The Role of Continuous Intraday Electricity Markets: The Integration of Large-Share Wind Power Generation in Denmark

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ABSTRACT

This paper suggests an innovative idea to examine the functionality of an intraday electricity market by testing causality among its fundamental components. Using Danish and Nordic data, it investigates the main drivers of the price difference between the intraday and day-ahead markets, and causality between wind forecast errors and their counterparts. Our results show that the wind and conventional generation forecast errors significantly cause the intraday price to differ from the day-ahead price, and that the relative intraday price decreases with the unexpected amount of wind generation. Cross-border electricity exchanges are found to be important to handle wind forecast errors. Additionally, some zonal differences with respect to both causality and impulse responses are detected. This paper provides the first evidence on the persuasive functioning of the intraday market in the case of Denmark, whereby intermittent production deviations are effectively reduced, and wind forecast errors are jointly handled through the responses from demand, conventional generation, and intraday international electricity trade.

Keywords: Intraday market, Wind power, VAR, Causality, Impulse response function

http://dx.doi.org/10.5547/01956574.38.2.fkar

INTRODUCTION

Wind power is the fastest growing electricity-generating technology among renewable energy sources, and its development plays an essential role in the current worldwide energy transition from fossil fuels to clean energy due to its ecological benefits. However, the increased penetration of wind generation has forced electricity systems to confront numerous challenges in renewable integration and system stability resulting from the high volatility and low predictability of wind generation. Since the deregulation of electricity markets in Europe, short-term market design has gradually divided electricity trading into several sequential markets with different time horizons. In contrast to quite common day-ahead trading schemes in many countries, intraday trading mechanisms have come into operation rather recently in the Nordic and some Western European electricity markets. Chronologically, generators can decide freely to sell their production one day before the day of operation (in day-ahead electricity markets) and/or to continue to trade close to the time of physical delivery, if the day-ahead planning needs to be corrected or reset (in intraday electricity

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markets). As wind outputs depend highly on meteorological conditions, which are subject to a limited predictability, the real schedule of wind power may deviate from the output planned in day-ahead markets. Closer to real time than the day-ahead trading, especially, the use of intraday trading allows wind generators (and other participants in the market) to modify their day-ahead production schedules according to updated and improved forecasts after the closure of the day-ahead market. Therefore, the intraday trading is regarded as an important tool to handle intermittent wind, and to foster its integration into the electricity system.

In the light of an increasing importance of the intraday market, the present paper is pioneering and well timed to provide a sound analysis based on this market design. The aims of this paper are: first, to explain how intraday prices deviate from the day-ahead ones; second, to investigate the fundamental drivers that cause these deviations; and third, to show how wind forecast errors are resolved. We propose a novel approach involving conventional econometric techniques to test for causality among the fundamental components of an intraday market in order to examine the market functionality. More specifically, by using Danish data, we explore causal links and interactions among the price differences between the intraday and day-ahead markets, and the deviations or forecast errors[1] of the real wind generation, conventional generation, and total demand compared with their committed day-ahead amounts, as well as the cross-border electricity trade in the Nordic intraday trading system. Time series techniques are applied to the data for two different trading zones in Denmark, namely Denmark West (DK1) and Denmark East (DK2).

Denmark is widely considered as a role model for the deployment of wind energy. This makes Denmark an ideal case to study the market influence of large wind penetration. Setting a high bar of wind integration in the coming years, the Danish short-term renewable target involves an achievement of 50% wind power in final consumption by 2020, and its long-term national goal requires complete independence from fossil fuels by 2050. Figure 1 displays the evolution of the accumulated installed wind power capacity and the share of wind feed-in in Denmark. As seen in Figure 1, since 2009, both the installed wind capacity and the share of wind power in final consumption have been steadily growing.

Due to the rapid development of wind power, the impacts of wind generation on electricity prices and volatility in day-ahead markets have gained considerable popularity recently (see, for example, Rintamäki et al., 2014; Pereira and Rodrigues, 2014; Stefano et al., 2015). Fabbri et al. (2005) analyzed the costs of wind forecast errors associated with the day-ahead wholesale market, but their model was built without considering an intraday trading mechanism. Indeed, the phenomena of massive price volatility and merit order effect[2] as a consequence of growing wind generation fed in the electricity system are, with no doubt, worth studying. However, up to now, the important role of a close-to-real-time trading mechanism (i.e. an intraday market), which is an essential market tool for handling the uncertainties posed by wind power in the electricity supply, has been overlooked. In contrast to the majority of studies concerning renewable power that have focused on day-ahead electricity markets, in this paper we focus on an intraday electricity market, and seek to

1. More precisely, other factors can also contribute to consumption or production deviations. For example, a generator may have an incentive to overstate or understate the production level in order to influence the spot prices or to trade electricity strategically in different markets to benefit from arbitrages. In this context, it may not be appropriate to call the quantity differences as "errors", as they result from such behavior. However, for linguistic simplification, we use production/consumption deviations and forecast errors interchangeably in this paper.

2. The merit order effect describes the lowering of power prices at the power exchange due to the increased supply of low marginal cost renewable energies, which shifts expensive conventional generation outside of the supply curve and yields lower clearing market prices.

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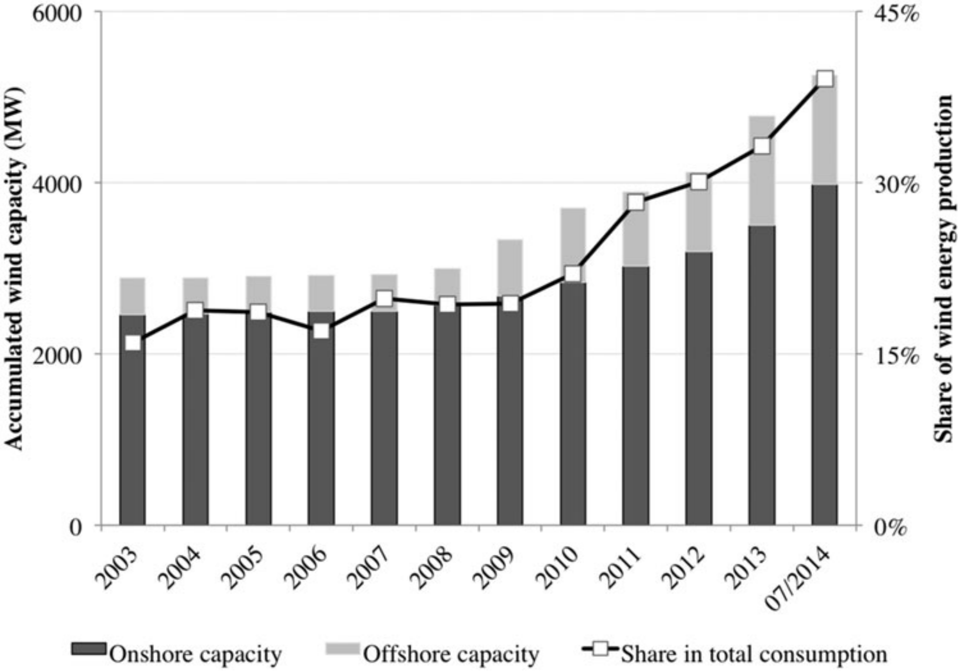
Figure 1: Accumulated Wind Capacity and Production



Notes: Accumulated wind capacity onshore/offshore (left axis) and wind power as a percentage of total electricity consumption (right axis) 2003—July 2014. Data sources: Authors' realization based on Danish Wind Industry Association (2014) and Danish Energy Agency (DEA) (2015).

investigate its role in responding to the aforementioned three types of forecast errors. The econometric techniques used here are not new in economic literature, but the originality of this paper comes from the unprecedented idea of investigating the functionality of an intraday market through causality tests. While a high level of liquidity has been viewed as a standard criterion for the effectiveness of an intraday market by some scholars (Weber, 2010; Furió et al., 2009), we have a different viewpoint: instead of focusing on the level of liquidity or intraday trade volumes, an intraday market can be considered effective if causality between price signals and market fundamentals can be established. As noted by Henriot (2014), an ideal intraday mechanism should not be targeting at a high trading volume *per se*, because economic agents behave according to the incentives that they receive from price signals. By the same token, our paper supports the author's argument, and more importantly, makes an innovation on testing the functionality of an intraday electricity market. To this end, our study distinguishes itself from all previous work, and it contributes to the literature at least in the following three aspects. First, it aims at providing the first empirical evidence on intermittent impacts of the Danish wind penetration on the intraday electricity market, and at showing how wind forecast errors affect intraday prices relative to day-ahead prices. Second, it investigates the causal relationships between the deviations in wind generation, fossil-based electricity generation, and electricity consumption from their day-ahead schedules as well as cross-border exchanges in the intraday market. The idea of studying these causal links is that they indicate how the paths of other market elements would differ in response to wind uncertainty in order to settle system imbalances, and to ensure supply security. Third, it provides further simulations based on impulse response functions in order to shed light on the persistence and duration of

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the price and quantity divergences resulted from a shock to forecast errors. The analysis of impulse response functions has been carried out, for example, by Aatola et al. (2013) in the market of European emission allowances in order to investigate dynamic relationships between carbon forwards and other energy commodity price series. Compared with former studies our paper provides a deeper, yet still straightforward, interpretation for the impulse response of the intraday market, which goes beyond the statistical links between time series.

The rest of the paper is organized as follows. Section I summarizes the literature related to wind integration and intraday designs. Section II introduces market mechanisms in the Nordic power market. Section III describes the dataset as well as the estimation method to be used in this study. Empirical results and discussions are presented in section IV and section V, respectively. Finally, section VI concludes the paper.

I. LITERATURE REVIEW

At present, only limited research has been done on the roles of intraday electricity markets; an even more limited number of these studies have been econometric in nature. The goal of intraday trading is to enable market participants to improve their positions following improvements in forecasts with respect to those already taken in the day-ahead market. As mentioned very recently by Hirth et al. (2015), the integration costs of wind power are presented by three components, namely temporal variability, uncertainty, and location constraints. Since electricity is not economically storable, and its supply and demand must be met instantaneously at the moment of physical delivery, wind producers' ability to reset a generation agenda with a short-lead time in an intraday market can effectively reduce both system costs for balancing and uncertainty on allocation of transmission capacities induced by lowered forecast errors (Borggrefe and Neuhoff, 2011; Chaves-Ávila et al., 2013; Hiroux and Saguan, 2010; Smeers, 2008). For instance, before the integration of Denmark into the Nordic intraday market, Holttinen (2005) had already pointed out that the introduction of this shorter lead-time trading scheme would help the Danish wind producers to deliver better forecasts. Besides reducing both uncertainty and system costs, an electricity market participant may also favor the use of intraday trading for other two reasons—to avoid using expensive balancing services together with to prevent penalties of imbalances imposed by the Transmission System Operator (TSO) (Bourry and Kariniotakis, 2009).[3]

Regardless of the potential benefits of intraday trading, low liquidity has been observed across several European intraday markets. A few scholars have offered the following explanations to this low liquidity issue. Chaves-Ávila et al. (2013) mentioned that the lack of liquidity is because most of the generators prefer to commit their production long ahead of time in the consideration of start-up costs and generation planning. However, this is not the case for wind generators as generation forecasts become more accurate when moving forward in time. Henriot (2014) suggests that oscillating predictions resulting in high trading costs can deter market players from participating in intraday markets. Using Danish data, Mauritzen (2015) distinguished wind shortfalls and surpluses, and suggested that the former would increase the probability of intraday trades while the latter would do the opposite due to the poorly designed Electricity Supply Act of 1999, which imposed a purchase obligation on the transmission system operator, and thus granted to the wind farms built before 2003 an exemption of balancing costs for a period of 10 years. Besides, the less

3. For a wind farm located in the North West of Denmark with installed capacity of 18MW, the authors showed that for a Danish wind producer, participation in the intraday market reduces the imbalance penalties by 18%.

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transparent pay-as-bid trading scheme of the intraday design may make market participants fear that their purchases or sales would affect the market price, and cause losses relative to the undisturbed price level. Therefore, the perspective of surpassing the intraday liquidity barrier is regarded as a cornerstone to improving the overall efficiency of market design (Weber, 2010).

Von Selasinsky (2014) uses a day-ahead uniform-price auction as a reference framework to study price setting of an intraday market. The decision of market participants to adjust their day-ahead position in the intraday market depends on the reference day-ahead price. If the intraday price were the same as the day-ahead price, they would be indifferent between adjusting their current position in the intraday market and remaining in this position. Setting the day-ahead price as an "indifferent offer price", which implies that generators are not making extra profits by trading additionally in intraday markets, forecast errors and their directions become fundamental variables in determining intraday transactions. Because the impact of wind generation penetration on power systems mainly depends on the costs of intermittency, it is important to take into account differences between intraday and day-ahead prices, since the additional gains or losses need to reflect system scarcity, and in turn, the true economic value added by wind power depends on this (Borenstein, 2012; Joskow, 2011). As a potential indicator of liquidity (Hagemann and Weber, 2013), intraday price deviations are found to be significant in most of the trading hours in the Spanish market (Furió et al., 2009), whereas Ito and Reguant (2014) report that the arbitrage behavior of wind producers in both markets contributes to a positive day-ahead market premium. Recent econometric work by Hagemann (2013) investigates the fundamentals that drive intraday price deviations in Germany, and shows that renewable forecast errors can lead to significant difference of intraday process from their day-ahead counterparts. However, none of these studies have examined causal relationships between price deviations and different sources of forecast errors altogether, or the persistence of forecast errors in intraday markets.

II. MARKET SETTINGS

Nord Pool Spot operates both the Elspot day-ahead and the Elbas intraday markets mainly in the Nordic (Denmark, Finland, Norway, and Sweden) and Baltic (Estonia, Latvia and Lithuania) regions.[4] A timeline illustrating the Nord Pool and the Danish successive trading scheme in the day-ahead, intraday, and balancing markets is shown in Figure 2. Contrary to Elspot, where prices are settled by a marginal rule through an hourly uniform-price auction, after the day-ahead gate closure at 12:00 CET, Elbas functions as a continuous market where trading takes place from 14:00 CET on the day before the day of operation up to one hour before physical delivery. Particularly, the intraday prices are set based on a first-come, first-served principle, that is, buyers and sellers choose directly the bids to be accepted in the market (Nord Pool Spot, 2015). The Danish day-ahead and intraday markets are a part of the Nord Pool electricity system, and the Danish TSO Energinet.dk is responsible for maintaining physical balances in the electricity system. It is important to mention that, as a fundamental principle of the Danish market model, market participants (consumers, producers, and electricity traders), including wind generators, are the Balancing Responsible Parties (BRP), meaning that they are financially liable for their own imbalances (Energinet.dk, 2011).[5] Next, during and subsequent to the day of operation, a balancing market, which

4. Nord Pool Spot also operates a day-ahead market called N2EX in the United Kingdom.

5. It is possible that a player does not hold balance responsibility, but in this case, she must assign it to a BRP. In practice, balancing is mostly achieved from the supply side, and consumers generally assign this obligation to electricity suppliers.

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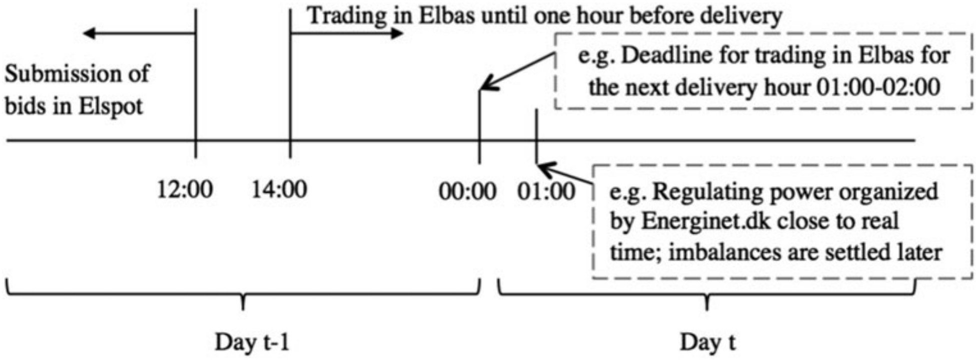
Figure 2: Timeline of the Nordic Sequential Electricity Trading



can be partitioned into a regulating and balancing power market, deals with the rest of imbalances. In the regulating power market, Energinet.dk purchases (upward regulation) or sells (downward regulation) electricity through BRPs in the common Nordic regulating power market. After the delivery hour, remaining incurred imbalances are neutralized financially by the TSO in the balancing power market (Energinet.dk, 2008).[6]

Nordic power market is often divided into various bidding areas, which can, if transmission between the areas is constrained, have area prices that differ from the system prices. Denmark is divided into the Denmark East and Denmark West bidding areas, as depicted in Figure 3.[7]

III. METHODS

A. Data sources

The Elspot day-ahead prices and the Elbas market prices are measured in euro per megawatt hour (€/MWh) in the two Danish bidding zones, retrieved from the Danish TSO Energinet.dk (2014). As mentioned in section II, since Elbas is operated as a continuous pay-as-bid market, for each hour, the information on the realized maximal, minimal, and average area prices is available.

While the share of wind generation fed in the system in Denmark is currently the world's largest, most remaining generation in that country comes from combined heat and power (CHP) plants. Among these plants, local CHP plants tend to follow actively heat demand rather than bid in the electricity market, but primary CHP plants are the principal players in the electricity market (Green and Vasilakos, 2012). Accordingly, wind forecast errors and primary CHP forecast errors are calculated as the difference between the realized productions and the day-ahead forecasted values. Analogously, consumption forecast errors are the deviations of the realized total consumption from the scheduled load. Forecast data are obtained from Nord Pool Spot (2014) and production data are sourced from Energinet.dk (2014) for both DK1 and DK2.

6. Since balancing power does not represent a market mechanism, and involves only financial settlements, in the rest of this paper we refer the terms balancing and balancing market solely to the regulating power market.

7. The two bidding zones were completely separated before 2010 until the commission of the Great Belt Power Link with a transmission capacity of 600MW.

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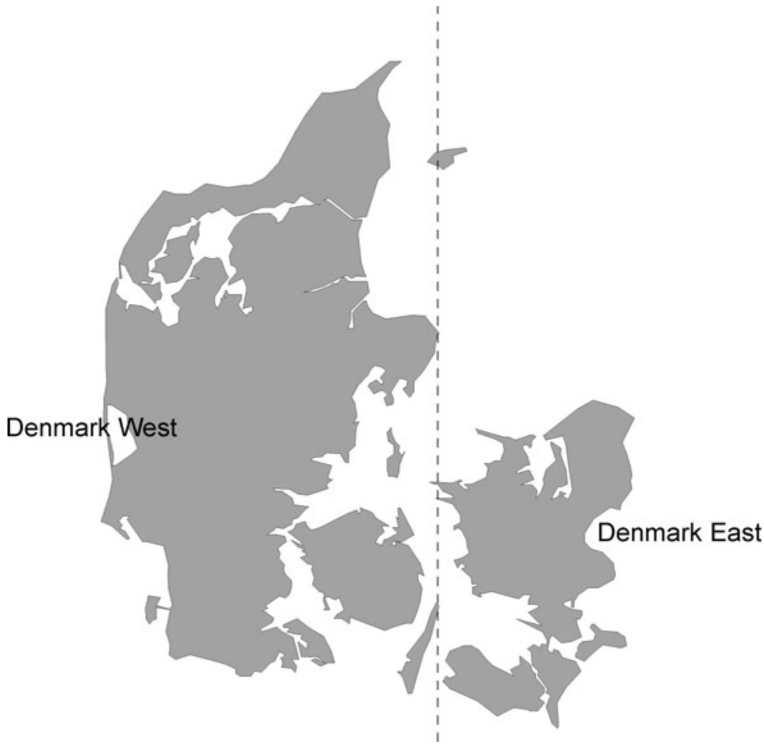
Figure 3: Map of Denmark West and Denmark East



As stated in the previous section, Denmark has extensive international transmission lines with its neighbors. Besides a market coupling built on the Danish-German border, both DK1 and DK2 are also well connected with their Scandinavian neighboring countries, namely Sweden and Norway, whose large supplies of hydropower can counterbalance fluctuations of the intermittent generation. Consequently, to take into account the influence of international electricity flows, using data from Nord Pool Spot, the net Elbas import flows are calculated based on the Elbas cross-border flows between a Danish bidding zone (DK1 or DK2) and its exchange partner. All quantity variables are measured in the unit of megawatt-hour (MWh). Finally, the dataset to be used covers the period from January 1, 2012, to May 31, 2014, containing 21,168 observations with hourly frequency, and each day has a length of 24 hours.

B. Data descriptions

Wind forecast errors

In order to have an impression on the magnitude of wind forecast errors, Figure 4 plots their distributions in DK1 and DK2. The majority of the wind forecast errors fluctuate around zero by 500 MWh in Denmark West, and by 250 MWh in Denmark East. The difference in magnitudes between these two zones can be explained by the fact that wind farms are more concentrated in the former region. The distributions in both regions do not appear to be symmetric. More importantly, Figure 4 shows that the wind output deviations hold a mean close to zero.

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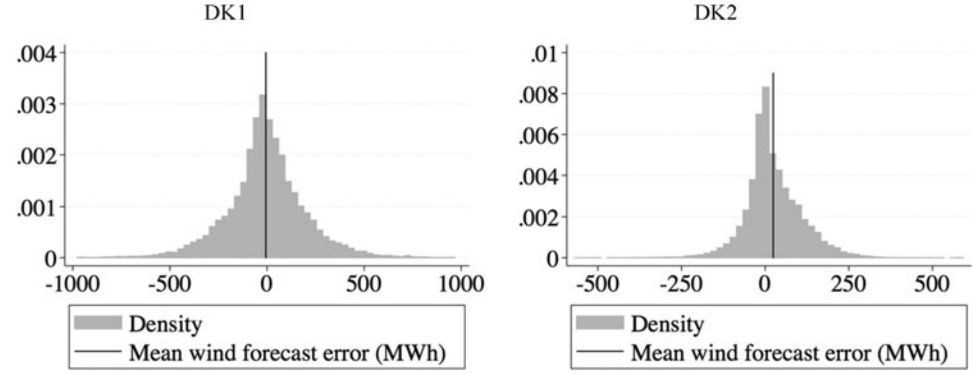
Figure 4: Distributions of Wind Forecast Errors in DK1 and DK2



Data sources: Authors' realization based on Energinet.dk (2014) and Nord Pool Spot (2014).

Table 1: Summary Statistics of Wind Forecast Errors

Zones	Mean	S.D.	Med.	Max.	Min.	Skew.	Kurt.	Nb. positive	Nb. negative	Nb. zero
DK1	-5.92	207.38	-10.00	1237.00	-1643.00	-0.10	6.15	9923	11188	57
DK2	24.05	83.62	10.00	592.00	-569.00	0.27	5.70	12147	8840	181

Notes: Summary statistics of the mean, standard deviation, median, maximum, minimum, skewness, kurtosis and numbers of observations with positive, negative and zero values of the wind forecast errors in each bidding zone.

Detailed statistics of the wind forecast errors are listed in Table 1, according to which, indeed, the means and medians of the wind forecast errors are relatively small. They are negative in Denmark West, but positive in Denmark East. The observed excess kurtosis in both regions means that the wind forecast errors are more concentrated in a near-zero interval compared with a normal distribution. Since the changes of wind outputs rely on weather conditions rather than market elements, they are exogenous to the electricity trading system. In spite of that, we may still suspect a correlation between variations of wind output and variations of demand because weather conditions could influence both of them. For example, low temperature might arrive often with high wind speed, and thus forecast errors of both wind output and electricity consumption might shift to the same direction. Fortunately, the exogeneity of wind power generation and the independence of wind forecast errors from other variables can be verified by calculating the correlations among them, and this has been done recently by Mauritzen (2015). Although a few exceptions may still exist, both assumptions are likely to be valid in the case of Denmark.[8] Therefore, we would expect that the wind forecast errors are exogenous to the system as long as wind generators could truly report their expectations on the production schedules. Hence, taking wind forecast errors as exogenous to the system, their correlations with market variables should have causal interpretations.

Besides wind forecast errors, summary statistics for the other variables involved in the analysis can be found in Tables A.1 and A.2 in Appendix A.[9]

8. The incentive to untruthfully report the expected value of wind production can be a violation of this exogeneity assumption. However, the ability of verification of the TSO, and the existence of subsidies make this situation unlikely. Moreover, the plausible dependence of wind forecast errors to wind power, consumption forecast errors, and market coupling can be ruled out by data analyses. For more details, see Mauritzen (2015).

9. Note that outages may be an influential factor on intraday market trading. We do not separate this factor given the low incident frequency. Furthermore, since we measure the deviation of the realized CHP production from its day-ahead schedule, the unplanned breakdowns are actually incorporated in this variable.

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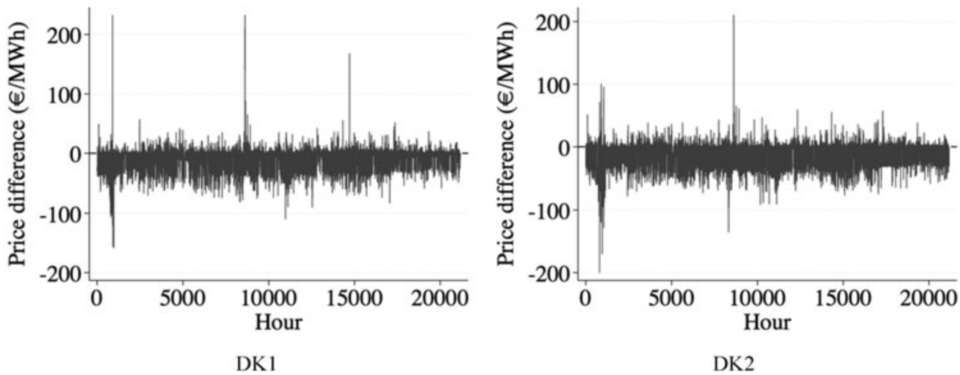
Table 2: Intraday Trading Hours as a Percentage of Total Hours

Bidding zone	2012	2013	2014
DK1	72.51%	77.91%	88.22%
DK2	61.16%	62.37%	72.43%

Data sources: Authors' calculations based on Energinet.dk (2014).

Figure 5: The Difference Between the Intraday and Day-ahead Prices Observed at Nord Pool Spot



Data sources: Authors' realization based on Energinet.dk (2014) and Nord Pool Spot (2014).

Day-ahead—intraday differences

The Elbas intraday market exerts a growing importance as more wind power enters the grid. Table 2 presents the fraction of hours when Elbas trades occur for both the Western and Eastern Denmark areas. It follows from Table 2 that both areas have achieved fairly good liquidity in intraday trading. The percentages of intraday usage have been rising during the period of the study. As the scales of generated electricity and installed wind capacity in Denmark West are larger than those in Denmark East, it is not surprising that the intraday market of DK1 is more liquid in terms of trade occurrences.

For those hours when no trade occurs in the intraday market, the intraday prices are displayed as zero at the Nord Pool power exchange. Showing these data, Figure 5 inspects the differences between the intraday and day-ahead electricity prices.[10] It is easy to observe, quite frequently, a noticeable day-ahead price premium in both bidding zones.

If the prognosis of the wind output is accurate enough, it should not be a daunting task to handle the intermittent energies only in the day-ahead market. However, often, recurrent wind forecast errors nudge electricity systems toward trade imbalances after the day-ahead transactions have occurred. By the nature of this market design, such imbalances should be reflected by the

10. On June 7th, 2013, DK1 reached the technical maximum curtailment price of 2000 €/MWh. This was due to revisions on thermal power plants that coincided with grid maintenance, and low wind power production at the same time (NER, 2014). The five hourly day-ahead prices affected by this event are replaced by the prices averaged over the same hours one day before and one day after.

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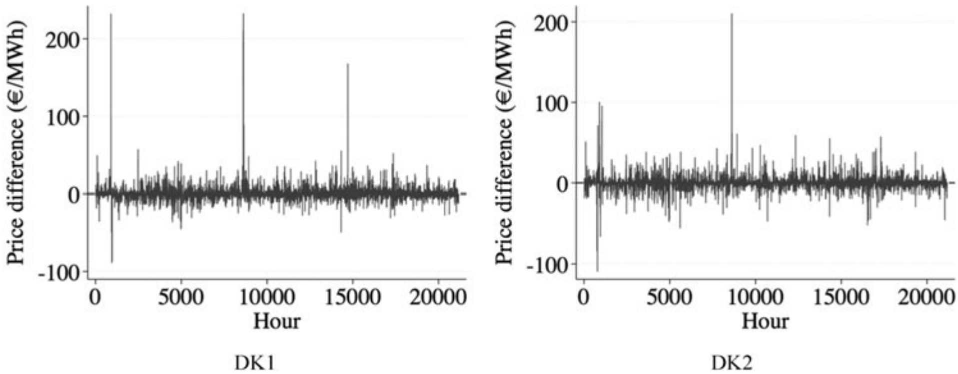
Figure 6: The Difference Between the Intraday and Day-ahead Prices to Be Used for Modeling



Data sources: Authors' realization based on Energinet.dk (2014) and Nord Pool Spot (2014).

price differences between the day-ahead and intraday markets, if forecast errors are mainly managed through the intraday mechanism. However, in the case where the intraday prices are set to zero because of insufficient liquidity (i.e. no trade takes place), the price differences between the intraday and day-ahead markets can no longer reflect the additional system costs as these costs are nil at the stage of intraday trading. As mentioned in section I, spreads between intraday and day-ahead prices should correctly reflect system scarcities and true economic values added by renewable energies (Borenstein, 2012; Joskow, 2011). Relying on this rationale, to estimate a reasonable and accurate econometric model, we thus consider the price differences between the intraday and day-ahead markets as zero when there is no electricity traded in the intraday market.[11]

The price differences after this data adjustment in DK1 and DK2, which will be used in estimations, are presented in Figure 6. In contrast to Figure 5, positive and negative price spreads are distributed more randomly around zero, which can be further confirmed according to the summary statistics in Tables A.1 and A.2 in Appendix A, where the means and medians of the price differences are close to zero, and the numbers of negative and positive observations are balanced. One may expect that the Elbas intraday price often exceeds considerably the day-ahead price to reflect the scarcity of the available generation as electricity trade approaches to real time. However, compared with the day-ahead prices, intraday prices spike very few times during the whole period. In contrast, the intraday prices plunged several times, especially at the beginning of the study period in DK2. Figure 6 shows that on average, the close-to-real-time trading is not more expensive than the day-ahead trading, and therefore, balancing generation assets are not scarce in the Nordic area. This is to some extent understandable since the abundant hydro reserves in Scandinavian countries may dampen the interest of close-to-real-time trades, because electricity is stored in the form of water. As will be discussed in section V, cross-border power exchanges indeed play an important role in the functioning of the intraday market and wind integration in Denmark.

11. An alternative way of thinking is that the shadow intraday prices need to satisfy a no-arbitrage condition when they are displayed as zero due to non-occurrence of trade in the intraday market. In this case, generators are at least indifferent between trading in Elspot and in Elbas in order not to deviate from their behavior of the day-ahead trading. This implies that the implicit intraday prices should be equal to the day-ahead prices, which makes the price differences between them to be zero.

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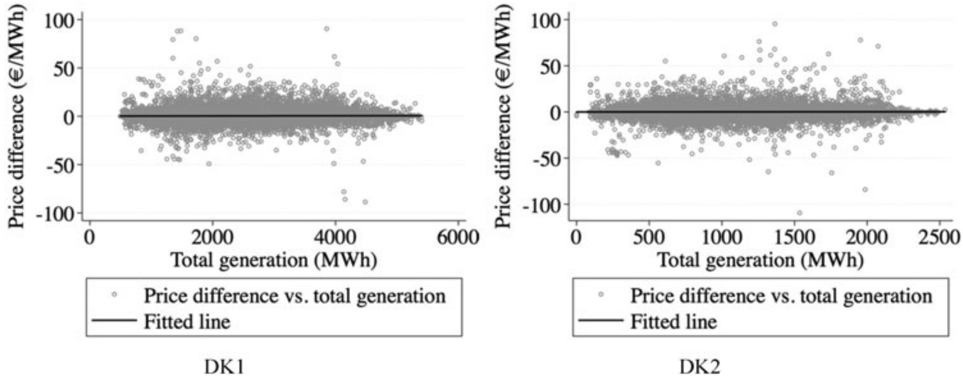
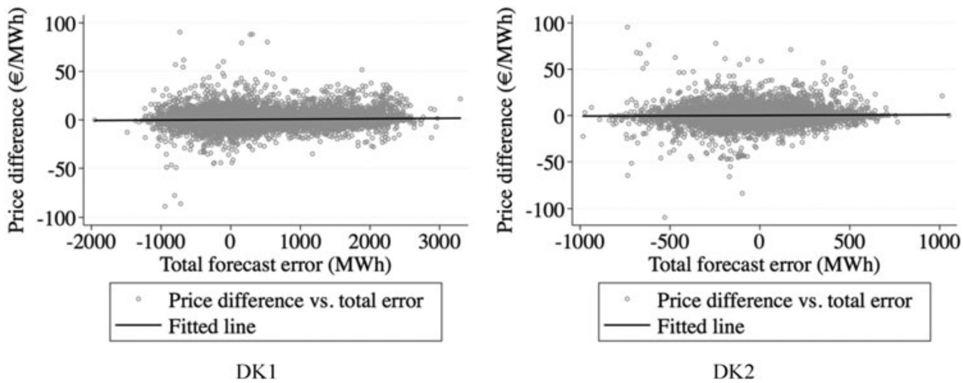
Figure 7: Hourly Price Differences versus Total Generation in DK1 and DK2



Data source: Authors' realization based on Nord Pool Spot (2014).

Figure 8: Hourly Price Differences versus Total Forecast Errors in DK1 and DK2



Data source: Authors' realization based on Nord Pool Spot (2014).

The lack of generation scarcities in the Nordic electricity market can be further verified by means of a scatter plot of the hourly price differences between the intraday and day-ahead markets against the total electricity generation. It follows from Figure 7 that the hourly price divergences stay stable even when the total generation becomes very large.

Additionally, a static investigation on the relationship between the price spreads and the forecast errors may help us to understand both the necessity and utility of dynamic modeling, which is what we turn to next. In order to do so, in Figure 8 we provide a scatter plot with ordinary least squares (OLS) regression line of the correlation between the price differences and the total system imbalances (i.e. the sum of all forecast errors in wind generation, conventional generation, and final consumption). The intraday price deviations are stable around zero, reasonably implying that the three sources of individual imbalances interact to each other in order to reduce the aggregate system imbalances. In the same vein, a decreasing trend of the price spread can be noticed in Figure 9, which depicts the intraday price deviations as a function of forecast errors only in wind generation. It is important to note that although some useful insights can be extracted from Figure 8 and Figure 9, the relationships displayed here by means of OLS regression lines are just static pictures of

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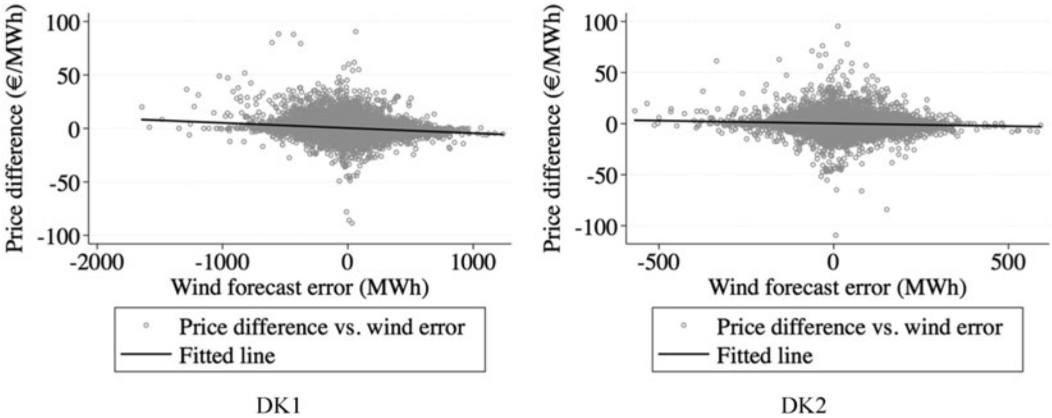
Figure 9: Hourly Price Differences versus Wind Forecast Errors in DK1 and DK2



Data source: Authors' realization based on Nord Pool Spot (2014).

temporally interrelated variables. As a consequence, the use of a model that is able to capture this temporal dynamics, and to describe more accurately the trajectories of the intraday price signal in response to the imbalances in the electricity system is motivated in the next section.

C. Empirical Methodology

We use time series techniques to address the research questions that are raised in the introductory section. For this purpose, a dynamic multivariate model can be specified, and then estimated. But before proceeding to the model, time series properties of the data should be examined in order to avoid any spurious estimation result. We apply the generalized least squares (GLS) augmented Dickey-Fuller test (DF-GLS) proposed by Elliot et al. (1996), and additional three GLS versions of the modified Phillips-Perron (1988) tests developed by Ng and Perron (2001). The DF-GLS test is based on the standard Dickey and Fuller (1979) and Said and Dickey (1984) unit root tests, and has the form:

$$\Delta y_t = \beta_0 y_{t-1} + \sum_{i=1}^{k} \beta_i \Delta y_{t-i} + \epsilon_t \qquad (1)$$

where y_t is a local-to-unity GLS detrended series.[12] Then the DF-GLS test consists of testing the null hypothesis of non-stationarity (i.e. $\beta_0 = 0$) against the alternative hypothesis of stationarity (i.e. $\beta_0 < 0$) by using a standard *t* test from an OLS estimate of Equation [1]. Elliott et al. (1996) showed that this strategy of GLS detrending of the data provides substantial power gains over the standard unit root tests. On the other hand, the unit root tests of Ng and Perron (2001), called the M tests, follow also the same strategy as in Elliott et al. (1996), and provide further improvements in terms of size and power properties. Indicating that in the case of unit root tests, the conventional procedures of lag length selection for the autoregressive terms (such as Akaike Information Criterion (AIC) or Bayesian Information Criterion (BIC)) are not sufficiently flexible, Ng and Perron (2001)

12. Since these unit root tests are widely used and understood in the time series literature, we do not repeat here in detail the presentation of their estimation strategies.

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also developed a modified information criterion (MIC), which is then shown to be more robust in the presence of negative moving average errors.

Once the order of integration of the variables is established, one can proceed to the model. In the case where the variables are all found to be stationary, the dynamic relationship between them should be estimated in a vector autoregressive (VAR) framework. The VAR model including the five variables under examination can be presented in the following form:

$$y_t = \Gamma_0 + \Gamma_1 y_{t-1} + \Gamma_2 y_{t-2} + \ldots + \Gamma_p y_{t-p} + \varepsilon_t \tag{2}$$

where $y_t = (Price\_dif_t, Wind\_er_t, CHP\_er_t, Load\_er_t, Flow_t)'$ is a vector of dependent variables in which *Price_dif* stands for the difference between the average hourly intraday prices and day-ahead prices; *Flow* represents net cross-border electricity flows; *Wind_er*, *CHP_er,* and *Load_er* denote respectively wind forecast errors, primary CHP forecast errors, and consumption forecast errors, as discussed above. Still in Equation [2], ε_t is a ($5 \ x \ 1$) vector of i.i.d. white noises, Γ_0 is a ($5 \ x \ 1$) vector of constant terms, and Γ_i are ($5 \ x \ 5$) parameter matrices including coefficients associated with the lagged values of endogenous variables for $i = 1, \ldots, p$. The optimal lag length p can be determined using the AIC. To investigate the causal relationships between two variables in the sense of Granger causality (Granger, 1969), the joint significance of the coefficients in Γ_i associated with a given independent variable should be tested. If some of these parameters are found to be statistically significant, this indicates that the dependent variable is caused by the independent variable under consideration. In this respect, the Wald statistics, which follow the chi-square distribution with degrees of freedom equal to the number of parameter restrictions, provide an accurate measure of significance. Thus, causal links can be explored by applying the Wald test to the estimated coefficients in Γ_i matrices.

Although the VAR model given in [2] can provide the required information about the causal relationships among the series, it cannot indicate how each variable responds to innovations in other variables, and how long the effect lasts. Using the estimation results of [2], the generalized impulse response (GIR) analysis developed by Koop et al. (1996) and Pesaran and Shin (1998) can be used to address this issue. Basically, a GIR function measures the effect of one standard error shock to an equation in the system given in [2] at time t on the expected values of y at time $t + n$. By doing so, it provides an efficient way to evaluate the effects of different forecast errors on electricity price deviations, and possibly *vice versa*. It should be added that the GIR analysis is not sensitive to the ordering of variables in the VAR system.

IV. RESULTS

As discussed above, in the first step of our empirical analysis, we test for a unit root by using the DF-GLS test (Elliot et al, 1996) and the M tests (Ng and Perron, 2001). The results are given in Table 3.

From Table 3 it follows that all series under consideration are stationary for both of the trading zones in Denmark (i.e. Denmark West, DK1; Denmark East, DK2), that is they are integrated of order 0 (i.e. an I(0) process). Hence, the conventional Granger causality test can be performed in the case of a VAR framework, which should involve all of these variables in their levels.

We estimated the VAR system given in [2], and then tested the joint significance of the parameters in order to assess the causal links between the variables. The results are depicted in Table 4.[13]

13. Recall that wind forecast errors are included as an exogenous variable in the VAR. The results are robust to standard robustness checks, which are not reported here to conserve space.

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Table 3: Unit Root Test Results

	Variables	DF-GLS	MZ_{α}-GLS	MZ_{t}-GLS	MSB-GLS
DK1	Price_dif	-19.84**	-499.8**	-15.80**	0.031**
	Wind_er	-13.80**	-361.0**	-13.43**	0.037**
	CHP_er	-13.36**	-486.9**	-15.60**	0.032**
	Load_er	-7.793**	-104.7**	-7.229**	0.069**
	Flow	-16.62**	-596.6**	-17.26**	0.028**
DK2	Price_dif	-21.93**	-806.3**	-20.07**	0.024**
	Wind_er	-16.37**	-654.8**	-18.09**	0.027**
	CHP_er	-12.20**	-297.4**	-12.19**	0.040**
	Load_er	-2.734**	-14.91**	-2.681**	0.179*
	Flow	-16.40**	-600.9**	-17.33**	0.028**

Notes: DF-GLS is the modified version of the augmented Dickey-Fuller test suggested by Elliott et al. (1996); MZ_{α}-GLS is the modified Phillip-Perron MZ test; MZ_{t}-GLS is the modified Phillip-Perron MZ test; MSB-GLS is the modified Sargan-Bhargava test which is also given by a ratio between MZ_{α}-GLS and MZ_{t}-GLS (i.e. MSB-GLS = MZ_{t}-GLS/ MZ_{α}-GLS). For all tests, lag lengths are chosen using the modified AIC (MAIC) suggested by Ng and Perron (2001). * and ** denote the rejection of the null hypothesis of unit root at the 5% and 1%, respectively.

Table 4: Results of Granger Causality

	Dependent variables	Price_dif	Wind_er	CHP_er	Load_er	Flow
DK1	Price_dif	-	92.17**	57.57**	45.99*	36.49
	CHP_er	38.71	330.5**	-	27.85	94.91**
	Load_er	57.71**	57.31**	60.25**	-	32.5
	Flow	33.23	123.6**	108.4**	24.11	-
DK2	Price_dif	-	62.12**	106.6**	24.06	47.10**
	CHP_er	45.85**	121.0**	-	157.8**	76.25**
	Load_er	40.30*	85.14**	156.1**	-	29.07
	Flow	56.02**	113.75**	78.02**	24.23**	-

Notes: χ^2-statistics are given for the hypothesis that the coefficients associated with the relevant variables are jointly zero. * and ** denote the rejection of the null hypothesis of non causality at the 5% and 1% respectively.

According to Table 4, the answer to one of the research questions of this paper concerning the fundamental drivers of the intraday and day-ahead price differences in the two Danish bidding zones can be found in the results of the *Price_dif* equations. One immediate conclusion to be drawn is that both wind and conventional power forecast errors significantly cause the intraday prices to deviate from the day-ahead values in both DK1 and DK2. This result implies that the deviations of intraday prices from the day-ahead values are supply-side driven, and that the production forecast errors (both wind and CHP) are to some extent digested in the intraday settings.

Besides the above-mentioned similarities, there are also some significant and notable differences with respect to causal relationships. In DK1, the demand side has also a significant role in electricity price deviations in the intraday market, while in DK2 the cross-border exchange flows additionally cause the intraday prices to diverge from their day-ahead values. Reciprocally, these

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price deviations in turn affect both the load deviations in DK1 and the net electricity flows in DK2. Furthermore, consumption forecast errors seem to be corrected via cross-border electricity transmission in DK2, which, once again, does not occur in DK1. On the one hand, the significant influence from the demand side in DK1 can be explained by a size effect, which means that the scale of power consumption in DK1 is much larger than that in DK2. For instance in 2013, electricity consumption in DK1 was on average 46% higher than that in DK2. This may induce larger load forecast errors and error variances in DK1, which may have a greater impact on the intraday market. DK1 has also a higher intraday trade share, and thus consumption "shocks" may be more influential on the price deviations. On the other hand, Nord Pool Spot's Elbas is generally the single marketplace for the intraday trading on the most of the interconnections between the Danish bidding zones and other coupling partners. One exception is given to the border between Denmark West and Germany, on which physical transmission rights are issued through monthly and yearly auctions via a capacity platform (DERA, 2015).[14] Therefore, the physical use of a long-term capacity sale on the border of DK1 and Germany may weaken the causal link between short-term intraday trading and cross-border exchanges in Western Denmark.

Concerning the uncertainty of wind power generation, our results offer a striking point that wind forecast errors not only drive intraday prices away from their day-ahead values, but also affect significantly CHP and load forecast errors, and intraday cross-border trade. Recall that the production forecast errors are calculated as the difference between the realized production and its forecasted level, so that these deviations from the day-ahead forecasts may also include the responses in real-time balancing markets. Therefore, the inevitable problem of wind generation's intermittency is tackled through the Elbas intraday trading, and also plausibly through the balancing mechanism. The above arguments altogether with the persistence of responses will be further discussed in the next section.

V. DISCUSSION

With the causality results in mind, a further analysis of the dynamic interrelationships between the variables involved in the VAR system can be carried out by studying the impulse response outputs of the model, which are depicted in Figure 10 and Figure 11. More specifically, these figures outline the paths of the price responses after one standard deviation shock from the market fundamentals (Figure 10), and the responses of quantity variables resulted from a shock in wind forecast errors (Figure 11) during the following 24 hours.

The inferences that we can draw from the GIR functions run parallel to the above-obtained causality results.[15] We first consider Figure 10, and discuss the main drivers of the intraday price divergences in DK1 and DK2, whose paths depict the way of functioning of the Nord Pool intraday market. As seen in Figure 10, wind forecast errors have a significantly negative impact on deviations between intraday and day-ahead electricity prices in both DK1 and DK2. That is to say, wind producers are indeed actively involved in intraday trading, so that the negative causality between the intraday–day-ahead divergences and the wind forecast errors indicates that wind generators

14. The allocation of available transfer capacity on the border of Denmark West and Germany can be found at https://www.intraday-capacity.com.

15. Note that in DK2 the transmission from the innovations in *Load_er* to *Price_dif* is not significant. However, in DK1, although the initial response of *Price_dif* to an innovation in *Flow* is marginally statistically significant, it quickly fades away after the first hour. This implies that *Flow* and *Load_er* do not exert a causal effect on *Price_dif* in DK1 and DK2, respectively.

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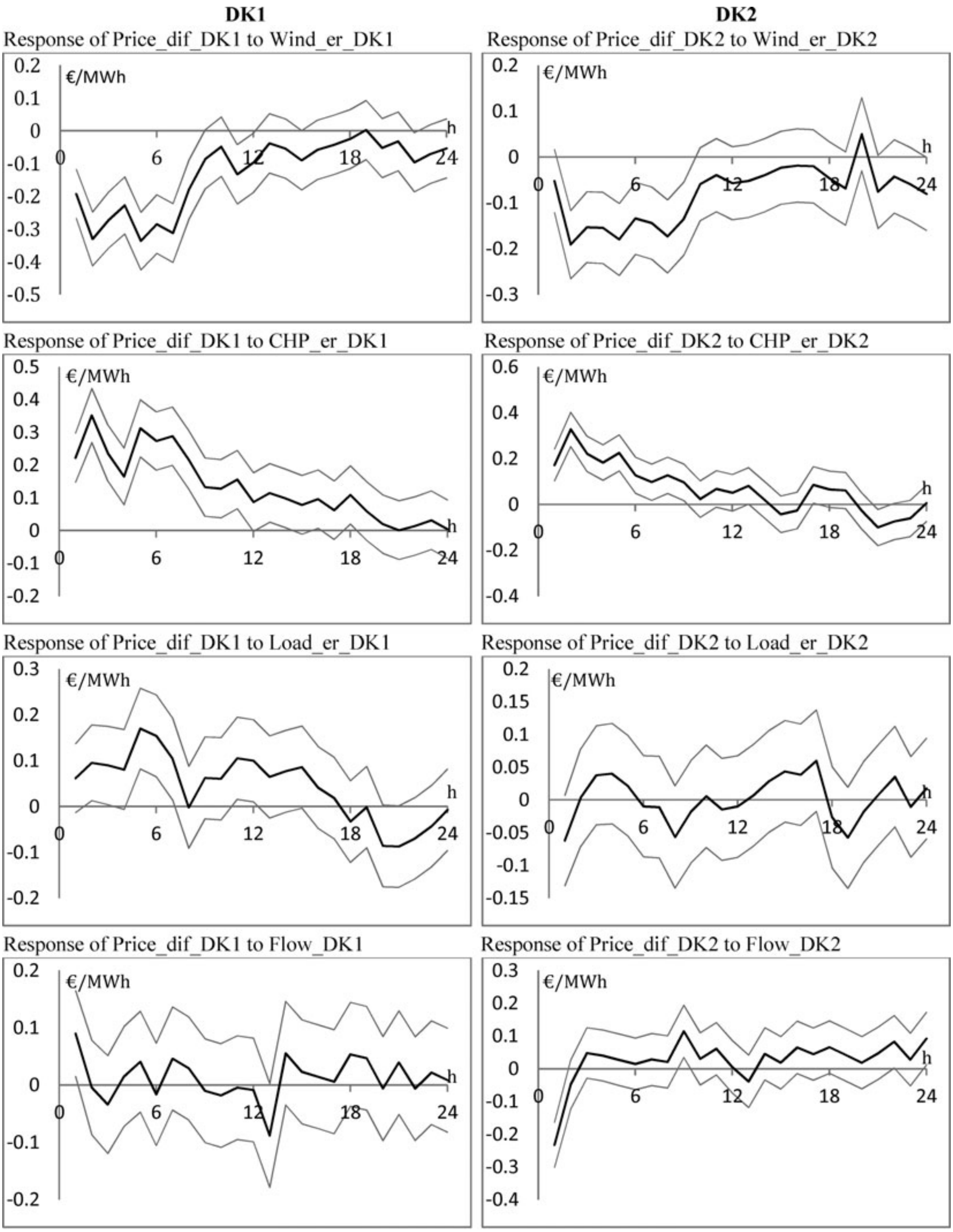
Figure 10: Responses of the Difference Between Day-ahead and Intraday Prices



Notes: Responses of the difference between day-ahead and intraday prices to generalized one standard deviation innovations in quantity variables in DK1 and DK2. The forecast horizon (h = 1,2, ,24 hours) is displayed on the horizontal axis. The vertical axis measures the magnitude of the response to the impulse. The responses represent deviations in €/MWh from the steady state of the variable *Price_dif*, and the impulses are scaled such that 1 equals one standard deviation in the variables *Wind_er*, *CHP_er*, *Load_er*, and *Flow*. The black lines plot the point estimates for the impulse responses, and the grey lines show 95% confidence bands with 2 standard errors.

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are willing to pay high when deviation shocks in production are negative, and to sell low when they are positive. In contrast, the impact on price responses turns out to be positive when we consider CHP errors. Although the Nordic intraday market conducts bilateral trading as a market rule, the merit order still matters at the margin. Considering the fact that the marginal cost of CHP generation is certainly higher than the nearly zero variable cost of wind generation, an unexpected increase in CHP generation requires a higher intraday price relative to the price level in the day-ahead market. Besides, a CHP plant must run at least a minimum of a few hours in order to effectively lower start-up costs, which should also be reflected in the intraday prices when CHP generators trade close to real time. Many works have been dedicated to the measure of the merit order effect in day-ahead electricity markets (e.g. Jónsson et al., 2010; Ketterer, 2014; Traber and Kemfert, 2011), but here, our results reveal clear evidence that this effect of reduction in prices resulted from wind generation exists not only in day-ahead but also in intraday market.

Additionally, in DK1, the bidirectional causality found between price deviations and load forecast errors tends to be positive, while in DK2 this causal relationship cannot be seen as a significant one. Before we discuss the results in Figure 11, let us illustrate this point also from a static perspective. The two scatter plots shown in Figure 12 indicate a slight positive correlation between intraday price deviations and consumption forecast errors in DK1, but no significant correlation between the same variables in DK2. Furthermore, instantaneous negative responses between price deviations and intraday exchange flows are prevailing.[16] In terms of the persistence of the impact of wind deviations on the intraday market, the departed price signals tend to fade away after 12 hours in DK1 and DK2, implying that one shock in wind generation deviations at a given hour is followed by generators' continuous adjustments according to their improved prognoses on real wind generation for the succeeding hours, and thus, the intraday adjustment resulted from the shock does not disappear quickly. All in all, our examination of intraday price signals relative to day-ahead price levels proves that the intraday market design is appropriate, and especially so for intermittent generation.

We now turn to Figure 11 that shows how the Danish intermittent generation interacts with other market elements. More precisely, we analyze the response functions of CHP and load forecast errors, and intraday exchange flows to the impulses of wind forecast errors, in order to backtrack how imbalances caused by wind variability are dissolved in the system. A comparison between DK1 and DK2 in Figure 11 shows that their diagrams in these two zones are quite consistent. The response patterns of the trade variable clearly show that wind forecast errors affect negatively the cross-border exchanges in the intraday market, which are measured by net inflows to the Danish bidding zones. More precisely, negative shocks to wind output in Denmark tend to stimulate power imports in the intraday market. Notice that this impact is significant during the upcoming 12 hours, which is reasonably consistent with the persistence of intraday price deviations. As a consequence, the causality running from wind deviations to both net exchange flows and intraday price deviations demonstrates that international connections provide a critical support to the Danish intraday trading when having a large scale of wind power fed in the system, and that they are especially advantageous as the Danish neighboring countries' possess abundant hydro power resources. Accordingly, as noted in section III, the formation of the Danish intraday prices does not generally reflect resource scarcities since Denmark's interactions with neighboring hydro reserves through imports and ex-

16. The GIR of Load_er_DK1 to Price_dif_DK1 is similar to that of Price_dif_DK1 to Load_er_DK1. The GIR of Flow_DK2 to Price_dif_DK2 is similar to that of Price_dif_DK2 to Flow_DK2. They are not presented in this section, but in Figure B.1 in Appendix B.

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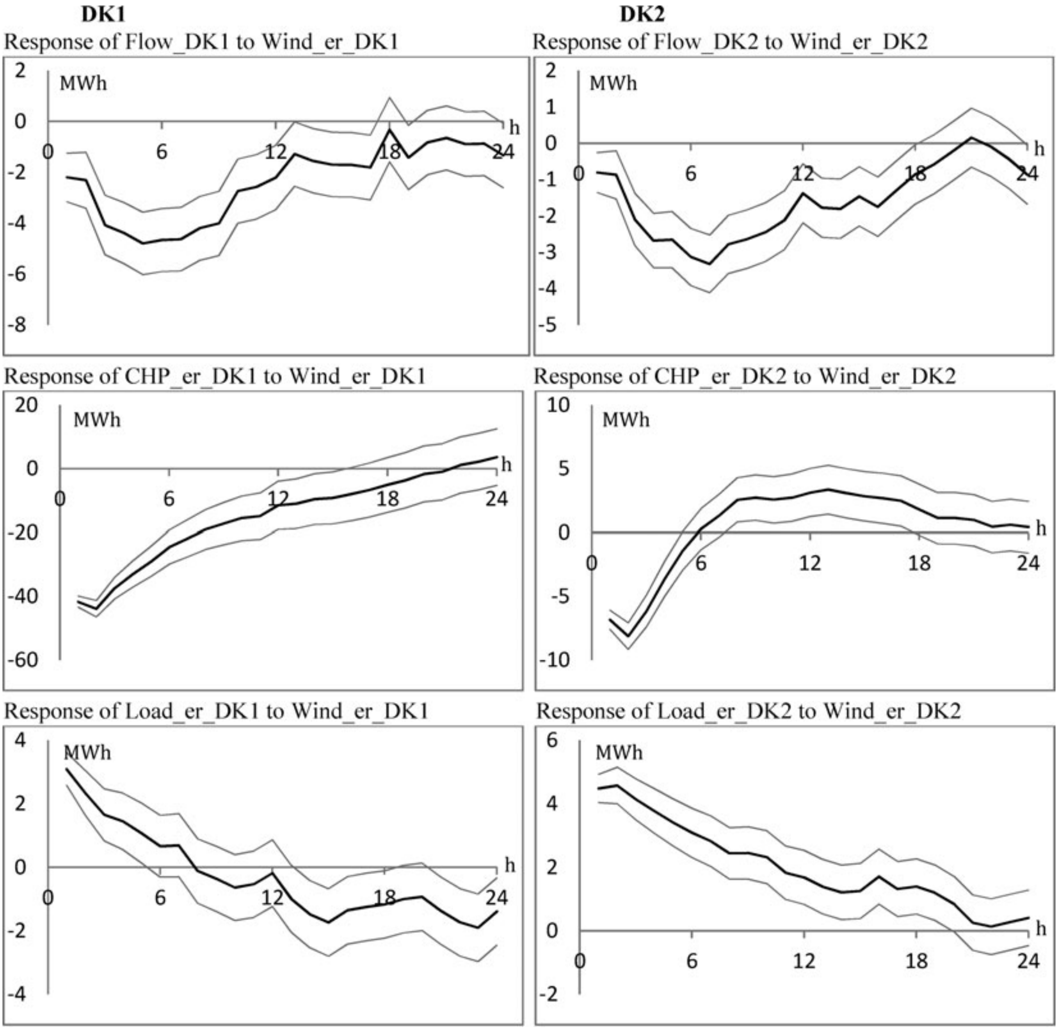
Figure 11: Responses of the Quantity Variables



Notes: Responses of the quantity variables to generalized one standard deviation innovations in wind forecast errors in DK1 and DK2. The responses represent deviations in MWh from the steady state following one standard deviation in the variable *Wind_er*. For further explanations, see notes to Figure 10.

ports are capable to smooth the variations in the price series. In support of this view, our empirical evidence suggests that wind forecast errors are strictly damped out in the intraday mechanism, because their causal influences on both price differences and cross-border trading are found.

Concerning the responses from the supply and demand sides, wind forecast errors exert a negative (positive) influence on conventional (load) forecast errors. That is to say, in order to keep the system balanced, the CHP power generation is adjusted in the opposite direction, and the consumption is adjusted in the same direction of the deviation shocks in wind power. It is worth mentioning again that the conventional generation can play a counterpart to the wind generation, either through intraday trading or real-time balancing, as both traded quantities are incorporated in the deviation terms. Nevertheless, given the fact that balancing quantities in Denmark are relatively

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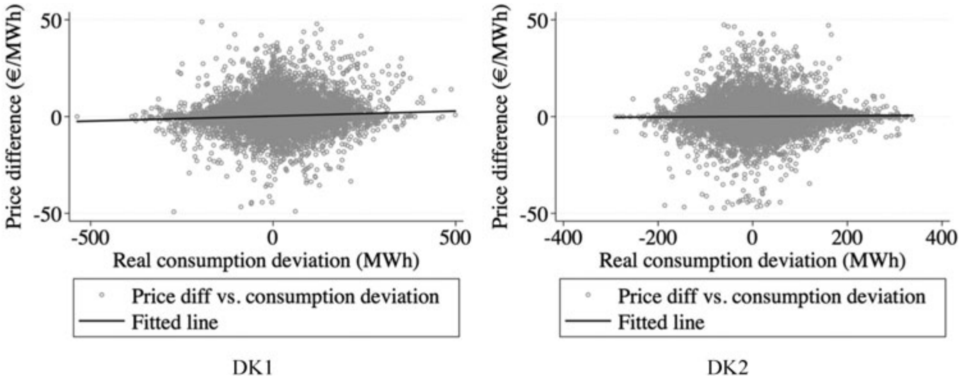
Figure 12: Price Differences versus Consumption Deviations in DK1 and DK2



Data source: Authors' realization based on Nord Pool Spot (2014).

small, and that CHP BRPs would pay penalties on their imbalances at the balancing stage, it is fair to say that the intraday market takes a major part in trading CHP generation deviations. Furthermore, the patterns of the reactions from consumption and conventional generation appear to be non-uniform in DK1 and DK2. In the former zone, an immediate response from demand seems to vanish fast, and the response from conventional production proceeds much more smoothly, whereas in the latter zone, it seems to be the opposite case. Given the complexity of electricity trading in sequential markets, providing explanations underneath these findings may be a hard row to hoe. Although untangling different demand and supply patterns in these two bidding zones is not straightforward, it is nonetheless important to emphasize the notable reactions from primary CHP generation and load, through which the intermittent nature of wind power is effectively handled.

VI. CONCLUSION

Intraday electricity markets are designed to provide a useful mechanism to allow electricity generators and consumers to adjust their day-ahead committed quantities according to improved forecasts. It has been argued that these markets are particularly important for the wind power generators given the fact that wind power is intermittent and poorly predictable. Despite its growing importance, particularly for the integration of wind power into the electricity system, the role and functionality of intraday markets has been overlooked in research in this field.

As the first attempt to test the functionality of an intraday market in a dynamic econometric framework, this paper investigated: first, the fundamental drivers of the deviations of the intraday prices from the day-ahead values with particular attention to wind forecast errors; second, the way in which wind forecast errors are dissolved by other market elements. In order to undertake this investigation, our innovative idea is to test causality among intraday market fundamentals by applying a methodology that consists of a VAR framework and GIR simulations. Using data from two Danish bidding zones, the paper studied the causal relationships among the price differences between the intraday and day-ahead markets, the deviations of wind generation, conventional generation, and total demand from their committed day-ahead levels as well as the cross-border electricity trades in the Nordic electricity market. Compared with earlier econometric studies in the field of energy economics, this study provides the first evidence not only on the effectiveness of the intraday electricity market, but also on the way in which the prices in this market are affected

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by wind power that deviates from its prognosis. The VAR and GIR techniques employed in this study have offered straightforward explanations on both the paths of intraday price deviations, and the interactions among market fundamentals. Thus, the results are able to give a reliable answer to the fundamental hypothesis tested in the framework of this research: the Nordic intraday electricity market can be regarded as effective if causality between the intraday price signals and the market fundamentals can be established.

Our empirical results suggest that the wind and conventional generation forecast errors are the fundamental factors that drive the intraday prices apart from the day-ahead values both in Denmark West and East, and that the relative intraday prices decrease with the level of wind forecast errors. Furthermore, wind forecast errors are absorbed by joint responses from cross-border intraday power exchanges and adjustments of conventional generation and consumption. The results also indicate some zonal differences concerning causality from wind forecast errors to price differences, and the response paths of market fundamentals. Finally, the responses in the intraday price signals and electricity trade following a shock in wind generation die out after 12 hours in the intraday market.

The bottom line is that our paper confirms the effective functioning of the intraday market in the case of Denmark, in which intermittent production deviations are explicitly reduced by intraday transactions, and in addition, wind forecast errors are jointly handled through the responses from consumption, conventional generation, and intraday cross-border trade.

Finally, it is nonetheless important to notice that two caveats should be put forward. First, our analyses give evidence on the practicality of an intraday market, but do not lead us to conclude that it is optimal. It has been argued that in an efficient market setting, adjustments from both supply and demand sides should be made to the largest extent in intraday markets given higher costs of balancing in real time. But in the Nordic region, these costs may not be significant due to a high level of hydro reserves. The examination of the overall system efficiency requires comprehensive cost and price comparisons between intraday trading and real-time balancing that relies on transmission capacities. Second, the assumption of exogenous wind forecast errors might not be entirely met in some cases, as wind producers can possibly intentionally overstate or understate their productions. This consideration is beyond the scope of our paper, but a relevant work appears to be an investigation on wind generators' strategic behaviors. These questions are therefore left open for future research.

ACKNOWLEDGMENTS

The authors thank Anna Creti, Jan Horst Keppler, Juan-Pablo Montero, and the participants of the Workshop on "Renewables and Electricity Prices: Modeling Approaches" at University Paris-Dauphine in June, 2015, as well as anonymous referees of this Journal for their insightful comments that helped improve the paper significantly. This paper has benefited from the support of the Chaire European Electricity Markets of the Paris-Dauphine Foundation, supported by RTE, EDF, EPEX Spot and the Groupe Caisse des Dépôts. The views and opinions expressed in this paper are those of the authors and do not necessarily reflect those of the partners of the CEEM.

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APPENDIX A. SUMMARY STATISTICS OF THE VARIABLES

Table A.1: Summary Statistics for DK1

Variable	Mean	S.D.	Med.	Max.	Min.	Skew.	Kurt.	Nb. Positive	Nb. Negative	Nb. Zero
CHP error	374.22	712.89	198.65	3171.40	-2082.50	0.77	3.17	13574	7592	2
Con. Error	15.46	81.82	7.00	1952.00	-537.00	0.83	20.19	12113	8712	343
Elbas flow	-12.40	93.38	0.00	890.60	-1149.50	-0.32	16.79	6235	9009	5924
Price dif	0.38	6.69	0.00	232.38	-88.63	8.53	260.54	8293	7980	4895

Notes: Summary statistics of the average, standard deviation, median, maximum, minimum, skewness, kurtosis and numbers of observations with positive, negative and zero values for each variable.

Table A.2: Summary Statistics for DK2

Variable	Mean	S.D.	Med.	Max.	Min.	Skew.	Kurt.	Nb. positive	Nb. negative	Nb. zero
CHP error	-62.42	159.73	-63.40	868.60	-1101.50	-0.06	3.90	6892	14270	6
Con. Error	11.67	69.22	4.00	338.00	-1930.00	-0.61	33.51	11319	9578	271
Elbas flow	10.24	59.79	0.00	1216.00	-336.00	2.50	30.55	7238	5875	8055
Price dif	0.10	5.85	0.00	210.00	-109.38	2.96	117.55	6610	6712	7846

Notes: Summary statistics of the average, standard deviation, median, maximum, minimum, skewness, kurtosis and numbers of observations with positive, negative and zero values for each variable.

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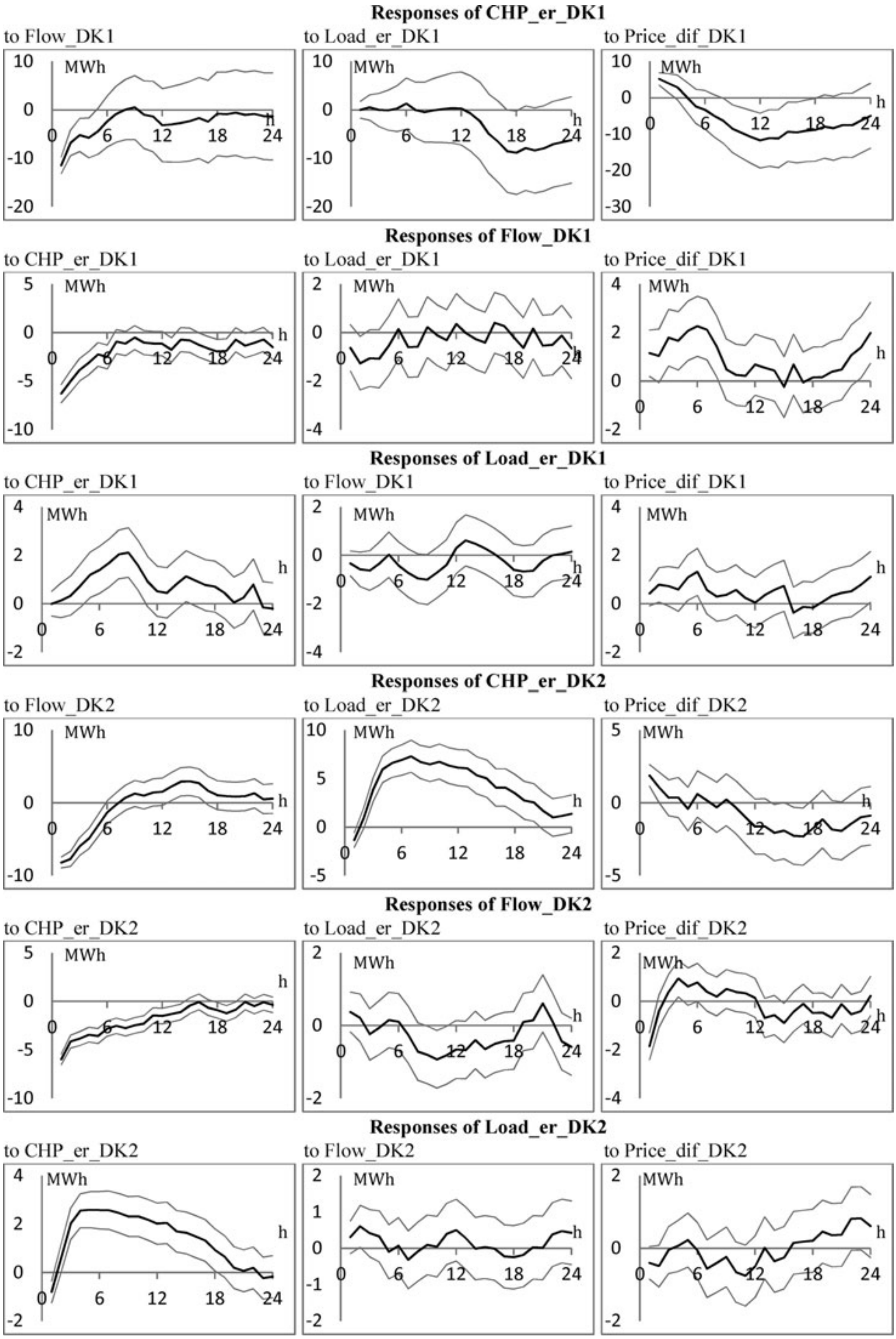
APPENDIX B. IMPULSE RESPONSE FUNCTIONS

Figure B.1: Responses in DK1 and DK2 to Generalized One Standard Deviation Innovations



Notes: See Figures 10 and 11 for explanations.

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