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It is windy in Denmark: Does market integration suffer?

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ABSTRACT

Some benefits of spot electricity markets integration include the optimization of renewable power, increasing transmission grid security and the decreasing need for internal generation reserves. The high penetration of wind power is known to have a clear influence on price convergence between electricity markets joined by market splitting. However, in multiple interconnected markets, cross-border flows can also play a role in the market splitting behaviour. Denmark, with a high penetration of wind power, is clearly the ideal case study. This paper aims to assess the influence of high penetration of wind power on the market splitting behaviour between West and East Denmark, taking into account cross-border electricity flows. This is modelled through logit and non-parametric models, estimating the probability of market splitting occurrence between both Danish bidding areas. Market splitting probability is found to be sensitive to wind power, nevertheless with distinct behaviour according to interconnection congestion configuration. The highest availability of wind power in West Denmark, which can reach a generation share of 1.5 times the demand, requires strong cross-border interconnections to allow the export of the excess generation. Policies governing a joint assessment of the requirements for additional interconnection and wind power expansion plans, should be developed.

1. Introduction

The fast expansion of renewable generation, resulting from the transition to a post carbon society, is creating one of the most demanding challenges to transmission grids and their operation [1–5]. In addition, the integration of the European electricity markets through HV (High Voltage) cross-border interconnections, is a substantial part of the European internal energy policy [6,7], aiming to offer numerous advantages under normal operating conditions, such as optimal power station daily production, increasing opportunities for operation with renewable energies, the promotion of competition and enhancement of supply security. However, cross-border interconnections are limited and congestions can arise in multiple operation conditions.

One of the best case studies, considering the high level deployment of wind power and with a long history of electricity market integration through market splitting, is Denmark. Its support to research and technological development of wind power, resulted in a strong player in the wind power turbine market, supplying about one third of the world demand for this technology [8,9].

Literature can be found regarding electricity market integration in different geographic areas. US regional electricity markets integration is studied in Refs. [10,11], using spot market electricity prices, the first through cointegration and a vector error correction model and the second through a vector auto-regression model. Electricity market integration in Australia is assessed in Refs. [12,13], through the use of MGARCH (Multivariate Generalized Autoregression Conditional Heteroskedasticity) models, to include time-varying conditional correlation spillovers across electricity markets and better describe price and price volatility interrelationships. Electricity market integration in Europe was assessed by a significant number of studies and these are unanimous in establishing that there is electricity market integration in the North European regional electricity market, the Nord Pool, which is composed currently by Norway, Sweden, Finland, Denmark, Lithuania, Estonia and Latvia. However, by using Markov switching fractional cointegration, Ref. [14] found that cointegration exists only when interconnections between bidding areas are

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not congested in a detailed analysis to the electricity price pairs West Denmark – Norway and East Denmark – Sweden. Furthermore, Ref. [15] used a PCA (Principal Component Analysis), unit root tests and a convergence test based on filtered pairwise price relations of wholesale electricity prices, demonstrating that convergence between both Danish bidding areas and between East Denmark and Sweden had been achieved. However, Ref. [16] through the use of cointegration and unit root analysis, found the Nordic electricity markets not to be integrated with Germany and the Netherlands. In an assessment of European spot electricity markets convergence, Ref. [17] used a fractional cointegration analysis and a MGARCH model, to report that Nord Pool is fractionally cointegrated with the remaining analysed electricity markets (Austria, Belgium, Czech Republic, France, Germany, Greece, Ireland, Italy, Poland, Portugal, Spain, Switzerland, the Netherlands and the UK), and that perfect integration had not been achieved. A summary table regarding the above studies can be found in Appendix B for easier reference.

Also, literature focussing the impact of high penetration of wind power can be found. Highlighted issues in Ref. [18] are: the importance of adequate interconnection and transmission capacities; the capacity incentives for dispatchable power plants; demand management, reduce electricity trading constraints and further research on energy storage technology. Moreover, Ref. [19] highlighted the risk of excessive production, the use of energy storage and exports through interconnections to address balancing issues, appropriate system security and ancillary services; and Ref. [20] stressed the importance of enough dispatchable backup capacity with fast response dynamics, system robustness and reserves to cover uncertainty and/or withstand eventual electrical faults, and adequate transmission grid capacities to transport eventual excess renewable generation; the importance of wind power forecasting, allowing for load management and system balancing, is highlighted in Ref. [21]. Furthermore, Refs. [22–32] all reported some level of decrease on the electricity spot market prices due to the increase in the share of RES-E (renewable energy sources electricity) generation. This is explained due to the almost inexistent marginal costs, associated bidding into the spot electricity market and the resulting merit order of power plant dispatch, which displaces higher marginal cost fossil fuel power plants. The influence of the existing high wind power penetration on the behaviour of electricity price differences was studied for the four ERCOT zones of Texas by Ref. [33], through the use of ordered-logit and log-linear regression models, establishing that high wind power loads in west Texas cause interconnection congestion and electricity price differences with the remaining zones. The RES-E influence on interconnection congestion was also analysed by Ref. [34] for Sicily and the rest of Italy electricity prices, through the use of a time-varying regime switching models and a dynamic probit ruling the transition between regimes, with distinct results as wind power is found to decrease interconnection congestion, which according to the author may be due to wind curtailment practices by the TSO (Transmission System Operator). Moreover, Italy was studied by Ref. [35] through the use of multinomial logit and three stage least square models, reporting that the probability of interconnection congestion increases with high wind power generation exiting a bidding area and decreases with high wind power generation in the destination bidding area. For Iberia, [36] through a non-parametric approach, found that increasing wind power generation, or furthermore, increasing low marginal cost generation has a clear influence on market splitting, increasing its probability.

Therefore, this research aims to assess the influence of high availability of wind power on the market splitting behaviour of the Danish bidding areas in the Nord Pool electricity spot market, taking into account cross-border electricity flows. The leading hypothesis considered in this study is that, in spite of the multiple existing interconnections and associated cross-border flows, wind power generation still influences market splitting in Denmark.

Following [36], expanded to a new multi-interconnected electricity market, logit and non-parametric models are herein used to express the probability response for market splitting of day-ahead spot electricity prices as a function of wind power generation share, electricity demand interconnection cross-border flows and market splitting of adjacent bidding areas. Logit models contribute with preliminary indications on market splitting behaviour, in spite of the known specification limitations. These limitations are subsequently overcome with the use of non-parametric models as demonstrated in Ref. [36].

The structure of the paper is the following: in Section 2 the Danish electricity market characterisation is presented, consisting of a survey of the EU legislative framework and Danish energy policy, an overview of the renewables deployment in Denmark and a brief explanation of the Danish electricity market as part of the Nordic electricity market. Data and model specification used in this study are presented in Section 3, followed by the presentation of the model results in Section 4 and the respective analysis and discussion in Section 5. Section 6 concludes with some recommendations and policy implications.

2. Danish electricity market characterisation

2.1. EU and the Danish energy policy

The absence of energy natural resources together with the oil crisis of the 1970's drove Denmark into a path of extensive efforts in R&D (Research and Development) of endogenous energy sources. Within the period until 1990, Denmark developed oil and natural gas production in the North Sea, decreasing its dependency on oil imports. Additionally, energy security of supply was achieved by replacing oil consumption by coal and natural gas, and on the demand side by implementing a challenging energy saving programme [37,38].

Bearing in mind that oil and gas resources are scarce and following the Kyoto accords to reduce CO_2 emissions, Danish energy policy turned into the development of renewable energy sources. Nonetheless, the formerly existing Danish energy policy was deemed to be insufficient to achieve the established target of 20% CO_2 emissions reduction by 2005 compared with 1988, which created the need for the so called “Green Energy Plan”, instigating the official “Energy 21” adopted in 1996. This plan comprised of the following measures: switching from electric heating to central heating, improving insulation and low-temperature district heating, utilisation of natural gas in district heating, diffusing the use of biomass, deployment of wind turbines (3000 MW by 2015), further stakeholder training and energy conservation [39]. These measures intended to attain the main objective of CO_2 reduction by also setting the following sub-targets: 20% improvement of energy conservation compared with 1994 and 12%–14% share of electricity consumption generated from renewable sources. Additionally, the chief goal of achieving 50% CO_2 reduction by 2030 compared with 1998, would be accomplished by increasing energy conservation to 55% above 1994 levels and 35% share of electricity consumption generated from renewable sources [37].

In 2005, the “Energy Strategy 2025” established the vision of total independence from fossil fuels. Targets were established to achieve a reduction of 15% for fossil fuel usage and keep a static overall energy consumption. Further specific targets were set for energy efficiency (1.25% annual growth), renewable energy (30% renewable energy share consumption by 2025) and more efficient new energy technologies (R&D support of new energy technologies). This strategy also depended on efficient markets and specifically on the electricity market where the expansion of transmission networks is fundamental for the supply reliability [40]. Danish energy policy for the years 2008–2011 expanded on previous policies by setting intermediate targets of 20% consumption share from RES (renewable energy sources) by 2011 and development of offshore wind by 2012 [8].

"Energy Strategy 2050" was launched in 2011, setting the same overall goal of fossil fuel independence, though giving it the deadline of 2050. The renewable energy share consumption of 30% was advanced to 2020, supporting and exceeding the EU target of 20%. Furthermore, measures like the electrification of heating systems, industry and transport, or the development of smart grids are part of this strategy. The Energy Agreement reached in March 2012 finally extended and brought Denmark closer to its strategy goals: 35% consumption share from RES; 50% electricity demand share from wind power; and 34% reduction in GHG (Greenhouse Gas) emissions compared to 1990 [38,41].

Danish energy policies were always aligned, if not a step ahead of EU (European Union) own policies. The release of the Council Directive 96/61/EC established common rules for pollution control and prevention and the EU Directive 2003/87/EC established the GHG emission allowance trading scheme. Almost simultaneously, in order to reduce dependency on imported fossil fuels and to allow the reduction in GHG emissions, the EU Directives 2001/77/EC and 2009/28/EC called for the promotion of electricity generation by renewable energy sources. On the electricity market side, the European Directives 96/92/EC, 2003/54/EC and 2009/72/EC established common rules for the various electricity markets in Europe.

2.2. Renewables deployment in Denmark

As referred in the above Section, Danish and EU policies for emissions reduction and energy security, together with the related aim to decrease the dependence from fossil fuels, led to the development of RES electricity generation. Given the limited hydropower potential, the Research and Development (R&D) was mainly focused on wind power and CHP (Combined Heat and Power) [42]. Almost inexistent in 1972, wind power share grew to 20% in 2008 [43], with some municipalities in West Denmark (DK1) fully supplied by wind power [44]. The main source of renewable electricity generation in Denmark is nowadays wind power, with a share of 51.1% of the electricity demand in 2014 [45].

Wind power R&D was enhanced through the establishment of a partnership between public and private institutions, aiming to keep Denmark as a major world player in wind power technology at competitive prices [40]. Additionally, wind power generation development in Denmark has been supported through strong financial support mechanisms, initially by price premiums paid to wind turbine owners and later after 1999 by feed-in tariffs. From 2004 onwards, subsidies were given as supplements to the electricity market price. These subsidies were later increased in 2008 and were limited to a maximum number of full-load operating hours, after which wind power is paid at electricity market prices [46]. A gradual reduction of subsidies to wind power is expected, due to its increasing technological competitiveness and the subsidy expiration of older units [47]. Additional details about wind power financing can be found in Refs. [44,48].

New concerns and challenges of high shares of RES-E are reported both in the technical sense and in the market design. On the technical sense: generation variability and uncertainty, adequate transmission capacity, flexibility and standby of dispatchable generation, electrical system regulation and frequency control, demand side response, RES-E curtailment, energy storage, adequate transmission grid and cross-border interconnections [26,49–51]; and in the market design: electricity market integration, transmission grid and cross-border interconnections cost allocation, intraday and reserve power markets, RES-E financial support schemes and capacity support mechanisms [18,51–53].

As seen in Fig. 1, thermal power generation capacity share is decreasing since 2000, with a steeper fall in 2011, whilst wind power generating capacity share steadily increased during the same period. Therefore, thermal generation was gradually being replaced with wind generation. The absence of hydro and nuclear power generation in Denmark is noteworthy: the former due to the absence of geographic conditions, and the latter, by a parliament resolution not to build nuclear power plants in the country [54]. By the end of 2013, wind power generation capacity reached 4820 MW in Denmark, which is equivalent to a 34.9% share of installed capacity. Solar power generation capacity share slightly start to

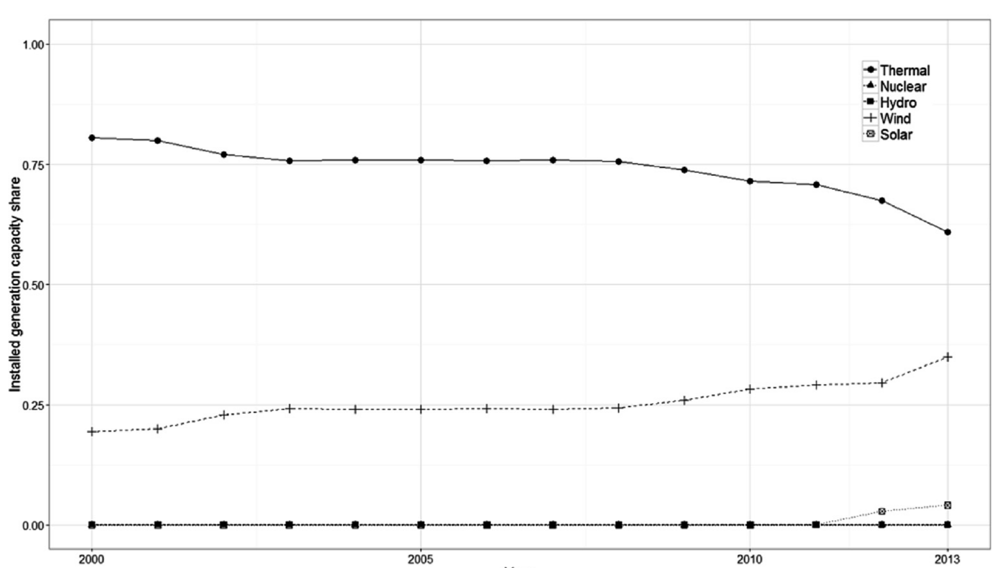

Fig. 1. Installed generation capacity shares of total installed capacity in Denmark [55].

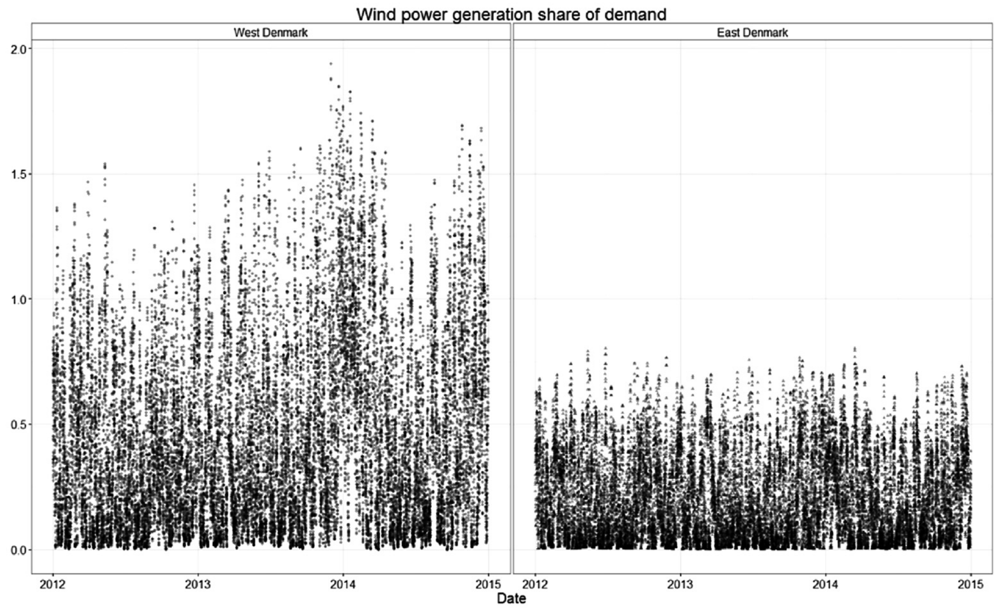

Fig. 2. Wind power generation share of demand in Denmark.

increase after 2011.

When analysing the extracted hourly data, wind power generation share of demand has been, surprisingly in more than a few hourly periods, above 1 in West Denmark (DK1). This means that not only wind generation was able to supply the complete electricity demand in West Denmark (DK1), but also that there was a surplus exported through the existing interconnections. This is not the case for East Denmark (DK2). However, wind power generation share is still quite high, frequently achieving values above 0.5 [45] (see Fig. 2).

2.3. Denmark in the Nordic electricity market

The Nordic electricity market, the Nord Pool, is composed by Norway, Sweden, Finland, Denmark, Estonia, Latvia and Lithuania. These countries are then sub-divided by bidding areas, taking into account transmission system capacities and constraints. The Nord Pool was established in 1996 with a joint Norwegian-Swedish power exchange, after the deregulation of the Norwegian electricity market in 1991. To complete the adhesion of the northern European countries, Finland joins Nord Pool in 1998 followed by Denmark in 2000. Consequently, Nord Pool is the oldest electricity market in Europe where a market splitting mechanism is implemented.

Elspot (Nord Pool's spot electricity market) calculates day-ahead prices for every hour and for each bidding area by establishing a balance between supply and demand bids. It also takes into account ATC (available transmission capacities) between the bidding areas. The congestion of interconnections between bidding areas creates the market splitting, with the electricity spot prices diverging. Bidding areas with lower prices export electricity to areas with higher prices through these limited capacity interconnections [56]. If the ATC is large enough to accommodate the exported electricity flows (no congestion), then the price is the same in both bidding areas. Therefore, this mechanism is supported on the calculation of the ATC, which is made by each TSO taking into account the safety and reliability of the electrical system. Depending on loop flows and technical constraints imposed by TSOs, import and export ATC can have different values [57].

Denmark is divided into two bidding areas, interconnected through the HV electricity grid. Moreover, Denmark is also interconnected with Norway and Sweden in the north and Germany in the south. The interconnection capacity between the two Danish bidding areas is 600 MW through a HV Direct Current cable. The interconnection capacities and bidding areas are shown in Fig. 3. Interconnections capacity between the considered areas are higher than the current EU recommended level of 10% of the peak demand of the smaller interconnected market [59]. Denmark has already surpassed this value reaching 23.8% between West and East Denmark (DK1-DK2), 15.9% between West Denmark (DK1) and Sweden bidding area 3 (SE3), 64.5% between East Denmark (DK2) and Swedish bidding area 4 (SE4), 23.8% between East Denmark (DK2) and Germany and 38.3% between West Denmark (DK1) and Germany, all of the peak demand observed in the period considered in this study.

3. Data and methods

Following the methodology described in Ref. [36], expanded to a new multi-interconnected electricity market, market splitting behaviour was modelled through logit and non-parametric models estimating the probabilities of its occurrence. In the estimated models the introduction of electricity flows and market splitting binary variables of surrounding interconnected bidding areas introduce an additional complexity in relation to the models used in Ref. [36], where the interconnection between Spain and France was not considered. In the estimated models the probability response for market splitting of day-ahead spot electricity prices is expressed as a function of wind power generation shares, electricity demands, five interconnection electricity flow shares and five market splitting binary variables. These variables correspond to the two Danish bidding areas, the Swedish bidding areas 3 and 4, the Norwich bidding area 2 and Germany, which are all adjacent.

By imposing a parameter approach, logit models provide a general indication of the effects of each variable ("ceteris paribus"), which might change with others. Additionally, logit models present known specification restrictions, such as:

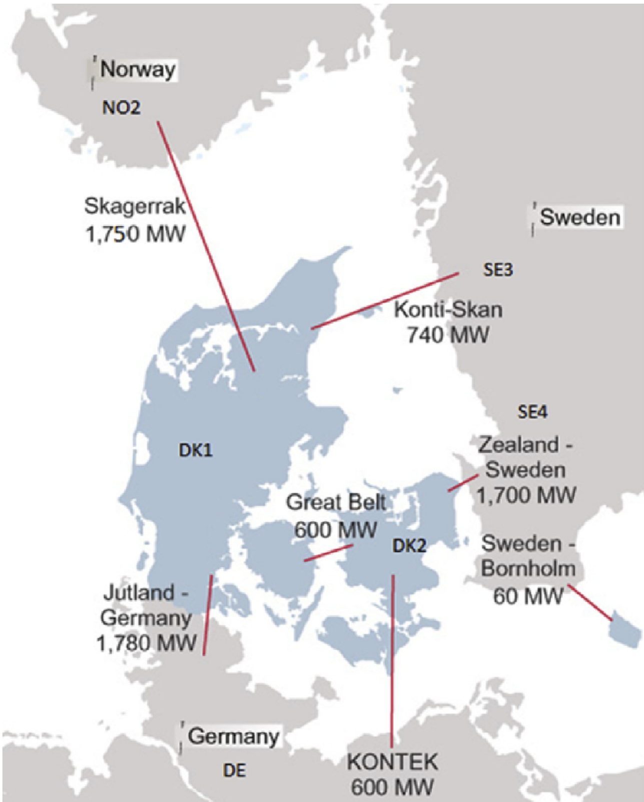

Fig. 3. Denmark's bidding areas and interconnections [58].

- The "Neglected Heterogeneity" specification issue, where the coefficient estimates may cause an underestimation of the effects – extraction of explanatory variables relative effects can still be of use [60,61];
- Heteroskedasticity of the error term – A correction can be used according with [62,63].

Yet, logit models can provide some preliminary indications about the model behaviour. The non-parametric models, herein used, do not require parametric assumptions for the underlying data generation process, therefore the logit specification limitations are avoided. One of the main set-backs of non-parametric modelling is the required computer processing resources when using large datasets, as it is inhere the case where the model estimation took several days to run, even with parallel processing. Furthermore, the "Curse of Dimensionality", related with the number of continuous explanatory variables, might deteriorate the convergence rate of the kernel functions, nevertheless models remain consistent [64]. In our models the sample size overcomes this issue.

In the following Section 3.1 the data used in this study is presented, followed by the logit model specification in Section 3.2 and the non-parametric model specification in Section 3.3.

3.1. Data

Day-ahead spot electricity prices in €/MWh, interconnection flows in MWh, Demand in MWh and Wind Power Generation in MWh, for each hour from the 2nd of January 2012 until the 31st of December 2014, were extracted from the Nord Pool Spot ftp server [45] and from EPEX Spot web site [65], for both Danish and adjacent bidding areas. This consists in a sample of 26,281 h.

The demand of the Danish electricity market has a peak of 6.5 GWh, which is comparably small with the demand in Norway, with a peak of 24.2 GWh, and the demand in Sweden, with a peak of 26.6 GWh. However, when these electricity markets are divided into bidding areas, the only bidding area that stands out is the Swedish bidding area 3 with a demand peak of 17.5 GWh [45]. Germany with its 77.2 GWh of peak demand is by large the biggest connected electricity market [66].

By using a rolling window procedure for the number of market splitting hours in a month, a trend is established and can be plotted. Therefore, a price convergence can be observed in the case of reducing number of market splitting hours in a rolling month. Between West and East Denmark (DK1-DK2), the number of market splitting hours in a moving month remains low, with an exception during a small period in the end of 2013 and 2014 (Fig. 4). Furthermore, it seems that there is a higher integration level between both Danish bidding areas and between East Denmark (DK2) and Sweden bidding area 4. In this period, market splitting between both Danish biding areas occurred in 23.3% of the total 26,281 h considered in our sample. Likewise, market splitting occurred 60.4% between West Denmark (DK1) and Norway bidding area 2, 44.3% between West Denmark (DK1) and Sweden bidding area 3, 24.3% between East Denmark (DK2) and Sweden bidding area 4, 64.8% between West Denmark (DK1) and Germany and 69.5% between East Denmark (DK2) and Germany, of the total sample.

Fig. 5 plots the spot electricity price differences between West Denmark (DK1) and East Denmark (DK2), showing that multiple market splitting hours occurred in the period herein considered. It is also observed that there are more data points below zero, which means that prices in East Denmark (DK2) are frequently higher than the ones in West Denmark (DK1).

In Fig. 6 the interconnection cross-border flows between Denmark and the Nord Pool adjacent areas are plotted. The interconnection transfer flows plot between both Danish bidding areas reveals that, most of the time the electricity flow direction is from West to East Denmark. This is consistent with the lower prices observed in West Denmark (Fig. 5). The interconnection transfer flows between East Denmark and Sweden have a slight tendency to be predominantly in the direction from Sweden to East Denmark, indicating lower prices in Sweden bidding area 4. No significant asymmetries are observed in the remaining interconnection flow plots, which indicate that there is no evident preferred direction for the cross-border flows.

In Appendix A, Table 5 with the summary statistics is presented for the considered time series. All price time-series have non-normal distributions, as determined by the rejection of the null for the Jarque-Bera normal distribution test.

3.2. Logit model estimation

Following the logit specification in Ref. [36], the estimated market splitting probability model expresses the probability of occurring different prices, thus interconnection congestion, between both Danish bidding areas.

The model specification used is:

$$P(Split = 1|X) = P(Split^{*} > 0|X) = P(X\beta + e > 0|X), \tag{1}$$

$$P(e > -X\beta|X) = 1 - P(e \leq -X\beta|X) = 1 - \Lambda(-X\beta) = \Lambda(X\beta), \tag{2}$$

where $\Lambda(X\beta) = \frac{\exp(X\beta)}{1+\exp(X\beta)}$.

Split is the binary dependent variable, X a matrix of explanatory variables and e is the independently distributed error term

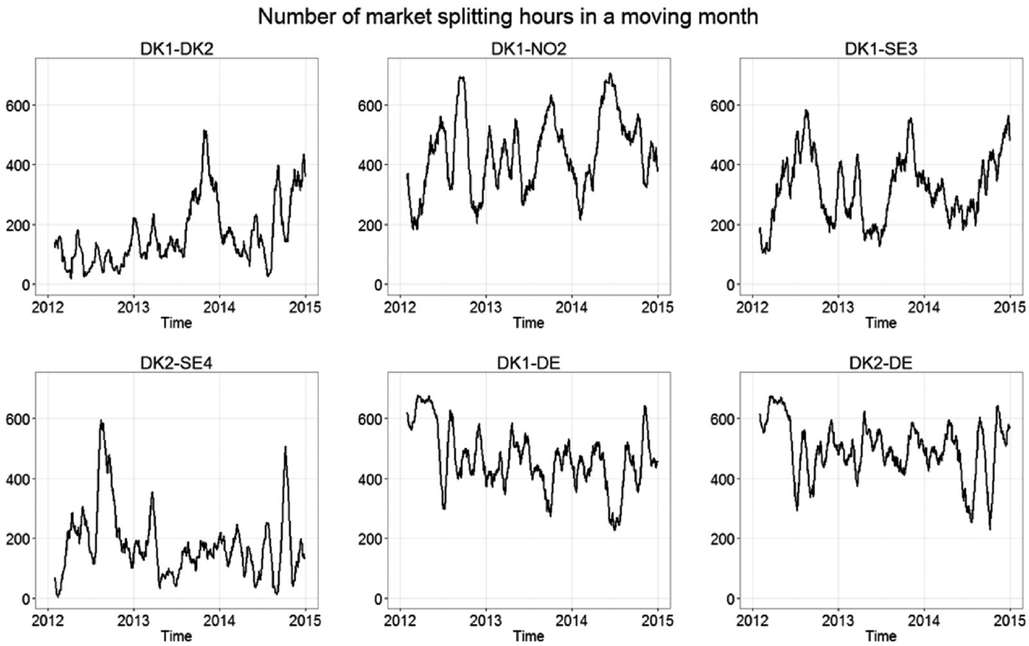

Fig. 4. Market splitting evolution.

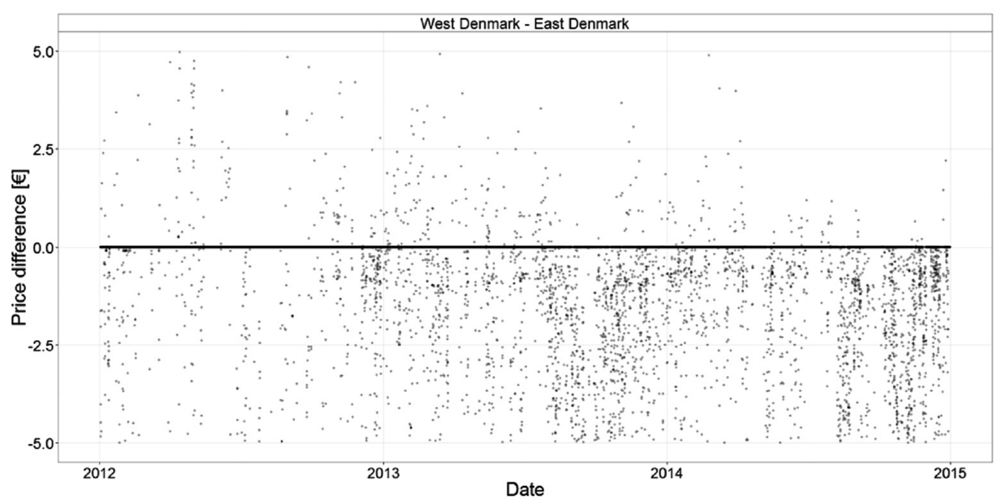

Fig. 5. Spot electricity price differences between Danish bidding areas.

independent from X and following the standard logistic distribution. The $Split^{*}$ latent variable is then expressed as follows:

$$\begin{aligned}Split^{*} = {} & \beta_0 + \beta_1 \cdot W_{DK1}/D_{DK1} + \beta_2 \cdot W_{DK2}/D_{DK2} + \beta_3 \cdot D_{DK1} \\ & + \beta_4 \cdot D_{DK2} + \beta_5 \cdot D_{NO2} + \beta_6 \cdot D_{SE3} + \beta_7 \cdot D_{SE4} + \beta_8 \cdot D_{DE} \\ & + \beta_9 \cdot Flow_{DK1-NO2} + \beta_{10} \cdot Flow_{DK1-SE3} \\ & + \beta_{11} \cdot Flow_{DK2-SE4} + \beta_{12} \cdot Flow_{DK1-DE} \\ & + \beta_{13} \cdot Flow_{DK2-DE} + \beta_{14} \cdot Split_{DK1-NO2} \\ & + \beta_{15} \cdot Split_{DK1-SE3} + \beta_{16} \cdot Split_{DK2-SE4} + \beta_{17} \cdot Split_{DK1-DE} \\ & + \beta_{18} \cdot Split_{DK2-DE} + e, \end{aligned} \tag{3}$$

where W_{DK1} and W_{DK2} are the hourly wind power generation in West and East Denmark, respectively; D_{DK1}, D_{DK2}, D_{NO2}, D_{SE3}, D_{SE4} and D_{DE} are the hourly electricity demand in West Denmark, East Denmark, Norway bidding area 2, Sweden bidding area 3, Sweden bidding area 4 and Germany, respectively; $Flow_{DK1\text{-}NO2}$, $Flow_{DK1\text{-}SE3}$, $Flow_{DK2\text{-}SE4}$, $Flow_{DK1\text{-}DE}$ and $Flow_{DK2\text{-}DE}$ are the hourly interconnection cross-border flows between West Denmark – Norway bidding area 2, West Denmark – Sweden bidding area 3, East Denmark – Sweden bidding area 4, West Denmark – Germany and East Denmark – Germany, respectively; *and* $Split_{DK1\text{-}NO2}$, $Split_{DK1\text{-}SE3}$, $Split_{DK2\text{-}SE4}$, $Split_{DK1\text{-}DE}$ and $Split_{DK2\text{-}DE}$ are the hourly binary variables representing market splitting between West Denmark – Norway bidding area 2, West Denmark – Sweden bidding area 3 East Denmark – Sweden bidding area 4, West Denmark – Germany and East Denmark – Germany electricity markets, respectively.

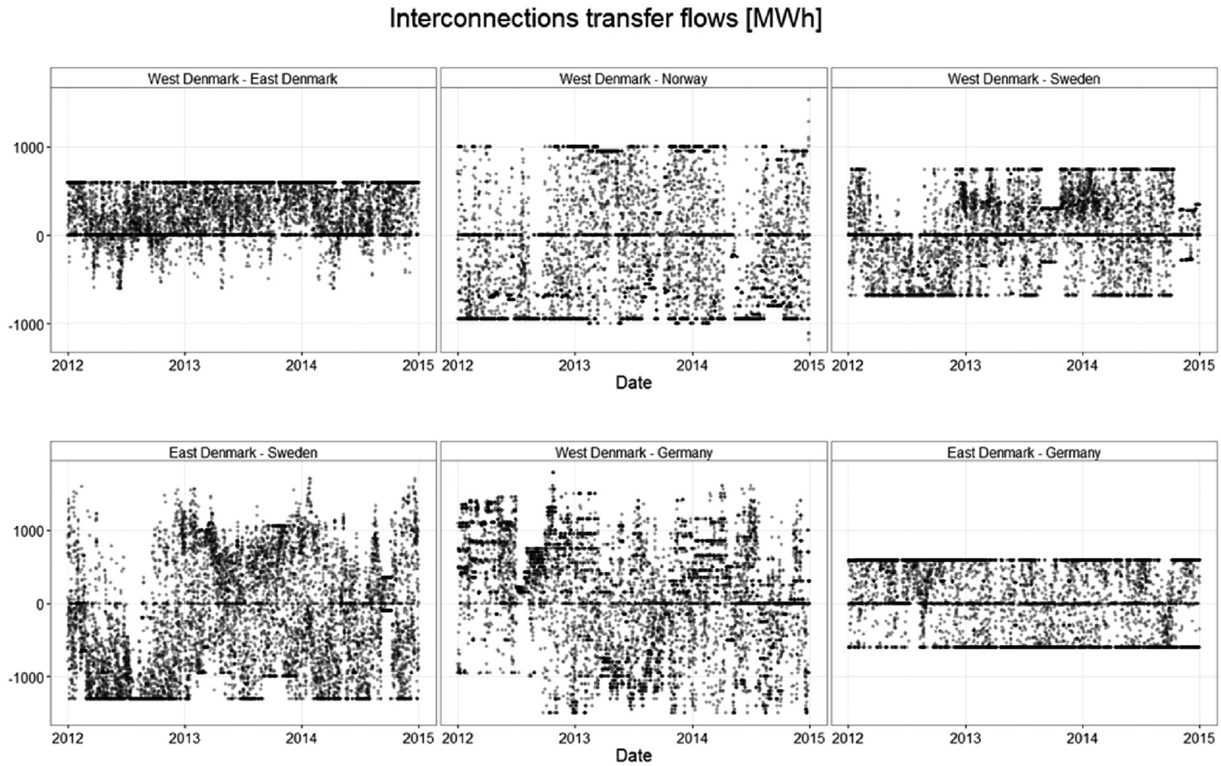

Fig. 6. Interconnection cross-border flows with Danish adjacent bidding areas.

3.3. Non-parametric model estimation

As described in Ref. [36] the underlying data generation process is not required for non-parametric models, avoiding specification issues that can question parametric models [67]. Model estimation is performed through kernel methods with the information provided by the data. An introduction to non-parametric modelling can be found in Refs. [64,68].

Therefore, by using the "npRmpi" package for non-parametric kernel estimation [68] developed in R [69], the models inhere used overcome the logit specification issues. With the required information from the data, model estimation is done through kernel methods and the associated bandwidth [70]. Parallel processing was used due to the large datasets analysed in this study.

The market splitting probability is estimated by the conditional PDF (probability density function) expressing the probability of occurring different prices between both Danish bidding areas, conditional on the considered explanatory variables. The conditional PDF is then:

$$\hat{f}\left(y^d \middle| x^d, x^c\right) = \frac{\hat{f}\left(y^d, x^d, x^c\right)}{\hat{f}\left(x^d, x^c\right)} \tag{4}$$

where $\hat{f}(y^d, x^d, x^c)$ is the joint PDF, $\hat{f}(x^d, x^c)$ the marginal PDF, y^d the discrete dependent variable, x^d the discrete explanatory variables and x^c the continuous explanatory variables. As described in Section 3.2 the variables used are: y^d is the binary variable *Split* expressing market splitting between both Danish bidding areas; x^d are the binary variables representing market splitting $Split_{DK1\text{-}NO2}$, $Split_{DK1\text{-}SE3}$, $Split_{DK2\text{-}SE4}$, $Split_{DK1\text{-}DE}$ and $Split_{DK2\text{-}DE}$; and x^c are the wind power generation variables W_{DK1} and W_{DK2}, the electricity demand variables D_{DK1}, D_{DK2}, D_{NO2}, D_{SE3}, D_{SE4} and D_{DE}, and the interconnection cross-border flow variables $Flow_{DK1\text{-}NO2}$, $Flow_{DK1\text{-}SE3}$, $Flow_{DK2\text{-}SE4}$, $Flow_{DK1\text{-}DE}$ and $Flow_{DK2\text{-}DE}$.

The joint PDF can then be estimated by:

$$\hat{f}\left(y^d, x^d, x^c\right) = \frac{1}{n}\sum_{i=1}^{n} L_{\lambda_y, Y_i^d, y^d} \cdot L_{\lambda_x, X_i^d, x^d} \cdot W_{h_x, X_i^c, x^c} \tag{5}$$

and the marginal PDF by:

$$\hat{f}\left(x^d, x^c\right) = \frac{1}{n}\sum_{i=1}^{n} L_{\lambda_x, X_i^d, x^d} \cdot W_{h_x, X_i^c, x^c} \tag{6}$$

where $L(\cdot)$ and $W(\cdot)$ are product kernel functions for discrete and continuous variables, respectively. For discrete variables:

$$L_{\lambda_x, X_i^d, x^d} = \prod_{s=1}^{r_{x,d}} l\left(X_{i,s}^d, x_s^d, \lambda_{x,s}\right) \tag{7}$$

$$l\left(X_{i,s}^d, x_s^d, \lambda_{x,s}\right) = \begin{cases} 1-\lambda_{x,s}, & \mathit{if}\ X_{i,s}^d = x_s^d \\ \dfrac{\lambda_{x,s}}{c_s - 1}, & \mathit{otherwise} \end{cases}, \tag{8}$$

where $l(\cdot)$ is the discrete univariate kernel function proposed by Ref. [71], $r_{x,d}$ the number of discrete explanatory variables, c_s the number of outcomes in x_s and $\lambda_{x,s}$ the bandwidth, with $\lambda_{x,s}\ \varepsilon\ [0, (c_s-1)/c_s]$. For continuous variables:

$$W_{h_x, X_i^c, x^c} = \prod_{s=1}^{r_{x,c}} \frac{1}{h_{x,s}} w\left(\frac{X_{i,s}^c - x_s^c}{h_{x,s}}\right) \tag{9}$$

$$w\left(\frac{X^c_{i,s}-x^c_s}{h_{x,s}}\right)=\frac{e^{\left(-\left(\frac{X_i-x^c_s}{h_{x,s}}\right)^2/2\right)}}{\sqrt{2\pi}}, \tag{10}$$

where $w(\cdot)$ is the continuous univariate Second-order Gaussian kernel function, $r_{x,c}$ the number of continuous explanatory variables and $h_{x,s}$ the bandwidth of variable s.

Bandwidth selection is a fundamental part of non-parametric estimation, therefore two methods were attempted: the “rule of thumb” and “likelihood cross-validation”.

The “rule of band of thumb” bandwidth is given by:

$$h = 1.06\cdot\sigma\cdot n^{-1/(2P+l)}, \tag{11}$$

where σ is the $\min(\sigma,\ \text{interquartile range}/1.349)$, n the number of observations, P the order of the kernel and l the number of continuous variables.

The “likelihood cross-validation” method selects the bandwidth (h) by maximizing the following log likelihood function:

$$\mathscr{L}=\sum_{i=1}^{n} log\left[\frac{1}{(n-1)h}\sum_{j=1,j\neq i}^{n} K\left(\frac{X_j-x}{h}\right)\right] \tag{12}$$

Finally, the most adequate method was then selected according to model performance [72].

By using the same explanatory variables as in the logit model, the non-parametric models were estimated with bandwidths calculated with both selection methods and considering the same data set.

4. Results

In the following Sections 4.1 and 4.2 results and performance are presented for both logit and non-parametric models.

4.1. Logit model results

All coefficients are statistically significant ($p < 0.01$) in the estimated model, with the exception of demand Norway area 2 and demand Sweden area 3, both significant at least to 10%, and the binary variables representing market splitting between West Denmark (DK1) – Sweden area 3 and East Denmark (DK2) – Sweden area 4 (Table 1) are not significant.

An attempt to correct the heteroskedasticity of the error term (Breusch-Pagan test in Table 2) was performed [36], but with little or no improvement on model performance. For the estimated model an accuracy of 0.9107 and a McFadden pseudo R-square of 0.544 were found (Table 2). The coeficients for the introduced correction variables in the skedastic function are significant ($p < 0.01$) with the exception of the cross-border flow share from West Denmark to Norway area 2 (significant to 10%) and the cross-border flow share from East Denmark to Germany (Table 1). Moreover, notwithstanding the “Neglected Heterogeneity” specification issue of the logit models, extraction of the relative effects can be made [60,61].

4.2. Non-parametric model results

In Table 3 confusion matrices for both estimated models are presented and in Table 4 the results for the bandwidth calculation are shown. Non-parametric models are revealed to have improved performance, in addition to the absence of the specification issues of the logit models. An accuracy of 0.9965 is obtained with the bandwidth selected by likelihood cross-validation, the highest amongst all estimated models.

In Fig. 7 the observed and the fitted number of market splitting hours in a rolling month are shown in the sample period, for the measured data, for the heteroskedasticity corrected logit model and for the likelihood cross-validation non-parametric model. As demonstrated, the performance of the non-parametric model is clearly better than the one obtained by the logit model.

5. Discussion

For clarification purposes, when market splitting probability is referred to, it means the probability of market splitting occurrence between West and East Denmark (the Danish splitting: DK1-DK2). No other market splitting probability is estimated in this study. Considering the results of the logit models and their marginal effects (Table 1), together with the 3D plots of the non-parametric models, it is possible to unveil the complex behaviour of the Danish electricity market splitting as observed in Figs. 8 and 9. Given that the “likelihood cross-validation” non-parametric model has the highest performance amongst all estimated models, the following interpretations are based on this model.

Fig. 8 shows (from top to bottom and left to right) the behaviour of market splitting probability response as a function of wind power generation in West and East Denmark: a) given market splitting occurrence between Denmark and all adjacent bidding areas (Denmark isolated); b) given market splitting occurrence between Denmark and all adjacent bidding areas with the exception of West Denmark (DK1) to Norway bidding area 2; c) given market splitting occurrence between Denmark and all adjacent bidding areas with the exception of West Denmark (DK1) to Sweden bidding area 3; d) given market splitting occurrence between Denmark and all adjacent bidding areas with the exception of East Denmark (DK2) to Sweden bidding area 4; e) given market splitting occurrence between Denmark and all adjacent bidding areas with the exception of West Denmark (DK1) to Germany; and f) given market splitting occurrence between Denmark and all adjacent bidding areas with the exception of East Denmark (DK2) to Germany. Fig. 9 shows (from top to bottom and left to right) the behaviour of market splitting probability response as a function of wind power generation in West and East Denmark: a) given no market splitting occurrence between Denmark and all adjacent bidding areas (absence of congestions, therefore it is expected a null probability of market splitting); b) given no market splitting occurrence between Denmark and all adjacent bidding areas with the exception of West Denmark (DK1) to Norway bidding area 2; c) given no market splitting occurrence between Denmark and all adjacent bidding areas with the exception of West Denmark (DK1) to Sweden bidding area 3; d) given no market splitting occurrence between Denmark and all adjacent bidding areas with the exception of East Denmark (DK2) to Sweden bidding area 4; e) given no market splitting occurrence between Denmark and all adjacent bidding areas with the exception of West Denmark (DK1) to Germany; and f) given no market splitting occurrence between Denmark and all adjacent bidding areas with the exception of East Denmark (DK2) to Germany.

The results obtained from the models express that, generally speaking, market splitting probability between both Danish bidding areas is sensitive to the wind power generation share in Denmark, nevertheless with distinct behaviour according to the congestion of interconnections with other bidding areas. The simplistic interpretation that can be done with the obtained logit marginal effects does not suffice. For example, the decreasing probability with increasing wind power in East Denmark can only be related with the situation when Denmark is isolated, with the

Table 1
Market splitting logit model.

Dependent variable: Market Split
Data: 2nd January 2012 to 31st December 2014
Coefficients (binomial model with logit link):

	No het. correction		Het. correction	
c	−8.3970	***	−11.0900	***
Wind share West Denmark	1.5030	***	1.7940	***
Wind share East Denmark	−3.0440	***	−4.5820	***
Demand West Denmark	0.0011	***	0.0016	***
Demand East Denmark	0.0013	***	0.0021	***
Demand Norway area 2	0.0002	*	0.0004	**
Demand Sweden area 3	−0.0001	**	−0.0001	*
Demand Sweden area 4	−0.0010	***	−0.0017	***
Demand Germany	0.0000	***	0.0000	***
Cross-border flow share West Denmark to Norway area 2	−2.6170	***	−3.0360	***
Cross-border flow share West Denmark to Sweden area 3	3.7040	***	4.8440	***
Cross-border flow share East Denmark to Sweden area 4	2.6360	***	4.3300	***
Cross-border flow share East Denmark to Germany	−1.2560	***	−1.1420	***
Cross-border flow share West Denmark to Germany	2.4670	***	4.2090	***
Market splitting West Denmark to Norway area 2	−0.6398	***	−0.7943	***
Market splitting West Denmark to Sweden area 3	−16.8500		−52.9300	
Market splitting East Denmark to Sweden area 4	22.1200		59.1200	
Market splitting West Denmark to Germany	0.2171	***	0.2820	***
Market splitting East Denmark to Germany	1.8210	***	2.3020	***
Latent scale model coefficients (with log link):				
Wind share West Denmark			−0.3352	***
Wind share East Denmark			0.9903	***
Cross-border flow share West Denmark to Norway area 2			−0.1555	*
Cross-border flow share West Denmark to Sweden area 3			−0.7277	***
Cross-border flow share East Denmark to Sweden area 4			−0.7724	***
Cross-border flow share East Denmark to Germany			−0.0223	
Cross-border flow share West Denmark to Germany			−0.6888	***

*** Significant at 1% level, ** Significant at 5% level, * Significant at 10% level.

exception of the interconnection West Denmark (DK1) – Sweden bidding area 3 (Fig. 8 bottom left), and the situation when Denmark is not isolated, with the exception of West Denmark (DK1) – Germany (Fig. 9 center right). The former can be associated with wind power from West Denmark (DK1) being able to be exported to Sweden and not to East Denmark (DK2), with the sudden drop of the West Danish electricity price (DK1) caused by the high wind power generation share originating a detour of the electricity flow into Sweden bidding area 3, and releasing some cross-border transmission capacity between West and East Denmark. The latter can be associated with increasing wind power in East Denmark (DK2) stopping incoming interconnection electricity flows from West Denmark (DK1), which can not flow into Germany. These findings expand on [33–36] and unveil a more complex behaviour of multiple interconnected electricity markets.

In the case that Denmark is isolated from the adjacent electricity markets (Fig. 8 top left), market splitting probability between West and East Denmark (DK1-DK2) increases when there is an increase of wind power generation share in both West and East Denmark.

Table 2
Market splitting logit model performance.

		No het. Correction		Het. Correction	
McFadden pseudo R-squared:		0.6046877 (df=19)		0.6339591 (df=26)	
Studentized Breusch-Pagan test					
data: ms.logit					
BP = 6837.368, df = 18, p-value < 2.2e-16					
In-sample performance					
Data: 2nd of January 2012 to 31st of December 2014					
Confusion Matrices		Predicted		Predicted	
		0	1	0	1
Observed:	0	19396	703	19570	529
	1	988	5047	1144	4891
Accuracy (CCR)		0.9353		0.9360	
Sensitivity (TPR)		0.8363		0.8104	
Specificity (SPC)		0.9650		0.9737	

Table 3
Market splitting non-parametric model performance.

		"Rule-of-Thumb"		"Cross-validation"	
Continuous Kernel Type: Second-Order Gaussian					
No. Continuous Explanatory Vars.: 13					
Unordered Categorical Kernel Type: Aitchison and Aitken					
No. Unordered Categorical Explanatory Vars.: 5					
No. Unordered Categorical Dependent Vars.: 1					
In-sample performance					
Data: 2nd January 2012 to 31st December 2014					
Confusion Matrices:		Predicted		Predicted	
		0	1	0	1
Observed:	0	20081	18	20087	12
	1	305	5737	80	5955
		"Rule-of-Thumb"		"Cross-validation"	
Accuracy (CCR)		0.9876		0.9965	
Sensitivity (TPR)		0.9495		0.9867	
Specificity (SPC)		0.9991		0.9994	

Table 4
Market splitting non-parametric bandwidth.

Dependent variable: Market Split DK1-DK2		
Bandwidth Type: Fixed		
Conditional density data (26146 observations, 19 variable(s))		
(1 dependent variable(s), and 18 explanatory variable(s))		
Bandwidth Selection Method:	Rule of Thumb	Likelihood cross-validation
	Bandwidth:	Bandwidth:
Market Split DK1-DK2	0	0.0005861131
Wind share DK1	0.205831	0.2665511
Wind share DK2	0.09888924	0.08285425
Demand DK1	288.2946	306.5095
Demand DK2	191.5344	279.4728
Demand Norway 2	442.999	131.7723
Demand Sweden 3	1331.377	722.8817
Demand Sweden 4	399.4506	207.3693
Demand Germany	6027.501	4565.185
Cross-border flow share DK1-NO2	0.1675775	0.1798814
Cross-border flow share DK1-SE3	0.118219	0.08754338
Cross-border flow share DK2-SE4	0.3212651	0.07702665
Cross-border flow share DK1-DE	0.1818036	0.1684009
Cross-border flow share DK2-DE	0.2038545	0.1028271
Market split DK1-NO2	0	7.853852e-08
Market split DK1-SE3	0	4.398261e-07
Market split DK2-SE4	0	0.1336549
Market split DK1-DE	0	4.344162e-10
Market split DK2-DE	0	1.369426e-06
Continuous Kernel Type: Second-Order Gaussian		
No. Continuous Explanatory Vars.: 13		
Unordered Categorical Kernel Type: Aitchison and Aitken		
No. Unordered Categorical Explanatory Vars.: 5		
No. Unordered Categorical Dependent Vars.: 1		

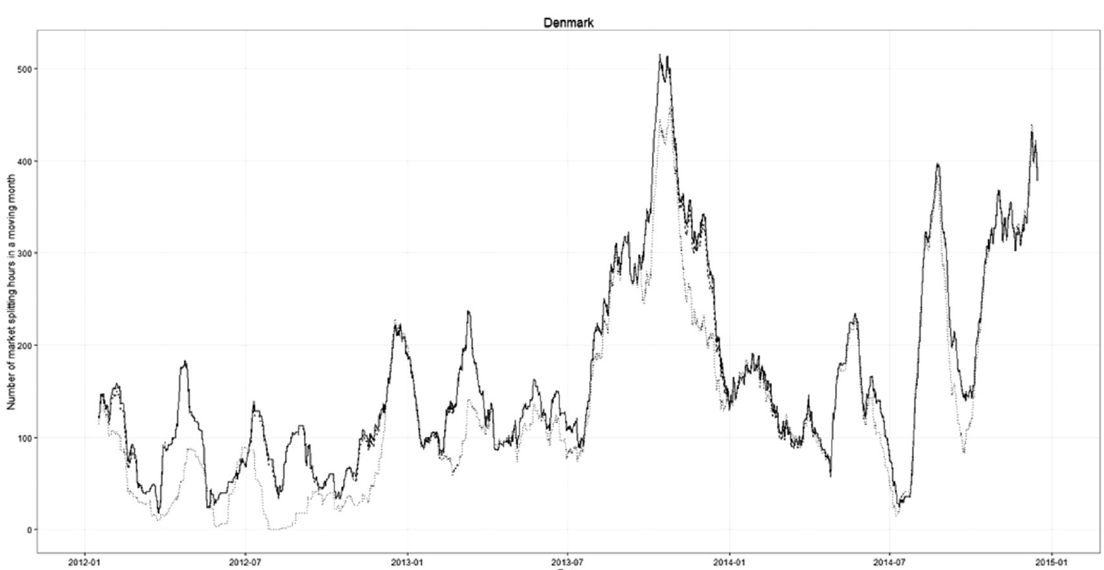

Fig. 7. Danish market splitting evolution (dotted – logit, dashed – non-parametric, solid – measured).

The shown behaviour can be explained by the asymmetric availability of low marginal cost electricity generated by the extensive existing wind power capacity in West Denmark (DK1), which is exported to East Denmark (DK2) with associated congestion of the Danish interconnection. The non-existence of market splitting between West Denmark (DK1) and Norway bidding area 2 (Fig. 8 center left) does not change significantly the market splitting response behaviour from the market configuration when Denmark is isolated (Fig. 8 top left). This demonstrates that the interconnection between West Denmark (DK1) and Norway bidding area 2 plays a limited role in the influence that wind power has on the behaviour of the Danish market splitting, perhaps due to the unnecessary import of electricity by Norway, which already has low cost electricity generation mainly from hydropower.

In the case that Denmark is not isolated from the adjacent electricity markets (Fig. 9 top left), the market splitting probability between West and East Denmark is null and the wind power generation share does not influence it. This behaviour can be explained by the ability of having all surplus electricity exported through the available cross-border interconnections and also not requiring external electricity infeed. Moreover, assuming Denmark not isolated from adjacent bidding areas with the exception of only

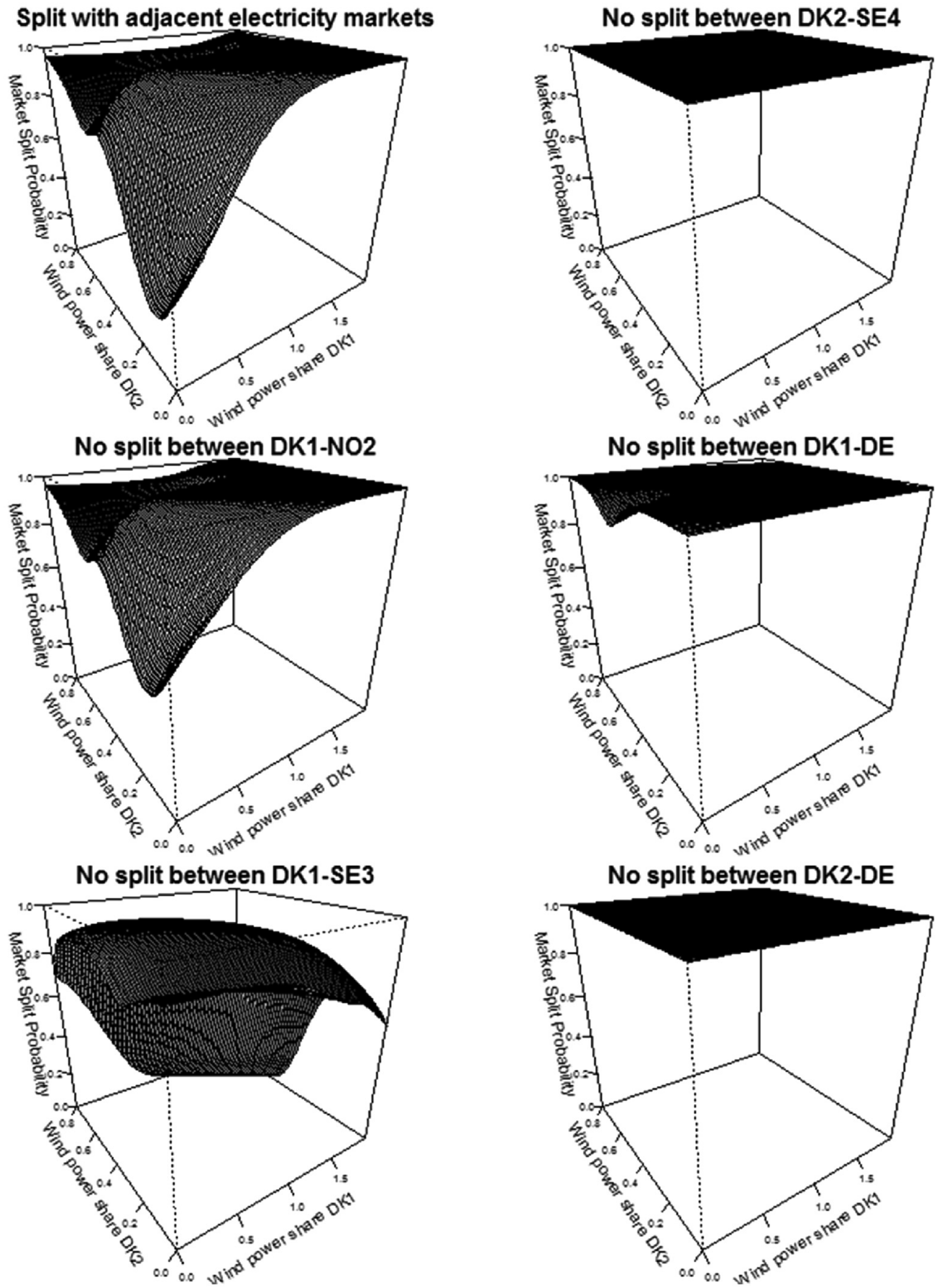

Fig. 8. Predicted probability response of market splitting between West and East Denmark to wind power generation share.

one of the interconnections with an adjacent bidding area, the probability response of the Danish splitting is also null. The available surplus of low cost electricity can always be exported through the available interconnections. As described above, with Denmark not isolated from adjacent bidding areas, with the exception of the interconnection West Denmark (DK1) – Germany (Fig. 9 center right), the probability response for the Danish splitting is high, even with low wind power generation, decreasing drastically with high wind power generation share in East Denmark (DK2). Thus, increasing wind power in East Denmark (DK2) may render unnecessary incoming interconnection electricity flows from West Denmark (DK1), which can not flow into Germany.

6. Conclusions

Two of the benefits of spot electricity markets integration are the optimization of RES-E generation and security of supply. In this context, the impact of increasing wind power generation on electricity spot market splitting in a multi-interconnected region is herein studied.

Being Denmark one of the best case studies due to the high level deployment of wind power and belonging to the oldest European integrated electricity market, the behaviour of market splitting between West and East Danish bidding areas was modelled through logit and non-parametric models, estimating the probabilities of its occurrence. Fundamentally, it is shown that wind power generation

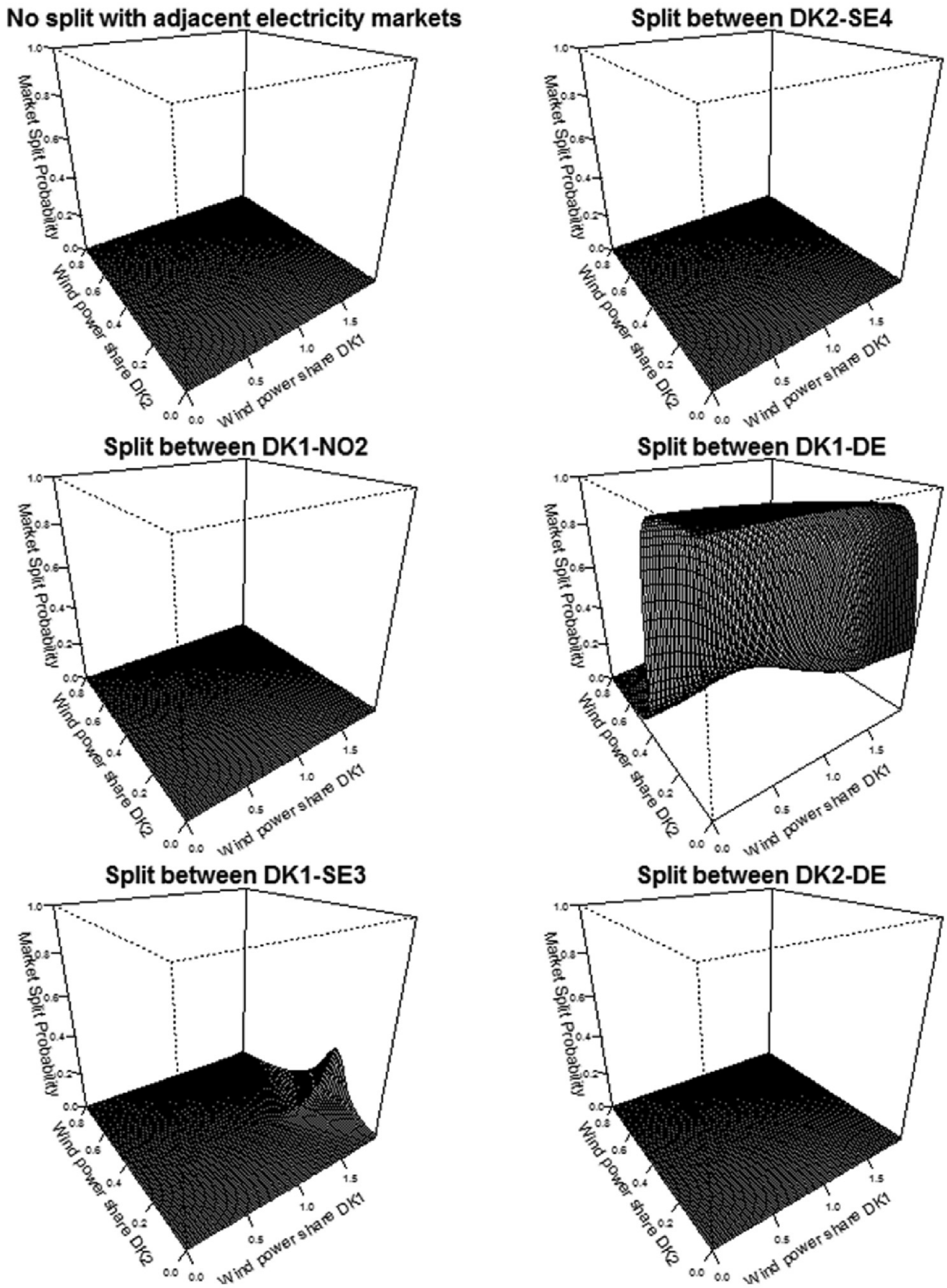

Fig. 9. Predicted probability response of market splitting between West and East Denmark to wind power generation share.

has a significant influence on market splitting behaviour. This behaviour, however, differs according to the congestion configuration of interconnections with adjacent bidding areas.

Considering the existing level of market splitting and the modelled behaviour we conclude that for the existing wind power generation, and furthermore, if there are intentions to further expand it, the existing interconnection between West and East Denmark is adequate, as the EU recommendation of 10% of the peak demand of the smaller interconnected market [59] is clearly surpassed, reaching a value of 16% in the considered data. Moreover, the occurrence of market splitting between West Denmark (DK1) and Germany should be avoided given the high probability of the Danish market splitting found to low West Denmark's (DK1) share of wind power (Fig. 9 center right). Therefore this cross-border interconnection should be reinforced in spite of the already 38,3% of the peak demand of the smaller interconnected market, which in this case is West Denmark's (DK1). Given that the cross-border interconnection between West Denmark (DK1) and Norway bidding area 2 does not have a meaningful impact on the probability response profile of the Danish market splitting, it is believed to have enough capacity and does not require reinforcing.

In order to decrease the market splitting probability level and the number of market splitting periods, resulting in increasing spot electricity price convergence and market integration, the requirements for interconnection capacity should be revised with the expansion of available wind power. Moreover, additional assessment should be made on the requirements for interconnection together with wind power expansion plans. Policies governing the coordination of both interconnection development and renewable incentives should be considered.

Further research should be focused in the analysis of other cross-border interconnections with Denmark, namely the new interconnections with the Netherlands, given the Price Coupling of Regions initiative. The complex dynamics existing in this electricity market setup might justify some of the obtained results, and a deeper analysis with additional electricity generation data could clarify some of these behaviours.

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Appendix A

Table 5
Time series summary statistics.

	Price DK1 [€/MWh]	Price DK2 [€/MWh]	Price NO2 [€/MWh]	Price SE3 [€/MWh]	Price SE4 [€/MWh]	Price DE [€/MWh]
Mean	35.377	36.482	37.956	31.501	31.258	37.732
Median	33.850	34.815	36.325	31.760	31.725	36.510
Maximum	2000.000	253.920	300.010	234.380	210.000	210.000
Minimum	−200.000	−200.000	1.380	0.590	0.590	−221.990
Std. Dev.	29.639	14.162	14.194	10.518	9.702	16.707
Skewness	50.852	0.598	3.741	2.744	1.832	−1.062
Kurtosis	3280.827	39.475	41.154	35.534	21.624	25.136
Jarque-Bera	1.17E + 10	1.45E + 06	1.65E + 06	1.19E + 06	3.92E + 05	5.39E + 05
Probability	0	0	0	0	0	0
Observations	26,146	26146	26146	26146	26146	26146
	Demand DK1 [MWh]	**Demand DK2 [MWh]**	**Demand NO2 [MWh]**	**Demand SE3 [MWh]**	**Demand SE4 [MWh]**	**Demand DE [MWh]**
Mean	2290.037	1541.256	3902.668	9907.371	2785.675	54633.017
Median	2238.000	1535.000	3799.000	9688.000	2732.000	54290.500
Maximum	4647.000	2520.000	6702.000	17466.000	5163.000	79120.000
Minimum	1159.000	829.000	2327.000	5057.000	1085.000	29201.000
Std. Dev.	495.104	328.932	760.786	2286.445	685.998	10351.346
Skewness	0.242	0.191	0.450	0.401	0.408	−0.005
Kurtosis	2.111	2.288	2.447	2.606	2.656	1.954
Jarque-Bera	1.12E + 03	7.11E + 02	1.21E + 03	8.70E + 02	8.54E + 02	1.19E + 03
Probability	0	0	0	0	0	0
Observations	26146	26146	26146	26146	26146	26146

	Cross-border flow DK1-NO2 [MWh]	Cross-border flow DK1-SE3 [MWh]	Cross-border flow DK2-SE4 [MWh]	Cross-border flow DK1-DE [MWh]	Cross-border flow DK2-DE [MWh]	Wind power DK1 [MWh]	Wind power DK2 [MWh]
Mean	−258.825	−5.938	−304.489	128.510	47.800	986.547	311.342
Median	−451.300	0.000	−382.400	150.000	0.000	770.000	234.000
Maximum	1632.000	740.000	1700.000	1780.000	585.000	3517.000	1032.000
Minimum	−1232.000	−680.000	−1300.000	−1500.000	−600.000	−2.000	2.000
Std. Dev.	683.133	436.225	781.972	708.107	497.014	794.581	266.154
Skewness	0.634	−0.066	0.318	−0.315	−0.210	0.822	0.701
Kurtosis	2.048	2.104	1.905	2.376	1.384	2.758	2.331
Jarque-Bera	2.74E + 03	8.93E + 02	1.75E + 03	8.57E + 02	3.04E + 03	3.01E + 03	2.63E + 03
Probability	0	0	0	0	0	0	0
Observations	26146	26146	26146	26146	26146	26146	26146

Notes: DK1 – West Denmark; DK2 – East Denmark; NO2 – Norway bidding area 2; SE3 – Sweden bidding area 3; SE4 – Sweden bidding area 4; DE – Germany.

Appendix B

Table 6
European electricity market integration references summary.

References	Electricity markets analysed	Methods	Main results
[14]	Electricity price from 3 January 2000 to 25 October 2003: • West Denmark • East Denmark • Finland • Mid Norway • South Norway • Sweden	• Markov switching fractional cointegration • regime switching multiplicative seasonal ARFIMA model	Cointegration exists only when interconnections between West Denmark – Norway and East Denmark Sweden bidding areas are not congested.

(continued on next page)

Table 6 (*continued*)

References	Electricity markets analysed	Methods	Main results
[15]	Electricity price from 2002 to 2006: • Austria • France • Germany • Netherlands • Spain • UK • Poland • Czech Republic • East Denmark • West Denmark • Sweden	• Principal Component Analysis (PCA) • Unit root tests • Convergence test	Convergence between both Danish bidding areas and between East Denmark and Sweden had been achieved.
[16]	Electricity prices from 1999 to 2006: • Netherlands • Germany • Austria • Scandinavia • Spain • France	• Unit root tests • Cointegration analysis	The Nordic electricity markets were found not to be integrated with Germany and the Netherlands.
[17]	Electricity prices from 1998 to January 2012: • Austria • Belgium • Czech Republic • France • Germany • Greece • Ireland • Italy • Poland • Portugal • Spain • Switzerland • the Netherlands • the UK	• Fractional cointegration analysis • Multivariate GARCH model	Nord Pool is found to be fractionally cointegrated with the remaining analysed electricity markets and that perfect integration had not been achieved.

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