | 0.59 (0.04)** | 0.62 (0.04)*** |
| River temperature restriction | −0.01 (0.04) | 0.04 (0.1) | 0.01 (0.04) |
| Log($Wind^{NL}$) | −0.004 (0.006) | −0.01 (0.005)** | −0.001 (0.003)*** |
| Log($Wind^{GER}$) | −0.03 (0.008)*** | −0.03 (0.005)*** | −0.02 (0.004)*** |
| Daylight | −0.0002 (0.0001)** | −0.00007 (0.00009) | 0.000009 (0.00006) |
| $Sun^{NL}$ | 0.003 (0.03) | −0.03 (0.02)** | −0.001 (0.01) |
| $Sun^{GER}$ | 0.03 (0.03) | 0.03 (0.02) | −0.01 (0.01) |
| Dummy Sunday | −0.11 (0.02)*** | −0.12 (0.01)*** | −0.06 (0.01)*** |
| Dummy Monday | 0.19 (0.02)*** | 0.21 (0.01)*** | 0.15 (0.01)*** |
| Dummy Tuesday | 0.16 (0.02)*** | 0.18 (0.02)*** | 0.10 (0.01)*** |
| Dummy Wednesday | 0.14 (0.02)*** | 0.16 (0.02)*** | 0.10 (0.01)*** |
| Dummy Thursday | 0.12 (0.02)*** | 0.16 (0.02)*** | 0.09 (0.01)*** |
| Dummy Friday | 0.08 (0.02)*** | 0.13 (0.01)*** | 0.09 (0.01)*** |
| AR(1) | 0.60 (0.04)*** | 0.70 (0.04)*** | 0.59 (0.04)*** |
| AR(2) | 0.11 (0.04)** | 0.08 (0.04)* | 0.15 (0.04)*** |
| *Variance equation* | | | |
| Constant | 0.02 (0.001)*** | 0.0005 (0.0005)*** | 0.004 (0.0002)*** |
| Residual$(-1)^2$ | 0.45 (0.07)*** | 0.32 (0.06)*** | 0.27 (0.05)*** |
| Adjusted $R^2$ | 0.82 | 0.91 | 0.82 |
| F stat. ARCH LM | 0.66 | 0.93 | 0.84 |
| No. observations | 715 | 730 | 728 |

Note: standard errors between brackets. *, ** and *** refer to 10%, 5% and 1% significance levels, respectively.

as generation capacity increased. The impact of both demand and gas price did not substantially change in this period.

Regarding the climate factors, we find that in particular wind speed in Germany affects electricity prices in the Netherlands. The price elasticity of German wind speed is about 0.03. Wind speed in the Netherlands appears to be far less important for the Dutch electricity prices. The relatively small impact of Dutch wind speed is particularly due to the fact that the magnitude of the installed wind capacity in the Dutch market is still very low compared to Germany. Interestingly, over the period 2006–2011, we do not find that the impact of wind speed increased, in spite of the strong growth in installed wind capacity. A 1% increase in wind energy in Germany (based on actual wind speed), results in a .03% decrease in the Dutch electricity price. This finding is quite in line with that of Mauritzen, who arrives at an elasticity of the same order of magnitude for the impact of Danish wind power on Norwegian price variation [35]. Our result is not particularly sensitive to replacing the variable “wind energy”, which is calculated on the basis of actual wind speed, by a variable which measures the actual feed in of electricity by wind mills into the German grid (see Appendix A). The same holds when we replace the variable ‘intensity of sun shine in Germany’ by a variable which refers to the actual solar production in Germany (see Appendix B).

As to daylight, we find a negative coefficient in the two of the three periods, as expected, but the coefficients are statistically insignificant. We also do not find robust estimates for the impact of sunshine on electricity prices. Hence, the increase in the installed capacity of solar cells seems not to have resulted in a change in the average price of electricity. Regarding the temperature of river water, we do find a positive influence for the whole period (see Appendix A), but the estimated coefficient is statistically insignificant. Again, we do not find a change in the impact of this variable.

We also included dummies for the weekdays to control for time effects in demand. Each of the dummies has a significant coefficient, as can be seen from Table 4. On Sundays, the price is below the price for Saturdays; on weekdays the day-ahead electricity price is higher, in particular on Monday and Tuesday.

Our results suggest that conventional power plants remain to be the marginal, price-setting power plants in the Dutch market, despite the enormous increase in wind and solar generation capacity in the German market, which is closely linked to the Dutch market.

## 4. Conclusions

Our findings suggest that the intersection of the demand and supply curve in the Dutch market is hardly influenced by the merit order effect of renewable energy. The growth in renewable energy has moved the supply curve to the right, but this shift apparently is too small to affect the price level where the demand curve intersects the supply curve. However, one should note that these results may be different during peak hours, when the supply curve is steeper than on average during the day. Our results may also be affected by constraints in the utilisation of the cross-border infrastructure, which may limit the impact of German wind and solar energy on the Dutch electricity prices, as has been shown by Mauritzen [35]. Further research into the magnitude of these constraints is required to come to grips with the impact of German renewable energy supply on the Dutch electricity market.

In addition, although we do not find an increasing influence of renewable energy sources on the electricity price in the Netherlands during the past six years, this may change when the magnitude of renewable energy production continues to grow. Then, at certain levels of renewable energy, electricity prices may become much less related to the marginal costs of conventional power plants. Instead, they might increasingly be driven by weather conditions on the one hand and scarcity in peak supply on the other. At which level of renewable energy this will happen also is a matter for further research.

## Acknowledgments

The authors are grateful for comments received from colleagues at NMa and RuG as well as from participants at the 32nd IAEE Conference in Venice, Italy, and to Mark Hartog van Banda for providing research assistance. The authors are of course fully responsible for any remaining shortcomings. The contents of this paper do not constitute any obligation on the NMa. Bert Scholtens wishes to thank EDGaR for providing financial support.

## Appendix A. Effects of explanatory variables on the log of the average daily APX price in two model specifications, 2006–2011.

| Explanatory variables | Model 1 (actual wind production in Germany) | Model 2 (wind energy calculated on actual wind speed in Germany) |
|---|---|---|
| Log(demand(−1)) | 0.46 (0.02)*** | 0.43 (0.01)*** |
| Log(RSI) | −0.25 (0.02)*** | −0.24 (0.02)*** |
| Log(gas price(−1)) | 0.61 (0.02)*** | 0.60 (0.02)*** |
| River temperature restriction | 0.01 (0.01) | 0.01 (0.01) |
| Log($Wind^{NL}$) | −0.01 (0.002)*** | −0.01 (0.002)*** |
| Log($Wind^{GER}$) | | −0.03 (0.003)*** |
| Log($windproduction^{GER}$) | −0.03 (0.004)*** | |
| Daylight | −0.0001 (−0.00005)** | −0.0001 (−0.00005)** |
| $Sun^{NL}$ | −0.006 (0.01) | −0.007 (0.01) |
| $Sun^{GER}$ | 0.02 (0.01)* | 0.01 (0.01) |
| Dummy Sunday | −0.08 (0.01)*** | −0.09 (0.005)*** |
| Dummy Monday | 0.20 (0.01)*** | 0.20 (0.01)*** |
| Dummy Tuesday | 0.16 (0.01)*** | 0.16 (0.01)*** |
| Dummy Wednesday | 0.13 (0.01)*** | 0.13 (0.01)*** |
| Dummy Thursday | 0.13 (0.01)*** | 0.13 (0.01)*** |
| Dummy Friday | 0.10 (0.01)*** | 0.11 (0.01)*** |
| AR(1) | 0.62 (0.01)*** | 0.64 (0.01)*** |
| AR(2) | 0.13 (0.02)*** | 0.12 (0.02)** |
| *Variance equation* | | |
| Constant | 0.01 (0.0003)*** | 0.01 (0.0003)*** |
| $Residual(-1)^2$ | 0.47 (0.04)*** | 0.48 (0.04)*** |
| Adjusted $R^2$ | 0.84 | 0.84 |
| F stat. ARCH LM | 0.42 | 0.42 |
| No. observations | 2173 | 2173 |

Note: standard errors between brackets. *, ** and *** refer to 10%, 5% and 1% significance levels, respectively.

## Appendix B. Effects of explanatory variables on the log of the average daily APX price in two model specifications, 2011.

| Explanatory variables | Model 1 (actual solar production in Germany) | Model 2 (intensity of sun shine in Germany) |
|---|---|---|
| Log(demand(−1)) | 0.21 (0.04)*** | 0.21 (0.04)*** |
| Log(RSI) | −0.04 (0.02)*** | −0.04 (0.02)*** |
| Log(gas price(−1)) | 0.94 (0.07)*** | 0.94 (0.08)*** |
| River temperature restriction | | |
| Log($Wind^{NL}$) | −0.007 (0.004)* | −0.008 (0.004)** |
| Log($Wind^{GER}$) | −0.03 (0.005)*** | −0.03 (0.005)*** |
| Daylight | 0.0000008 (−0.00007) | −0.00002 (−0.00007) |
| $Sun^{NL}$ | −0.03 (0.02)* | −0.03 (0.02) |
| $Sun^{GER}$ | | −0.02 (0.02) |
| Solar $production^{GER}$ | −0.000003 (0.000002) | |
| Dummy Sunday | −0.09 (0.01)*** | −0.09 (0.01)*** |
| Dummy Monday | 0.13 (0.01)*** | 0.13 (0.01)*** |
| Dummy Tuesday | 0.12 (0.01)*** | 0.12 (0.01)*** |
| Dummy Wednesday | 0.12 (0.02)*** | 0.12 (0.01)*** |
| Dummy Thursday | 0.12 (0.01)*** | 0.12 (0.01)*** |
| Dummy Friday | 0.11 (0.01)*** | 0.11 (0.01)*** |
| AR(1) | 0.55 (0.06)*** | 0.56 (0.06)*** |
| AR(2) | 0.19 (0.06)*** | 0.18 (0.05)*** |
| *Variance equation* | | |
| Constant | 0.003 (0.0003)*** | 0.003 (0.0003)*** |
| $Residual(-1)^2$ | 0.34 (0.13)*** | 0.36 (0.13)*** |
| Adjusted $R^2$ | 0.75 | 0.75 |
| F stat. ARCH LM | 0.81 | 0.83 |
| No. observations | 360 | 360 |

Note: standard errors between brackets. *, ** and *** refer to 10%, 5% and 1% significance levels, respectively. As the temperature of river water did not exceed the environmental threshold in 2011, this variable cannot be included in the model for this year.

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