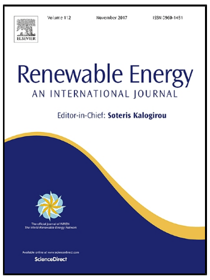

The marketability of variable renewable energy in liberalized electricity markets – An empirical analysis

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The marketability of variable renewable energy in liberalized electricity markets – An empirical analysis

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Nonstandard Abbreviations[1]

Abstract: The price effect of the rising share of renewable electricity, which is called 'merit-order-effect', leads to noticeable changes in the German power industry and debates about the electricity market design. This paper estimates the merit-order-effect induced by variable renewable energy in the German-Austrian electricity sector with a multivariate regression model. The research focus lies on the impact of the estimated effects on the marketability of variable renewable electricity generation. The results show a systematic decline of the average market revenues for wind and photovoltaic plants in the period from January 2011 to December 2013. Current market data shows a continuation of this trend into 2016. According to the German long term goals for the use of renewables, wind and solar power will play a crucial role in the future electricity generation mix. If investments in these technologies will be profitable without any regulatory remuneration mechanisms in addition to the market revenues, depends on the further cost degression and the development of the merit-order-effect.

Keywords: Photovoltaic, Wind power, Merit-order-effect, Marketability, German energy transition

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[1] VRE = Variable renewable energy
CRE= Controllable renewable energy
MOE = Merit-order-effect
EEG= Erneuerbare Energien Gesetz
EPEX = European Power Exchange
WTPI = Wind Turbine Price Index

1 Introduction

Renewable electricity generation has strongly increased in many electricity sectors worldwide. In terms of climate, environment and health protection, the electricity production from renewable energy sources is an effective way to reduce greenhouse gas emissions to reduce local emission of hazardous substances as well as to reduce energy dependence by lowering fossil fuel imports. The revenues on liberalized electricity markets are usually not high enough to trigger private investment in renewable electricity production. Therefore, states use different kinds of instruments to make renewables a profitable investment and to reach energy and climate political aims. Several countries pursue specific long term goals for the use of renewables in the energy or even in the electricity sector.

Renewable generators can be divided into controllable and variable energy sources. Variable renewable energy (VRE) generators are characterized by very low marginal costs and large fixed costs [1].Their electricity production is dependent on the availability of the main natural power resource. For example, photovoltaic (PV) systems need direct solar radiation, wind power stations need a certain level of wind speed and hydro power need the seasonal energy sources of rivers.[2] Another important characteristic of VRE technologies is that the time profile and the amount of the produced electricity are highly dependent on the location [2,3]. On the other side, controllable renewable energy (CRE) generators use bioenergy or biofuels for electricity production and are characterized by high marginal costs and lower fixed costs (compared to VRE). The electricity produced from CRE technologies is not dependent on the short term availability of natural power sources and the output is directly adjustable. Thus, CRE generators have similar economic and technical characteristics as fossil power plants, except of their carbon-neutral electricity production, of course.

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[2] Other variable renewable technologies are e. g. wave power, tidal power, geothermal power and concentrated solar power (CSP). Geothermal and CSP are not as volatile as e. g. the production of PV or wind generators. However, because of limited potential, these technologies are not widely used in Germany [4].

If the political renewable electricity generation aims require a high amount of VRE, they can have significant impacts on the electricity sectors. VRE would be the dominant electricity producer due to of their direct dependence on natural resources, they are unable to meet demand at any point of time. Fossil power and CRE generators would still be needed as reserve plants with fewer full load hours, compared to today, and additional options for flexibility on the demand side would be required to ensure system reliability [5,6,7]. Apparently, the usual roles of the different technologies are changed within the transformation towards a renewable electricity system. Associated with this transformation, the price formations will change systematically as VRE produce electricity with marginal costs that are close to zero. They bid into the market with these low marginal costs and thus, during the periods with high VRE electricity production, fossil power stations with fuel costs are squeezed out of the market. As a result of this shift of the supply curve, the wholesale power price decreases. This price effect is known as the ‘merit-order-effect’. The existing literature uses electricity market simulation models or regression analyses of historical market data to analyze the merit-order-effect [8,9]. While simulations are often used for the welfare evaluation of the renewable support policy by comparing simulated prices in hypothetical non-renewable scenarios with empirical price data, regression analyses are used for the estimation of the merit-order-effect with a straight focus on the price and distributional effects. In this paper, the merit-order-effect is also estimated with a regression analysis that shows some major differences compared to existing studies and uses additional data. However the focus of the research lies on the impact of the merit-order-effect of VRE production on the marketability of VRE technologies. If there is a systematical reduction of the wholesale prices in situations with a high VRE generation, the market revenues for VRE will decline with their further expansion (see [10] for wind and PV in Germany and [11] for PV in Italy). As a consequence, the intended financing of VRE technologies through the liberalized electricity markets without a regulatory instrument is threatened.

The article is divided into 6 parts. Following this introduction, the concept of marketability is defined and the remuneration scheme of VRE in Germany is described in Section 2. The method and the data, which are used in the regression analysis, are presented in Section 3. Within this section, the estimation model is explained and the descriptive statistics of the variables are shown. In Section 4, the estimation results of the models and robustness checks are presented. Afterwards, Section 5 compares the estimation results with those of other comparable studies and discusses the impact of the merit-order-effect on the marketability of VRE technologies. Finally, Section 6 concludes and looks at implications for the economics of VRE as well as suggests future research.

2 Marketability of variable renewable electricity

2.1 Definition

Today's VRE electricity generation was achieved through the implementation of support instruments for renewables. A regulatory remuneration is necessary as long as renewable technologies still have higher costs than conventional plants and external costs of non-renewable energies are not fully internalized [12]. One of the most effective and popular instruments are feed-in-tariffs (FIT), that offer a fixed, technology specific price per produced kilowatt-hour (kWh) to VRE generators over a determined amount of time. The height of the FIT should correspond to the levelized cost of electricity (LCOE) of the respective technology and should adequately compensate VRE investors and producers. However, the government needs a lot of information to set the FIT at the right height. Otherwise, investors and producers will be overcompensated and a welfare loss for society is created. Another common critic of FITs is the distortion of the electricity sector due to the reallocation charge that has to be paid by the consumers [13]. Next to adjusting the amount of the fixed price, there are other FIT policy design options to ensure the cost-efficiency [14] as wells as the dynamic efficiency [15]. These are the market-dependent schemes on one side and the market-independent schemes on the other side. In Germany, some of those elements, like responsive mechanisms to adjust the FIT level for PV plants, have been implemented and the market has already responded to them [16].

Despite the development and implementation of several design elements, the FIT of the Renewable Energy Source Act (Erneuerbare Energien Gesetz, EEG) in Germany is still under criticism for not being cost-efficient and having strong distributional effects [17,18]. The critics suggest to switch to other, more market-based and cost-efficient, promotion schemes. The example of Germany shows that there is an ongoing debate on how to remunerate renewable electricity in a way that facilitates a fast technology development and cost reduction as well as a demand-oriented production. The discussion is based on the general claim that VRE must get competitive and reach their marketability. But what does this mean exactly?

Private investments in VRE technologies seem to be profitable if their LCOE are below the specific individual retail electricity price. This concept, which however ignores important economic facts, is called ‘grid parity’. Neither the time nor the location nor forecast errors are taken into account. Another crucial shortcoming is that grid fees, energy taxes or a levy for the renewable remuneration scheme has to be paid for electricity consumption from the grid in addition to the generation costs [19,20]. Thus, when a VRE technology has already reached grid parity, it does not mean that this technology can be financed solely through revenues on competitive wholesale electricity markets. Based on these considerations, the concept of ‘marketability’ is defined: A generation technology is marketable if the average revenues on competitive wholesale electricity markets during its life time are high enough to cover its average total generation costs, the LCOE, without recourse to regulatory remuneration schemes. In the case of VRE, this would mean that an investment in VRE would be profitable even if there were not any regulatory mechanisms like a FIT or green certificates in addition to the market revenues.[3]

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[3] In contrast, an emission trading scheme for internalizing the external costs of greenhouse gas emissions or air pollution from the use of fossil fuels is an instrument that makes the wholesale electricity market competitive.

2.2 Remuneration and market integration of VRE in Germany

In 2014, renewable-based electricity generation was about 161.4 terawatt-hours (TWh) and had a share of 27,4% of gross electricity consumption in Germany, whereby, wind energy onshore reached about 9,5% (55.8 TWh) and PV covered about 6.0% (35.2 TWh) share of the consumption [4]. This was mainly achieved though the EEG, which consists of a FIT. The aim of the EEG [21] is to increase the renewable electricity share of gross electricity consumption in Germany to 40-45% by 2025, 55-60% by 2035 and to at least 80% by 2050. Even though the intended shares for 2050 of the different renewable technologies are not predetermined, the capacity expansion rates are predefined until 2035. According to the EEG [21], new gross installations of wind energy onshore capacity shall amount to 2.8 - 2.9 gigawatt (GW) per year, new gross installations of PV capacity shall amount to 2.5 GW per year and overall wind energy offshore capacity shall reach 6.5 GW in 2020 and 15 GW in 2030.[4] Apart from the expansion rates of the EEG, a meta-analysis of several greenhouse gas emission reduction scenarios for Germany from Schmid et al. [22] shows that a high share of VRE capacity, respective VRE electricity generation, is needed to achieve the political aims. It can therefore be assumed that there will be a large scale expansion of VRE capacities in the German electricity sector in the next decades.

In the classical EEG scheme, VRE generation, respective the day ahead forecast, that is fed into the grid are sold on the spot markets by the network operators via price inelastic bids. Since the most recent amendment of the EEG in August 2014, the market premium model is mandatory for renewable electricity-generating facilities with a maximum power output that is higher than a predetermined value. In contrast to the initial FIT remuneration scheme of the EEG, VRE electricity must be sold on the wholesale power markets or to private consumers. As a consequence, the remuneration consists of the market-dependent sales and the ‘market premium’ that can vary monthly and reconciles the difference to the technology-specific amount of the FIT. One main contrast to the classical FIT is that the predicted VRE electricity

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[4] In this context, gross installations are the overall new installations per year and net installations are the overall new installations minus the removal of existing capacity per year.

generation is not sold by the network operators, but by specialized marketers, and that the bids are not price-inelastic, but rather oriented on the amount of the monthly market premium [23]. Another main contrast is that a certain VRE-technology plant with a more demand-oriented electricity generation with a higher market value than the overall average of this VRE-technology can achieve higher financial revenues (see [24] for PV). In both cases, the cost difference between the amount of the FIT and the average spot market revenues are financed through a levy that is paid by electricity consumers.[5]

The objectives of the introduction and the ongoing expansion of the obligation for using the market premium model include the market integration of VRE. It means that they should participate directly in the electricity markets and be incentivized for adapting their production to market conditions [23]. The market integration of VRE electricity is expected to have a positive effect on their marketability and lower their integration costs [25] as a result of technological innovations and improvements in the market operations of VRE electricity producers and traders. However, an ongoing technology-specific merit-order-effect can lead to a decline of market revenues due to the simultaneity of variable renewable electricity generation within a market area. Hirth et al. [10,25] calls the costs for variability and simultaneity ‘profile costs’. Another, and a more metaphorical description for declining VRE market revenues with an increasing share is the term ‘cannibalism effect’ [24].

For analyzing the impact of this cannibalism effect on the marketability of VRE technologies, the technology-specific merit-order-effect in the German electricity market, which is connected to the Austrian market, is quantified. Furthermore, the estimated height of the merit-order-effect is discussed in connection with the technical development and cost degression of VRE technologies.

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[5] Some well-defined electricity consumers, mainly electricity-intensive industry corporations, pay only a small amount of the levy [8].

3 Data and Methods

A multivariate regression model is used for estimating the merit-order-effect of VRE electricity production in the German-Austrian electricity sector. Similar analyses were made by Würzburg et al. [9] and Cludius et al. [8] for Germany as well as by Gelabert et al. [26] for Spain. The present analysis uses modified and new variables for modelling the electricity spot price on the EPEX (European Power Exchange) SPOT day-ahead market.

The day-ahead market is the most important trading platform for VRE electricity due to the large share of trading volume and the obligation, under the German regulation for network operators, to sell the EEG electricity there. In the EPEX SPOT day-ahead market, hourly contracts for electricity are traded for the 24 hours of the calendar day. As the focus of this paper lies on the long-term marketability, and not on the short-term optimization, of VRE electricity production, I use the daily average price PHELIX (Physical Electricity Index) as the dependent variable (*phelix*) for reducing noise and excluding exceptional events at particular hours within a day. The explanatory variables are the daily net electricity consumption (*consump*), the day-ahead forecast of wind and PV electricity generation (*wind*, *pv*), the marginal costs for using coal and gas for electricity production, including the costs for carbon emissions (*burncoal*, *burngas*) and the commercial electricity trade between Germany, Austria and the surrounding neighbors (*trade*).

The variable *consump* consists of the net daily electricity consumption data by the European Network of Transmission System Operators for Electricity (ENTSO-E). In contrast to Würzburg et al. [9] who use the forecast of the vertical load[6], I use the actual consumption data. The vertical load is an adequate indicator for electricity consumption in a system with a majority of conventional large power stations that usually feed into the transmission grid. However, VRE plants usually feed their electricity generation into the subordinated distribution grid. If the consumers that are connected to the distribution grid consume less

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[6] The vertical load is the sum of all flows out of the transmission grid to connected end consumers and to the subordinated distribution grid (see the glossary of ENTSO-E for the detailed description, available at https://emr.entsoe.eu/glossary)

electricity than the connected VRE generators are producing, this surplus electricity is transferred into the transmission grid. As a result, the vertical load becomes negative. In a system with a rising share of VRE generation, this situation can occur frequently. Hence, using the vertical load as an indicator for electricity consumption is problematic within an analysis of an electricity sector with a high share of VRE electricity. A decisive key advantage of using the net daily consumption is that the whole electricity consumption in the analyzed electricity sector is covered and the previously mentioned issue of a negative vertical load is not problematic. A disadvantage is that the used data is not a forecast. An important and necessary assumption for the chosen regression methodology is that the height of the consumption is not dependent on the height of the spot price, meaning the short term electricity demand is perfectly price inelastic. This is the usual assumption made by similar studies that use regression models for quantifying the merit-order-effect because the vast majority of the consumers do not buy their electricity on the spot market and do not receive the short term price signal. Within the same regression studies, the electricity consumption usually has a high influence on the spot market price [8,26,9]. The German consumption data provided by ENTSO-E consist of aggregated data by the four German transmission grid operators. As their databases have been improved since January 2014 though, the data before January 2014 and after not directly comparable as a result.[7] To avoid biased estimators due to this changeover of the data collection, the analysis period is set from January 1, 2011 to December 31, 2013.

The variables *wind* and *pv* consist of the day-ahead VRE electricity generation forecast by the transmission grid operators for Germany and Austria.[8] The forecasts are the relevant

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[7] Until December 2013, the representativity of the consumption data was estimated to be at 91%. Since January 2014, the representativity of the consumption data was estimated to be at 98%. Unfortunately, it is not known in which hours which consumption data is exactly covered. For this purpose, a simple transformation of the hourly data is not possible.

[8] The German transmission grid operators are 50HertzTransmission, Amprion, TenneT TSO and TransnetBW. The Austrian grid operator is Austrian Power Grid (APG).

data as these are the basis for the price settlement on the day-ahead market. Again, the daily average of the hourly data is used for the analysis.

The variable *burncoal* consist of the monthly future for ARA-black coal for energy generation that is traded daily on the European Energy Exchange (EEX) and the daily price for carbon emissions (per ton) that are also traded on the EEX. The variable *burncoal* reflects the costs for burning one ton of ARA-black coal for generating electricity at time *t* and is calculated as follows:[9]

$$burncoal_t = price\ blackcoal_t + carbon\ price_t * emission\ factor_{blackcoal} \qquad (1)$$

The variable *burngas* consists of the European Gas Index EGIX for monthly futures on the German market places for natural gas NCG and Gaspool, which is traded daily on the EEX. The variable *burngas* reflects the costs for burning one MWh of natural gas for generating electricity at time *t* and is calculated by the same principle as *burncoal*: [10]

$$burngas_t = price\ natural\ gas_t + carbon\ price_t * emission\ factor_{natural\ gas} \qquad (2)$$

The variable *trade* consists of the commercial final schedule published by ENTSO-E. Thus, commercial trade data is used instead of physical flow data. As this data has been available since January 2011, this date has been chosen as the starting date for the analysis. The variable *trade* reflects the net commercial electricity trade between Germany and its neighbors (numbered with *j*), except for Austria, at time *t* and is calculated as follows:[11]

$$trade_t = \sum_{j=1}^{N} exports_{j,i} - \sum_{j=1}^{N} imports_{j,i} \qquad (3)$$

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[9] The emission factor is 2.3655, meaning that 2.3655 emission allowances per burned ton of blackcoal are needed. It is calculated by multiplying the energy content of 6.978 kWh per kg of ARA-black coal and the carbon emission factor for blackcoal of 0.339 kg per kWh [27].

[10] The emission factor is 0.202, meaning that 0.202 emission allowances per burned MWh of natural gas are needed [27].

[11] A positive value of *trade* reflects electricity exports from Germany to its neighbors and vice versa. The neighbors, which have been considered, are France, Switzerland, Poland, Sweden, Denmark, Czech Republic and the Netherlands.

Table 1 shows the descriptive statistics of the variables for each of the three years and Table 2 shows the descriptive statistics for the whole analysis period. The daily average electricity price declined constantly and its minimum during the analyzed period is negative. The daily average electricity consumption went down by 4% between 2011 and 2013 mainly because of the financial crisis and less because of higher energy efficiency. Another noticeable point is the rising daily average electricity generation from PV and wind generators. The minimum PV generation is almost zero and the maximum is clearly lower than the installed PV capacity between 2011 and 2013. The reason for this is that PV generation is directly connected with the solar radiation during the day. The minimum of the average daily wind generation lies below 1 MWh, which shows that there are less compensation effects with regards to the average wind speed in the area of Germany and Austria. The costs for burning 1 MWh of natural gas increased about 6% from 2011 to 2013, primarily due to rising costs for natural gas. The price for carbon emission allowances instead dropped about 65% from 2011 to 2013. The same applied to the price for black coal, which dropped about 29% from 2011 to 2013. As a consequence, the price for burning a ton of black coal distinctly decreased about 39% from 2011 to 2013. The trade balance became increasingly positive, meaning that Germany became an electricity exporter.

Table 1: Descriptive statistics for the years 2011-2013

		2011 *N=365*		2012 *N=366*		2013 *N=365*	
	Unit	*M*	*SD*	*M*	*SD*	*M*	*SD*
phelix	€/MWh	51.12	8.32	42.60	12.82	37.78	11.48
consump	GWh	63.17	7.64	61.32	7.65	60.82	7.02
wind	GWh	5.26	4.10	5.71	4.05	5.92	4.48
pv	GWh	2.24	1.27	3.19	1.98	3.46	2.38
burngas	€/MWh	26.17	1.43	26.53	1.63	27.70	0.71
burncoal	€/t	117.75	8.22	90.37	4.63	72.22	3.70
trade	GWh	-1.09	2.59	0.08	1.70	0.46	2.11

Abbreviations and nomenclature: *M*=mean/ *SD*=standard derivation/ phelix=daily average electricity price/ consump=daily net electricity consumption/ wind and pv=day-ahead forecast of wind and PV generation/ burngas and burncoal=marginal costs for using gas and coal for electricity production, including the costs for carbon emissions/ trade= commercial daily electricity trade between Germany, Austria and the surrounding neighbors.

Table 2: Descriptive statistics for the whole analysis period

	N	*M*	*SD*	*Min*	*Max*	*Q1*	*Q3*
phelix	1096	43.83	12.33	-56.87	98.98	36.64	52.01
consump	1096	61.77	7.50	43.66	77.40	55.94	67.28
wind	1096	5.63	4.22	0.57	24.63	2.54	7.58
pv	1096	2.97	2.00	0.07	8.54	1.25	4.35
burngas	1096	26.88	1.47	22.64	29.97	25.73	27.94
burncoal	1096	93.44	19.61	66.18	132.78	73.99	113.81
trade	1096	-0.18	2.26	-6.08	5.70	-1.89	1.43

Abbreviations and nomenclature: *N*=number of observations/ *M*=mean/ *SD*=standard derivation/ *Min*=minimum/ *Max*=maximum/ *Q1*=lower quartile/ *Q3*=upper quartile/ phelix=daily average electricity price/ consump=daily net electricity consumption/ wind and pv=day-ahead forecast of wind and PV generation/ burngas and burncoal=marginal costs for using gas and coal for electricity production, including the costs for carbon emissions/ trade= commercial daily electricity trade between Germany, Austria and the surrounding neighbors.

As an initial step, before describing and estimating the regression model, the daily time series are tested for unit roots and stationarity using the augmented Dickey-Fuller (ADF) test [28]. The test statistics (see Table A.1) indicate that four of the time-series are I(1) with a 1% critical value. As a consequence, the regression model will be estimated in first differences.

The regression model includes several dummy variables to control for the seasonality of electricity prices. Six variables for the seasonality during the week (Monday to Saturday, whereby Sundays and statuary holidays are combined in one variable), eleven variables for the seasonality during a year (January to November) and two variables for each year (2011 and 2012). The variables *burncoal* and *burngas* have a time-lag of *t-1* because a plant operator decides his bid price for the day-ahead market on the basis of the fuel and carbon prices on the day before the compliance.

Considering the above, the following regression model is estimated:

$$\Delta phelix_t = \beta_0 + \beta_1 \Delta consump_t + \beta_2 \Delta wind_t + \beta_3 \Delta pv_t + \beta_4 \Delta burngas_{t-1} + \beta_5 \Delta burncoal_{t-1} + \beta_6 \Delta trade_t + \sum_{k=1}^{6} \beta_{k+6} dd_{k,t} + \sum_{l=1}^{11} \beta_{l+12} dm_{l,t} + \sum_{m=1}^{3} \beta_{m+23} dy_{m,t} + u_t \qquad (4)$$

where the variable *phelix* stands for the daily average electricity price, *consump* for the daily net electricity consumption, *wind* and *pv* for the day-ahead forecast of wind and PV generation, *burngas* and *burncoal* for the marginal costs for using gas and coal for electricity production, including the costs for carbon emissions, and *trade* for the commercial daily electricity trade between Germany, Austria and the surrounding neighbors.

The first differences are represented by the symbol Δ, the subscript t represents the time, *dd* (daily), *dm* (monthly) and *dy* (yearly) are the dummy variables and u is the standard error term. Due to the large number of independent variables, a check for the existence of multicollinearity is required. The correlation matrix (see Table A.2) indicates that there are no problems of pairwise multicollinearity.[12] According to the calculations of the variance inflation indicator (VIF), the VIF for the estimated regressions is smaller than the often-used critical value of 10, originally suggested by Chatterje and Hadi [30], for every case. This implicates that problems related to multicollinearity are very unlikely to exist.

Ordinary least-squares (OLS) estimation is used in the analysis. I use the Durbin's alternative test for autocorrelation [31]. According to the test statistics and the corresponding *p*-values (see Table 3), the null hypothesis of no autocorrelation of order 1 in the residuals is rejected in each case. As a consequence, Newey-West standard errors [32] that are robust to heteroscedasticity and autocorrelation are used for the estimations. The number of lags is chosen following Newey and West [33] who recommend that $p = integer[4 * (T/100)^{2/9}]$.[13]

The unit root test indicated that some variables (in levels) have a non-stationary character. From a theoretical point of view, there could be a relation between the non-stationary variables *burngas* and *burncoal* due to the gas-oil price link that was relevant for a long time. To avoid problems with spurious regressions between these non-stationary time series, an

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[12] The frequently used critical values for problems with pairwise multicollinearity by Farrar and Glauber [29] lies between a correlation factor of 0.8 and 0.9.

[13] p means the optimal lag length and T the number of observations. Robustness tests with a number of lags following Greene [36] who suggests that $p = T^{1/4}$, as well as tests with a number of lags following Newey and West [32] who recommend that $p = integer$ $[4 * (T/100)^{1/4}]$, came to the qualitatively equal results.

Engle-Granger test for cointegration is conducted [34].[14] According to the test statistics and the critical values by MacKinnon [35] the OLS residuals are non-stationary. Therefore, the tested variables are not cointegrated and the first differences of the time series can be used without causing statistical problems.

4 Results

The results of the OLS regressions are displayed in Table 3. Equation (4) is estimated in different versions. Model 1 only includes the daily, monthly and yearly dummies as explanatory variables. The results for this specification show that the daily average electricity price follows a timely pattern to a significant extent. The daily average electricity consumption is added in model 2 which increases the explanatory power of the estimation. The coefficient of the variable *consump* is positive and significant in all models. This result corresponds with the economic theory that says that a higher consumption (or demand) increases the price of the product. In model 3, the aggregated day-ahead VRE electricity generation forecast (sum of the variables *wind* and *pv*) is added as another explanatory variable. The VRE generation has an eminent influence on the daily changes of the spot market price. The coefficient is negative and significant. For a more detailed result, the VRE generation is split up into wind and PV generation and the explanatory variables *burngas*, *burncoal* and *trade* are added in model 4. The coefficients of the variables *pv* and *wind* represent the specific merit-order-effect, i. e. the average impact of an additional gigawatt hour (daily average) PV or wind generation on the daily average day-ahead electricity spot market price [8]. According to the estimation results, the average specific merit-order-effect from 2011 to 2013 was about 1.32 €/MWh for wind and 1.4 €/MWh for PV electricity generation that was fed into the grid. The higher average effect of PV generation during the analysis period is due to the so called 'correlation effect' that describes the positive correlation of a typical average PV generation profile in Germany and the electricity demand that increases the price [10].

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[14] The test was conducted by using the Stata module EGRANGER by Schaffer [37].

The results for the annual models 4a to 4c show that the specific merit-order-effect of wind generation steadily increased from 1.08 €//MWh in 2011 over 1.12 €/MWh to 1.54 €/MWh in 2013. The estimation results for the specific merit-order-effect of PV generation do not show a constant trend and decreased from 1.43 €/MWh in 2011 to 1.03 €/MWh in 2012 before increasing again to 1.45 €/MWh in 2013. The reasons for the relative small PV effect in 2012 may be due to the usage of daily averages instead of hourly data, leading to an underestimation of the correlation effect [38]. Furthermore, it may also be due to meteorological variations in 2012. The coefficients of variables *burngas*, *burncoal* and *trade* do not show any significance in all models. In the case of *burngas* and *burncoal,* the usual bilateral long-term contracts for gas and coal supply between plant operator and fuel supplier, and the little importance of wholesale spot markets for gas and coal offer a plausible explanation. A stronger influence of the marginal costs of coal and gas electricity generation on forward markets is supported by the results of Kallabis et al. who show a relevant impact of carbon prices on German electricity future prices [39]. The non-significant coefficient of the variable *trade* coincides with the results of Würzburg et al. [9] who use physical flow data.

In order to get more precise results about the specific merit-order-effect of VRE generation, a low-load and a high-load model are estimated.[15] As the results show, the specific merit-order-effect of wind is higher in the low-load model than in the high-load model. The opposite is true for the effect of PV generation. This difference makes sense, as the average wind generation is higher in the autumn and winter months and the average PV generation is higher in the spring and summer month.

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[15] The low-load model covers the observations in the first electricity consumption quartile and the high-load model covers the last electricity consumption quartile. Due to problems with multicollinearity, the dummies of the low-load and the high-load model only distinguish between a usual weekday on the one side and Saturdays, Sundays as well as statuary holidays on the other side. Additionally, in the high-load model, the dummies for the months June, July, August and September are not used, as the high-load days are not found in the summer months.

For checking the robustness of the estimation results, another model with weekly data was estimated. Due to the results of the ADF-test, the weekly model is also estimated in first differences (see Table A.3). The coefficient of *consump* is positive and significant. The aggregated VRE variable (*wind* plus *pv*) is negative as well as significant and the height of the merit-order-effect lies in the range of the results of the daily model. In order to check for the robustness without outliers, another regression model was estimated. An outlier detection using Cook's Distance [40] indicates that two dates in December 2012 influence the regression results greatly (see Figure A.1). The daily average spot market price on December 25, 2012 (-56.87 €/MWh) and on December 26, 2012 (-45.77 €/MWh) were very low because of the unusual combination of the high wind generation during these days and the commonly low demand during Christmas in 2012. These two observations are deleted from the original data set and model 3, 4 and 4b are estimated again. The results show that, as might be expected, the adjusted R-squared increase slightly without the outliers (see Table A.4). As another foreseeable result, the coefficients of *wind* in model 4 and 4b are slightly lower and the coefficient for *pv* is slightly higher. All in all, the robustness checks show that the initial daily estimations with the complete dataset provide robust results for the specific merit-order-effect of VRE.

Table 3: Results of the OLS estimation of daily changes in the day-ahead electricity spot market

	Model 1	Model 2	Model 3	Model 4	Model 4a	Model 4b	Model 4c	Model 5a	Model 5b
	$\Delta phelix_t$	$\Delta phelix_t$	$\Delta phelix_t$	$\Delta phelix_t$ Split up	$\Delta phelix_t$ Split up 2011	$\Delta phelix_t$ Split up 2012	$\Delta phelix_t$ Split up 2013	$\Delta phelix_t$ Low-load	$\Delta phelix_t$ High-load
$\Delta consump_t$		1.004***	0.895***	0.895***	0.794***	1.033***	0.986***	0.753***	0.913***
		(0.1205)	(0.0997)	(0.0986)	(0.1432)	(0.1841)	(0.1161)	(0.1812)	(0.0512)
$\Delta(wind+pv)_t$			-1.314***						
			(0.0676)						
$\Delta wind_t$				-1.315***	-1.081***	-1.118***	-1.542***	-1.449***	-1.275***
				(0.0659)	(0.1098)	(0.1169)	(0.0976)	(0.2222)	(0.1068)
Δpv_t				-1.398***	-1.426***	-1.031***	-1.453***	-1.275***	-1.459***
				(0.1433)	(0.3547)	(0.2263)	(0.2117)	(0.3144)	(0.4382)
$\Delta burngas_{t-1}$				0.863	0.357	2.12	1.658	0.332	1.681
				(0.4872)	(0.3849)	(1.3493)	(0.9869)	(1.7535)	(1.0828)
$\Delta burncoal_{t-1}$				-0.045	-0.09	-0.266	0.346	-0.38	-0.0986
				(0.1218)	(0.1262)	(0.3159)	(0.2776)	(0.5244)	(0.226)
$\Delta trade_t$				0.023	0.088	-0.672	0.196	-0.28	-0.094
				(0.1904)	(0.32)	(0.4063)	(0.2344)	(0.3481)	(0.4852)
Daily dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes (mod.)	Yes (mod.)
Monthly dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Yearly dummies	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes
Observations	1096	1096	1096	1095	364	366	365	273	274
Adjusted *R²*	0.48	0.536	0.742	0.742	0.759	0.68	0.84	0.416	0.74
Altern. Durbin	17.191	40.355	55.57	51.96	24.98	9.64	73.66	3.9	26.525
p-value	0.000	0.000	0.000	0.000	0.000	0.002	0.000	0.048	0.000

All the models include an intercept. Alternative Durbin reports the test statistic according to Durbin [31] and the corresponding p-value. As a consequence, the standard errors in parenthesis are robust to heteroscedasticity and autocorrelation according to Newey and West [32]. The number of lags (p) was determined by Newey and West [33] who recommend that $p = integer\left[4 * (T/100)^{2/9}\right]$ as the optimal lag length.*** indicates p<0.001, *** indicates p<0.01, *** indicates p<0.05.

5 Discussion

5.1 Comparison with other studies

As stated before, the regression coefficients β_2 for wind and β_3 for PV (see also in equation 5) correspond to the specific merit-order-effect (MOE). As stated, that is the average impact of an additional gigawatt hour (daily average) PV or wind generation on the daily average day-ahead electricity spot market price. The impact of the actual aggregated wind and PV electricity generated in one year on the result of the price formation in one year, that means the EPEX spot market price, is another interesting indicator. This indicator is called the absolute merit-order-effect in year *t* and is calculated as follows [08]:

$$MOE^{absolute}_{t} = \underbrace{\overbrace{\beta_{2,t} * wind^{mean}_{t}}^{\substack{absolute\ average\ MOE \\ of\ wind\ generation}} + \overbrace{\beta_{3,t} * pv^{mean}_{t}}^{\substack{absolute\ average\ MOE \\ of\ PV\ generation}}}_{absolute\ average\ MOE\ of\ the\ aggregated\ VRE\ generation} \quad (5)$$

where *MOE*^{absolute} stands for the absolute average MOE of the aggregated wind and PV generation in year *t, wind*^{mean} and *pv*^{mean} for the average day-ahead forecast of wind and PV generation in year *t* (see Table 1), β_2 and β_3 stand for the regression coefficients for *wind* and *PV* (that means the specific MOE) in year *t* corresponding to the regression results of the models 4a, 4b and 4c (see Table 3).

It is possible to compare the results of this study with four other comparable studies that also use regression analysis [8,9] or simulation models [41,42]. These studies estimate either the absolute merit-order-effect of PV and wind generation or the effect of the cumulated renewable energy (RE) generation in the German-Austrian wholesale electricity market. In Figure 1, the estimation results of models 4, 4a, 4b and 4c are compared with the results of other studies. In contrast to the specific merit-order-effect, the absolute merit-order-effect of wind energy lies above the effect of PV in most cases due to the higher average wind generation in a year. The estimation results of this study for the years 2011 and 2012 lie within a range of the regression results from Cludius et al. [8] and Würzburg et al. [9]. The PV effect calculated by Peter and Krampe [42] is significantly lower, which probably has to do with the fact that a very high amount of PV generation capacity was installed in Germany in 2012 and that the authors underestimated this new capacity in their simulations. Hohmeyer and Wingenbach [41] instead use historical installation and production data for their simulations and come to a similar results for the absolute merit-order-effect of cumulated renewable energy electricity generation.[16] For the year 2013, no comparable studies can be found to the author's knowledge. The absolute merit-order-effect increased steadily from 2011 to 2013. This is, on one hand, due to the increased specific merit-order-

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[16] Cumulated renewable energy means VRE plus biomass and hydrogen power.

effect (see Table 3) and, on the other hand, due to the increasing average PV and wind electricity generation (see Table 1). To sum up, the comparison shows that the estimation results and the results of comparable studies are similar. The relatively small variance results from different methodologies (regression analysis versus simulations), different regression variables and different temporal resolution of the data used (hourly or daily). The overview over the results illustrates the increase of the absolute merit-order-effect from 2011 to 2012 that continued in 2013.

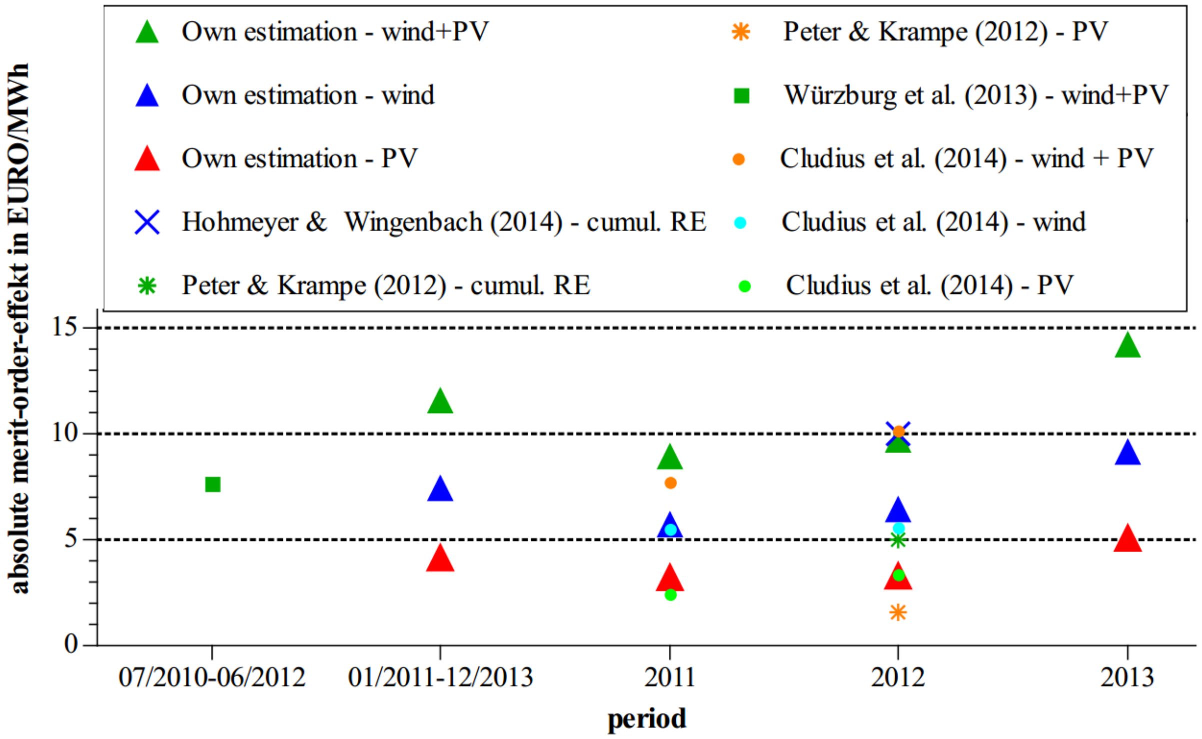

Figure 1: Comparison of the estimation results for the absolute merit-order-effect with other studies

5.2 Perspectives of the marketability of VRE

The apparently increasing absolute merit-order-effect contributes a part on the ongoing decline of the EPEX SPOT market prices that fell from an average price of 51.1 €/MWh in 2011 to 37.8 €/MWh in 2013. The comparison with the absolute merit-order-effect of the aggregated PV and wind electricity generation that increased from 9 €/MWh in 2011 to 14 €/MWh in 2013 (see Figure 1) indicates that the impact of PV and wind generation on the average price formation is very relevant. In consideration of the high specific merit-order-effect, the average daily price systematically declines on those days that show a high average VRE electricity generation. Conversely, this means that the analysis reveals a trend that VRE generation systematically earn lower spot market proceeds due to their own increasing generation. Thus, the empirical results confirm the cannibalism effect that is also displayed by the descriptive statistics of the absolute market value (Figure 2) that is equivalent to the average price per unit of energy produced by the specific VRE technology [24]. The price decrease obviously began in 2011, the year of the Fukushima nuclear disaster in Japan and the decision of the German government for phasing out nuclear power, starting with the immediate shut-down of the seven oldest reactors. Since then, the absolute market value of onshore wind and PV, as well as the average market price (EPEX SPOT base), steadily declined to 2016. That indicates that the fundamental regression results for quantifying the merit-order-effect in 2011 to 2013 still hold as the expansion of wind and PV generation is ongoing in Germany. It is remarkable that the absolute market value of PV declined faster than the average market price during 2011 to 2016. In contrast, the decline of the absolute market value of onshore wind slowed down and was noticeably smaller than the decline of the base price from 2015 to 2016. This may be linked to the technological progress towards system friendly wind turbines in the recent years that generate more electricity at low wind speeds, have a higher capacity factor and achieve a better market value than conventional wind turbines [43,44].

Figure 2: Absolute market values of onshore wind and PV generation (Data: EPEX SPOT, German TSO's)

The development of the average market revenues for wind and PV plants is of crucial importance for reaching their marketability. If the revenues keep declining with the expansion of VRE generation, the LCOE will need to decline faster based on the fact that wind and PV have not yet reached their marketability in Germany as of today. Typically, fix costs make up a large part of the LCOE of VRE technologies, which require no fuels and therefore have small variable costs. The module costs are responsible for about half of the investment costs of small scale PV plants with a maximum 100 kW peak power output. In the case of larger PV plants, the cost share can be even higher ([45], p. 9). A price index for crystalline PV modules, sold over the European wholesale market by the brokerage platform 'pvXchange', shows a clear downward trend for the past six years.[17] Since 2014, the price regression has notably flattened though. According to the International Renewable Energy Agency ([46], p. 82ff.), the costs for inverter, electrical cabling, racking etc. and the soft costs that include the customer acquisition, installation as well as the permitting provide the largest opportunity for future PV cost reductions. It should be noted that the German PV market is very competitive and the soft costs are relatively low compared with other markets.

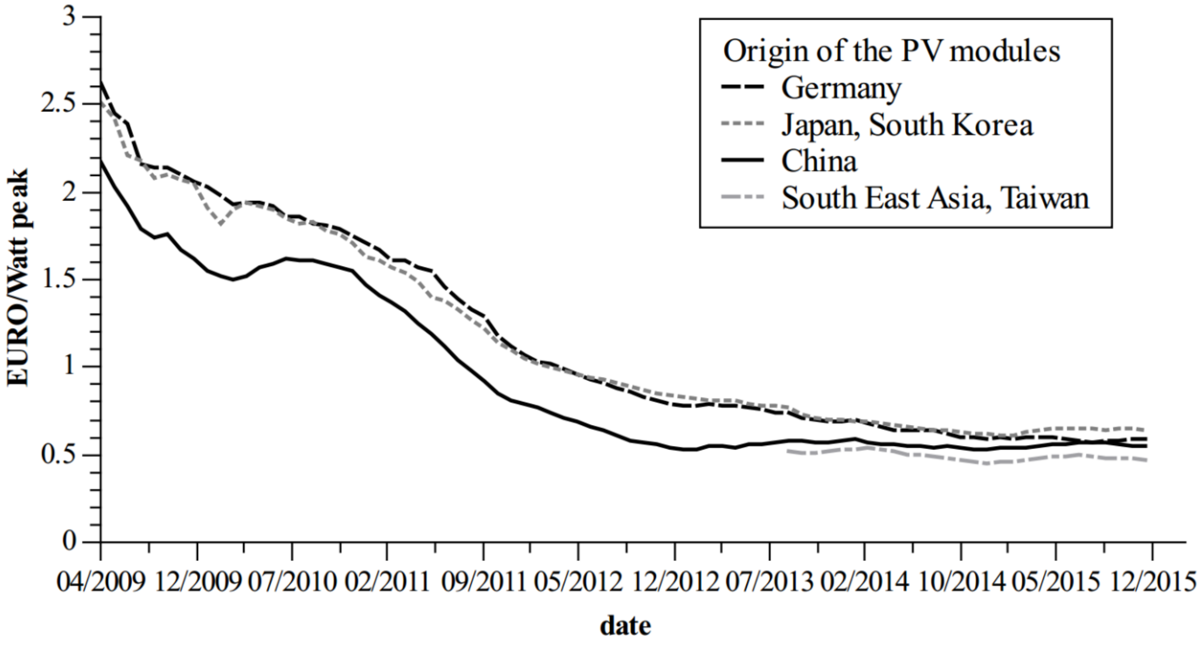

Figure 3: Development for crystalline PV modules on the European wholesale market (Data: pvXchange.com)

In the case of onshore wind power plants, the turbine is the largest cost component with a share of about 75% of the investment costs [47]. The Wind Turbine Price Index (WTPI) by Bloomberg New Energy Finance is therefore a representative indicator for the cost development of wind energy. Since July 2012, the index separates between models with a

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[17] The price index represents average nominal prices without value added tax. The price for Chinese modules includes the protective duty implemented by the European Union.

rotor diameter above and below 95 meters. The increase of the index in 2009 was due to rising costs for raw materials, labor and civil engineering as well as due to a tight supply and the introduction of larger turbines with higher capacity factors ([46], p. 59). The higher capacity factors leads to lower LCOE that are not fully covered by the WTPI. From January 2009 to July 2014, the WTPI fell from 1.1 to 0.8 million Euros per megawatt as a result of lower material consumption and higher worldwide production capacity. IRENA ([46], p. 144) sees an increasing importance of balance project costs, operating and maintenance costs and financing costs for future cost reductions of wind energy. Another important factor for the country specific LCOE is the penetration of wind energy and the closely related availability of good wind sites.

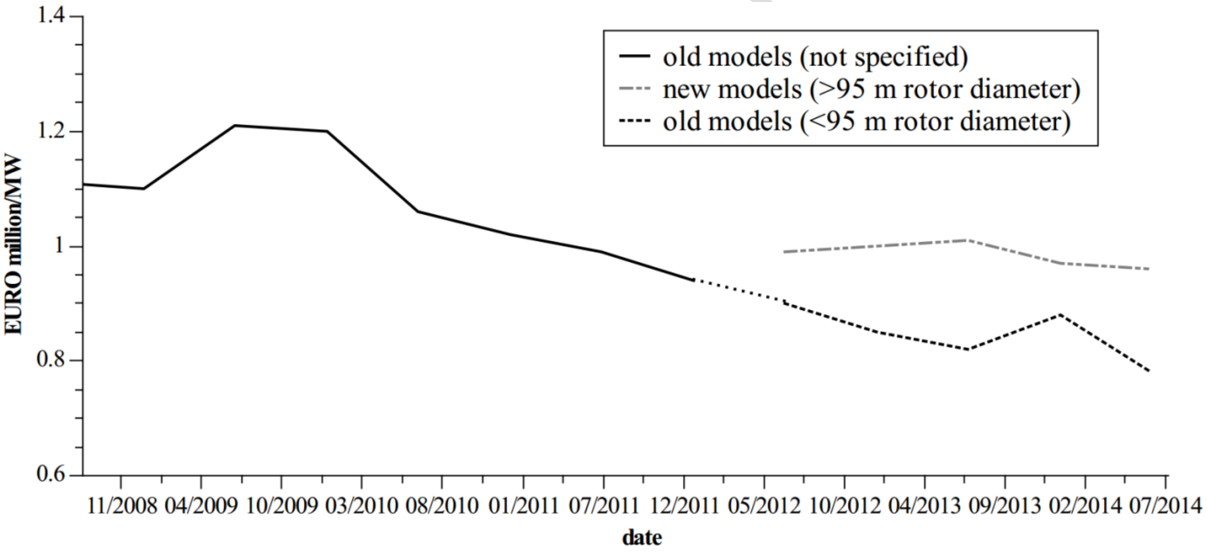

Figure 4: Bloomberg New Energy Finance Wind Turbine Price Index (Data: Bloomberg)

Hirth [10] and Kopp et al. [48] state that the value of VRE electricity decreases in liberalized electricity markets as more capacity will be installed, even at high carbon prices. The estimation results of this study confirm the results. The prognosis by Energy Brainpool [49], which is required by the German Energy Regulator, calculates a drop of the relative market value for PV from about 1, today, to 0.85, in 2020, and for onshore wind from about 0.9, today, to 0.75, in 2020, in the trend scenario.[18] If the described and statistically significant trend continues and the forecast is right, the achievement of the marketability of wind and PV electricity is threatened by the merit-order-effect in the context of the planned VRE expansion in Germany.

6 Conclusions

This paper is linked to the research that analyzes the impact of VRE electricity generation on wholesale prices by estimating the merit-order-effect. The impact of this effect on the marketability of VRE electricity technologies has not been sufficiently considered in existing literature. In order to fill this gap, I present a further developed regression analysis for estimating the merit-order-effect in the German-Austrian electricity market, a comparison of the results with other estimations and a discussion of the consequences of the estimated merit-order-effect on the VRE marketability perspectives.

The specific merit-order-effect of wind increased from 1.08 €/MWh in 2011 over 1.12 €/MWh to 1.54 €/MWh in 2013. The development of the estimated effect of PV generation is not constant and decreased from 1.43 €/MWh in 2011 to 1.03 €/MWh in 2012 and rose again to 1.45 €/MWh in 2013. The results reveal a systematic reduction of the average day-ahead electricity spot market on days that show high VRE generation. The absolute merit-order-effect of VRE generation steadily increased during the analysis period. In relation to comparable studies, the estimation results are similar and seem to be resilient.

As a consequence of the merit-order-effect, the average market revenues for VRE also decrease due to the simultaneity of VRE electricity generation within Germany and Austria. From 2011 to 2016, the average proceeds of wind and PV declined faster than the average market price on the EPEX SPOT market, which is the central exchange for VRE in the analyzed electricity sector. The technological progress to wind turbines with a higher capacity

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[18] The relative market value of a technology is equivalent to the ratio of the technology specific average sales revenue per unit of energy and the average market price per unit of energy in the considered period.

factor seems to slow down the decline of the market revenues for onshore wind. Regarding the even higher capacity factor of offshore wind turbines and the political aim to increase the still relatively small offshore capacity to 15 GW in 2030 in Germany, this could have significant impacts on the average market price as well as on the absolute market value of offshore wind. Both effects can be quantified by future research with the methodology of this study. Price indices for the elementary cost components of PV and wind plants reflect a considerable decline of the LCOE of VRE generation in the past but there is still large potential for further cost degression. However, the systematically downward trend of the VRE market value is opposed to the achievement of the marketability of wind and PV electricity.

In order to address this concern, the market conditions and the regulatory framework should be adopted to the intended future electricity system with a high share of VRE, which is an important part of the German energy transition (Energiewende). There is a set of research that investigates the electricity market and regulatory framework design for a sector with high VRE generation, but with a focus on providing resource adequacy and fossil generator revenue sufficiency [7,50,51]. Possibilities for decreasing the specific merit-order-effect while increasing the market revenues for VRE technologies may be interesting topics for future research in the field of power system design. First promising approaches are strengthening the emission allowances price signal [52], reducing subsidies to non-renewable energy sources [12], improving the flexibility of thermal generators, the electricity storage capacity and the short term price elasticity of demand [5,6,53] as well as adapting the trading conditions and products [54] and incentivizing system friendly renewables [24, 43].

If these, or other measures, prove not to be sufficient for increasing the average VRE revenues, or at least lowering their decline rate, further research in the design of long term remuneration schemes for VRE electricity generation should be undertaken. The empirical results show that from today’s perspective, it cannot be assumed with certainty that VRE technologies achieve their marketability in the liberalized German-Austrian electricity market if the German government wants to maintain its long-term renewable objectives.

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Appendix A

Table A.1: Augmented Dickey Fuller test statistics (probabilities)

	In levels	In first differences
phelix	0.000	0.000
consump	0.004	0.000
wind	0.000	0.000
pv	0.801	0.000
burngas	0.038	0.000
burncoal	0.622	0.000
trade	0.036	0.000

A trend variable was included. The number of lags (*p*) was determined by Schwert [55] who recommends that $p = integer\left[12 * (T/100)^{1/4}\right]$ as the optimal lag length. The probabilities (p-values) were calculated according to MacKinnon [56]. The tests for rejection of a null hypothesis of a unit root with MacKinnon [57] critical values came to the same results. The variables *burngas* and *burncoal* have both a time lag of *t-1*. Robustness tests with a number of lags that is determined by minimizing the Akaike Info Criterium [58] come to the qualitatively equal results.

Table A.2: Correlation matrix (in first differences)

	phelix	*consump*	*wind*	*pv*	*burngas*	*burncoal*	*trade*
phelix	1.000						
consump	0.732	1.000					
wind	-0.4541	-0.029	1.000				
pv	-0.054	-0.004	-0.155	1.000			
burngas	-0.004	-0.023	0.028	0.002	1.000		
burncoal	-0.011	0.006	-0.006	0.006	0.291	1.000	
trade	-0.497	-.0347	0.496	0.146	0.052	-0.011	1.000

The variables *burngas* and *burncoal* have both a time lag of *t-1*.

Table A.3: Results of the OLS estimation of weekly changes in the day-ahead electricity spot market (weekly data, robustness checks)

	Model 6
	Δphelix_t
	weekly
$\Delta \text{consump}_t$	1.15***
	(0.2514)
$\Delta (\text{wind+pv})_t$	-1.353***
	(0.1032)
$\Delta \text{burngas}_{t-1}$	0.789
	(0.8642)
$\Delta \text{burncoal}_{t-1}$	0.102
	(0.1704)
Δtrade_t	0.466
	(0.2293)
Daily dummies	No
Monthly dummies	Yes
Yearly dummies	Yes
Observations	156
Adjusted R^2	0.683
Altern. Durbin	11.61
p-value	0.001

All the models include an intercept. Alternative Durbin reports the test statistic according to Durbin [31] and the corresponding p-value. As a consequence, the standard errors in parenthesis are robust to heteroscedasticity and autocorrelation according to

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Newey and West [32]. The number of lags (p) was determined by Newey and West [33] who recommend that $p = integer[4 * (T/100)^{2/9}]$as the optimal lag length.*** indicates p<0.001, *** indicates p<0.01, *** indicates p<0.05.

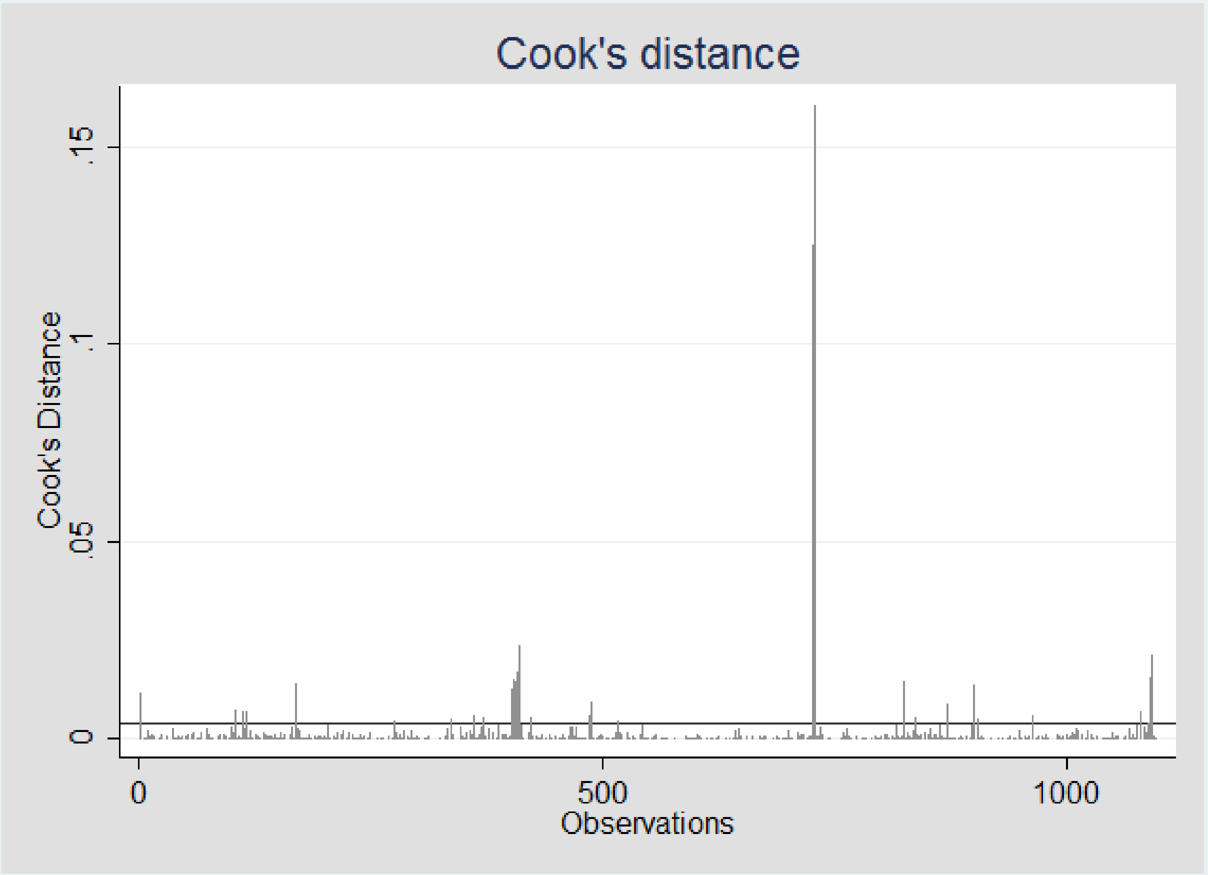

Figure A.1: Diagram of Cook's Distance for model 3

Table A.4: Results of the OLS estimation of daily changes in the day-ahead electricity spot market without outliers (robustness checks)

	Model 3	Model 4	Model 4b
	$\Delta phelix_t$	$\Delta phelix_t$	$\Delta phelix_t$
		Split up	Split up
			2012
	trimmed	trimmed	trimmed
$\Delta consump_t$	0.842***	0.849***	0.919***
	(0.0744)	(0.0776)	(0.1160)
$\Delta(wind+pv)_t$	-1.282***		
	(0.0606)		
$\Delta wind_t$		-1.299***	-1.075***
		(0.0627)	(0.0942)
Δpv_t		-1.426***	-1.102***
		(0.1409)	(0.2185)
$\Delta burngas_{t-1}$		0.853	1.974
		(0.4862)	(1.4045)
$\Delta burncoal_{t-1}$		-0.044	-0.272
		(0.1213)	(0.3099)
$\Delta trade_t$		0.105	-0.503
		(0.1775)	(0.3809)
Daily dummies	Yes	Yes	Yes
Monthly dummies	Yes	Yes	Yes
Yearly dummies	Yes	Yes	No
Observations	1094	1093	364
Adjusted *R²*	0.789	0.789	0.79
Altern. Durbin	102.22	98.33	31.44
p-value	0.000	0.000	0.002

All the models include an intercept. Alternative Durbin reports the test statistic according to Durbin [31] and the corresponding p-value. As a consequence, the standard errors in parenthesis are robust to heteroscedasticity and autocorrelation according to Newey and West [32]. The number of lags (p) was determined by Newey and West [33] who recommend that $p = integer\left[4 * (T/100)^{2/9}\right]$as the optimal lag length.*** indicates p<0.001, *** indicates p<0.01, *** indicates p<0.05.

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Highlights:

- A multivariate regression analysis is used for estimating the merit-order-effect.
- The results show a systematic decline of the average market revenues for VRE plants.
- The achievement of the marketability of VRE is threatened by the merit-order-effect.
- The market conditions and the regulatory framework should be adopted.