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A Long-Term Analysis Studying the Effect of Changes in the Nordic Electricity Supply on Danish and Finnish Electricity Prices

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Abstract

The aim of this research was to perform a multinational analysis that estimates the marginal effect of changes in different sources used to generate electricity on wholesale Nordic electricity prices. Three price series were selected: 1) the Nord Pool market clearing price, 2) western Denmark's area spot price (DK1), and 3) Finland's (FI) area spot price. Data were drawn for the 16 years, 2000-2015. Linear regression was used. The results showed that changes in the energy sources used to supply electricity had varying impacts, showing that average annual prices were affected more when there was a decrease in nuclear production levels rather than an increase. This study highlights the fact that unilateral decisions made by an individual country in an integrated market can have large consequences on other nations' wholesale electricity prices.

Keywords: market coupling; electricity prices; Nordic market; renewable energy

Highlights:

- Swedish nuclear energy had a greater impact on Finland's price than Denmark's.
- Interconnectivity can lead to a decrease in prices.
- Interconnectivity can make importer nations vulnerable to exporter nations' policies.
- In integrated markets, regional energy policy could be used to shift power from national actors.

1 Introduction

1.1 The European Setting

In 1996, the first Internal Market in Electricity (IME) Directive was written by the European Parliament and went into effect in 1999. It is a document that outlines the preliminary steps for creating a higher level of market integration by joining international energy exchanges and making them into one Pan-European energy exchange (European Parliament and of the Council, 1996). By increasing the number of producers, accounting for the regional differences in demand patterns, and the energy flowing across borders, the IME was viewed as a way forward to not only increase energy security and competition, but to also reduce electricity prices (Helm, 2014). While European wholesale electricity prices have dropped (European Commission, 2014), to what degree the IME goals have been reached has come into question (Zachman, 2008; Bunn and Gianfreda, 2010). This too has been recognized by the European Commission and Regulation 714/2009/EC states “at present, there are obstacles to the sale of electricity on equal terms… in particular, non-discriminatory network access and an equally effective level of regulatory supervision do not yet exist in each Member State, and isolated markets persist” (European Parliament and of the Council, 2009).

1.2 Conflict between National Policies/Agendas

One example is limited interconnection between Spain and France (IEA, 2015b), where in Spain, wind energy produces roughly 20.4% of electrical supply (IEA, 2016a), and France, whose largest share of electricity (77%) is from the state-backed nuclear industry (IEA, 2016b). Spain’s electricity interconnection capacity has remained low, with it being roughly only 4% of installed capacity in 2014 (IEA, 2015b). The first new interconnection of a 1.4 GW at Santa

Llogaia–Baixas was inaugurated in February 2015 (IEA, 2015b). It had almost been three decades since the last interconnection project in Spain (IEA, 2015b). One hypothesis why interconnection has been so minimal is in part the fear of the impact that Spanish wind power would have on France's own national interests and its nuclear power industry (Oliver, 2014).

While the conflict between France and Spain is an example of a disconnect due to political objectives, in 2012 Norway and Sweden formed a common market for renewable electricity certificates (REC) (Blindheim, 2013). While Norway has been characterized as a country with exceptionally high wind resources, the REC common market has overall been ineffective in developing more wind power in Norway due to the political uncertainty created by the complaints of opponents (Blindheim, 2013). Furthermore, Norway and Sweden do not have feed-in-tariff policies such as Denmark, where generators using renewable energy sources are paid a premium per kilowatt hour of electricity produced; feed-in-tariffs have been found more effective in developing renewable energy than certificate programs (Mitchell et al., 2006). Wizelius (2014) claims that Sweden's use of "anything but feed-in-tariffs" has led to a muddled path for the development and ownership of wind power. So, while it was more optimal for Norway to develop a higher penetration of wind power, the overall share of wind power in Sweden climbed from 2.4% in 2010 to 7.3% in 2014 of total electricity production (IEA, 2016f, 2016g). In the same period of time, Norway's share of wind power also increased, but only from 0.7% to 1.5% (IEA, 2016d, 2016e). However, Sweden is moving into a position requiring it to find other energy sources to support its electricity generation as it seeks to remove 2.7 GW from its nuclear capacity (World Nuclear Organization, 2015).

1.3 Data Transparency

The examples cited illustrate how a range of factors can play a role in shaping the development of renewable energy sources and the common electricity market. The European Commission has called for more harmonization between countries (European Commission, 2014). However, for optimal plans to be designed, there must also be a high level of transparency and coordination between nations in terms of the data published that would support these types of analyses. The topic of data accessibility was addressed in 2011 when Regulation 1227/2011/EU, also known as the Regulation on Wholesale Energy Markets Integrity and Transparency (REMIT), went into force (European Parliament and of the Council, 2011). It obliged both transmission system operators and market participants to publish a range of "transparency data" (European Parliament and of the Council, 2011). The REMIT regulation has now been in effect for several years and there have been some improvements. However, there still remain large differences in the data published by the various stakeholders.

To illustrate this point, the Nordic market energy exchange, Nord Pool, publishes hourly wind energy data and weekly hydro-energy data, but no other categories such as nuclear or natural gas, for example. To obtain this type of data it is possible to go to the different national statistics agencies. Gaining the needed information, however, can be stymied as there is no standardized categorization for these types of data. In addition, the data may be presented at different temporal levels. For example, the Finnish Energy Agency now publishes hourly electricity supply data (2010-2015) but the data records thermal power divided into three different categories: cogeneration of district heat, industry, and separate electricity generation (Finnish Energy Agency, 2016). In contrast, for instance, Statistics Sweden publishes electricity supply data at a monthly level and categorizes its thermal generation into four types (Statistics

Sweden, 2016). Assessments of electricity prices are often done at either the hourly or daily level (see e.g. Jónsson et al., 2010; Gelabert et al, 2011). The issue that arises when estimating the effect of variables at different temporal resolutions is that either the fine scale variable needs to be aggregated or the coarse scale variable needs to be repeated as a constant for multiple fine scale observations. Both conditions will affect modeling. Also, due to differences in classification for power plants, a researcher needs to make subjective decisions as to how to group or classify power plants across nations, and such decisions might not be traceable in future assessments.

1.4 Nord Pool

In order to identify the limitations that still persist in electricity data, it was of interest to perform a long-term, multinational analysis that estimated the effect of various energy sources from many countries on national wholesale electricity prices. The Nordic day-ahead electricity spot market, Nord Pool, became fully integrated in 2000, when the Denmark grid finally became physically interconnected with the grids of Norway, Sweden, and Finland and with a single pricing mechanism for the entire region (Nord Pool, 2015b). Due to its longevity of operation, it allows a sixteen-year analysis (2000-2015). While this is a strength of the analysis, it also is a limitation, because there are only a few sources that publish electricity supply data in a standardized format that go this far back in time.

Nord Pool calculates an unconstrained market clearing price, which is based on all of the bids and offers from the market participants. All contracts for next-day delivery are submitted by 12:00 central European time (Nord Pool, 2017b). In reality, there are transmission constraints that constrict the flow of electricity, which becomes a cost that is passed on to the consumer

(Singh and Papalexopoulos, 1998). Congestion is managed in Nord Pool by using geographical zones that are defined by the transmission system operators (Nord Pool, 2017b). Each market participant must indicate the area in which the bid or offer originated (Nord Pool, 2017b). The locational differences form different demand and supply curves, resulting in price differences between the areas and which result in arbitrage opportunities (Sioshansi et al., 2009). Implicit auctioning is a tool used by Nord Pool that is intended to level out locational price differences (Nord Pool, 2017b). After the initial prices have been calculated for each area, according to which area has the least supply (i.e., a higher area price), the transmission system operators will decide on a planned cross-border volume that may be exported from the lower priced area (surplus supply) to the higher priced area (Nord Pool, 2017b). The result is that the price differences are less or even equal (Nord Pool, 2017b). Hence, increased transmission capacities are critical in curtailing negative market behavior from producers (Borenstein et al., 1997; Shrestha and Fonseka, 2004; de La Torre et al., 2008; Küpper et al., 2009).

We hypothesize that, as the Nordic market becomes more interconnected (i.e., increased transmission capacity), the marginal effect on electricity prices will be less when there is a decrease in supply. The paper is organized as follows. Section 2 presents a description of how the Nordic market functions, along with the data description and methods. In Section 3, the results are presented with a discussion of findings, followed by the conclusions in Section 4.

2 Data and methods

Currently, there are fifteen pricing areas in Nord Pool (Nord Pool, 2017a). However, only three price series were retrieved from Nord Pool for this analysis: 1) western Denmark (DK1), 2)

Finland (FI), and 3) the Nordic market clearing prices (SP). The reason for limiting the number to these pricing areas (DK1 and FI) is because, over this period of sixteen years (2000-2015), there have been many additions and changes to the geographical boundaries of the pricing areas. For example, until October 2011 Sweden constituted only one pricing area. In November 2011, Sweden was divided into four areas (Nord Pool, 2017a). However, western Denmark and Finland's boundaries have not changed over the analyzed period. Given that the system price is unconstrained, it is assumed that these changes and additions have not affected the system price. It is acknowledged that this assumption is a limitation of the study that future research should attempt to resolve.

The original unit of the price series was euros per megawatt hour (EUR/MWh). All three spot price series were at the hourly level and then aggregated to the monthly resolution using the average value of the data. Before the data was aggregated to the monthly level, there was an inspection to identify extreme outliers. In 2009, Nord Pool implemented a negative pricing floor (Nord Pool, 2016b). Negative prices occur when there is a high supply of an inflexible energy source, such as wind, and extremely low demand (Fanone et al., 2013). The negative prices did not fall below -200 EUR/MWh. As Denmark continues to increase its electricity supply from wind generation, negative prices may occur more frequently; therefore, they were kept in the analysis. At certain times it was observed that spot prices jumped to extreme values (1,400 EUR/MWh) which occurred as the result of a shortage of supply when a Swedish nuclear plant went offline, coupled with unusually cold weather (Nord Reg, 2010). These data points were not omitted. Therefore, all data remained in the analysis.

In 2013, Nord Pool began publishing two hours with the exact same time stamp, so that there is one day in a year with 25 hours to account for daylight savings. To remove duplicates, in the case when the data was identical in both rows, one row was removed. In some years the rows with identical time stamps did not have identical data. This was handled by removing both observations, leaving the day with only 23 hours.

The prices were converted from nominal to real 2015 euros using the European Harmonized Consumer Price Index for Danish Electricity (Eurostat, 2016). While there are conversion indices for every nation, it was decided to use only the Danish Index for electricity on all three price series, since there is no index or system price for the Nordic region. This was to create a more standardized approach. Furthermore, since the price data was originally at the hourly level and the inflation data was at the monthly level, the use of different indices may mask other effects.

Figure 1 presents average monthly prices from January 2000 to December 2015 for the system price (SP), western Denmark (DK1), and Finland (FI) in 2015 real terms. The dynamics of hourly electricity prices are inherently volatile with mean-reversion (prices tend to fluctuate around a long-term equilibrium mean) due to seasonality (Huisman and Mahieu, 2003; Escribano et al., 2011; Janczura and Weron, 2010) the demand for electricity is inelastic, storability is limited (Borenstein, 2002), and the transmission system requires that there are only small frequency deviations (+/- 200 mHertz) from 50 Hertz (ENTSO-E, 2015). Since these average prices have been aggregated to a monthly resolution, hourly variance has been smoothed out. However, temporal correlations are still present, as shown in Figure 1.

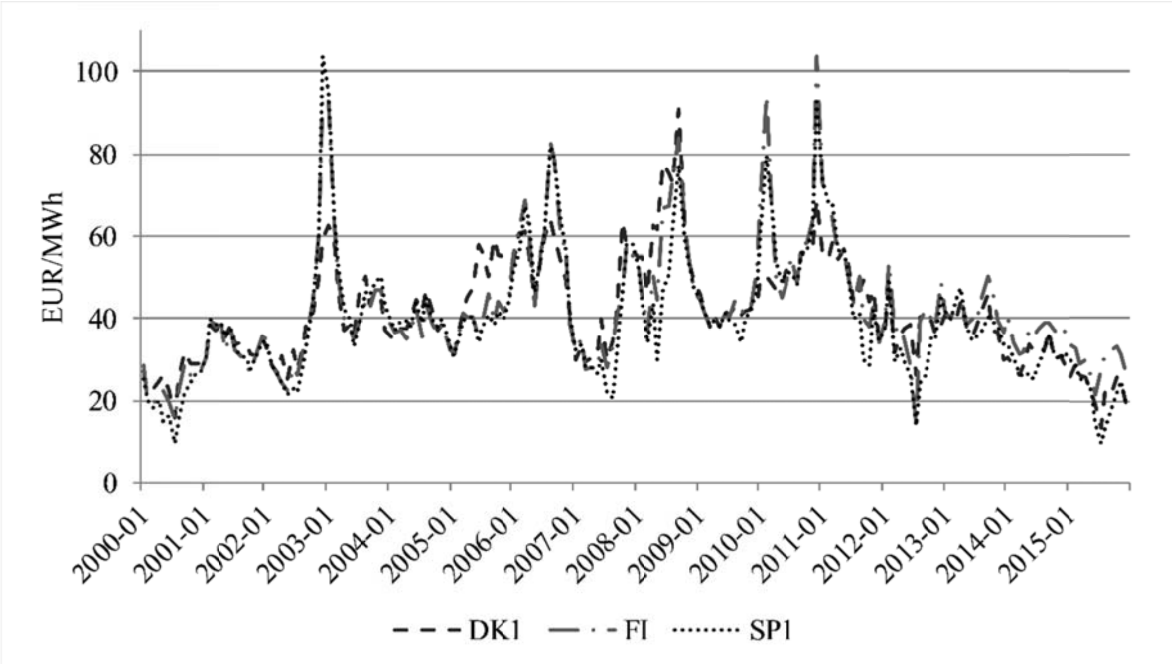

Figure 1 Monthly average spot prices in constant 2015 euros from Jan. 2000 to Dec. 2015.

The price series presented in Figure 1 are described in Table 1 for the years 2000, 2005, 2010, and 2015. The highest annual mean prices and variability correspond to 2010 when the system price (SP1) was 60.6 EUR/MWh. The lowest averages for SP (21 EUR/MWh), DK1 (22.9 EUR/MWh), and FI (29.7 EUR/MWh) were observed in 2015.

Table 1 Annual spot price averages for the Nord Pool system price (SP), western Denmark (DK1), and Finland (FI) in 2015 real terms.

	SP				DK1				FI			
	Mean	Std. Dev.	Min	Max	Mean	Std. Dev.	Min	Max	Mean	Std. Dev.	Min	Max
	EUR/MWh											
2000	19.91	5.25	9.86	26.52	25.54	4.24	15.97	31.82	23.14	4.38	15.18	29.03
2005	38.61	3.81	30.97	44.60	48.95	9.30	30.05	59.18	40.00	4.59	31.21	46.23
2010	60.63	13.41	48.35	92.78	52.96	6.07	46.98	68.75	63.25	18.45	45.10	103.79
2015	21.01	6.35	9.58	29.90	22.94	4.23	13.69	29.10	29.68	3.66	21.58	33.60

Presented in Table 2 are the descriptive statistics for gross consumption, and indigenous electricity production (TWh), which is the sum of all electrical generation production (including pumped storage) measured at the output terminals of the main generators (IEA, 2016h), categorized by the different energy sources used to generate electricity (IEA, 2015a). The IEA offers a broader list of electricity supply data in terms of the different categories for energy sources; however, it is only provided at the annual level (IEA, 2016h). The electricity supply data at the monthly level is in gigawatt hours (GWh). There are four categories of energy sources: 1) combustibles fuels, 2) nuclear, 3) hydro, and 4) all other renewable energy sources (RES). While hydropower is considered to be from a renewable energy source, due to its ability to store energy and flexibility to meet demand, it stands as its own category.

Table 2 Descriptive statistics for monthly electricity generation mix and consumption in TWh (Source: IE 2016a).

	2000				2005				2010			
	Mean	Std. Dev.	Min	Max	Mean	Std. Dev.	Min	Max	Mean	Std. Dev.	Min	M
	TWh											
DK Gross Production	2.87	0.65	1.88	3.98	2.87	0.66	1.91	3.79	3.07	0.84	1.90	4.
DK Gross Consumption	2.02	0.65	1.47	3.20	2.96	0.25	2.57	3.31	2.95	0.34	2.55	3.
DK Combust. Fuels	2.51	0.56	1.66	3.46	2.31	0.50	1.60	3.17	2.42	0.75	1.47	3.
DK Hydro	0.003	0.001	0.001	0.004	0.002	0.001	0.001	0.004	0.002	0.001	0.001	0.0
DK RES	0.36	0.11	0.20	0.51	0.55	0.20	0.31	1.08	0.65	0.16	0.40	0.
FI Gross Production	5.61	0.86	4.51	7.00	5.65	1.23	3.70	7.39	6.43	1.37	4.68	8.
FI Gross Consumption	6.31	0.57	5.39	6.93	6.99	1.34	4.11	8.54	7.09	1.16	5.63	9.
FI Combust. Fuels	2.60	0.71	1.48	3.78	2.62	1.03	0.78	4.16	3.50	1.25	1.71	5.
FI Nuclear	1.80	0.20	1.42	1.99	1.86	0.16	1.53	2.02	1.82	0.21	1.35	2.
FI Hydro	1.20	0.20	0.84	1.49	1.13	0.18	0.78	1.40	1.06	0.16	0.89	1.
FI RES	0.006	0.002	0.003	0.01	0.03	0.01	0.01	0.05	0.05	0.01	0.04	0.
NO Gross Production	10.03	1.71	7.83	12.43	10.44	1.79	8.07	13.21	10.88	2.61	7.72	14
NO Gross Consumption	9.94	1.68	7.61	12.12	10.12	1.84	7.54	12.84	10.93	2.61	7.77	14
NO Combust. Fuels	0.05	0.01	0.04	0.06	0.07	0.01	0.06	0.09	0.45	0.12	0.23	0.
NO Hydro	11.56	1.16	9.80	13.53	11.32	1.97	9.04	14.36	9.72	2.68	6.31	14
NO RES	0.009	0.003	0.01	0.02	0.05	0.02	0.03	0.08	0.09	0.03	0.05	0.
SE Gross Production	11.80	1.95	8.72	14.35	12.88	1.61	10.77	15.53	12.11	1.58	9.56	14
SE Gross Consumption	11.86	1.76	9.16	14.23	12.19	2.13	9.02	15.19	12.20	2.52	9.06	16
SE Combust. Fuels	0.71	0.35	0.33	1.28	0.99	0.37	0.55	1.45	1.65	0.64	0.66	2.
SE Nuclear	4.56	1.65	2.00	6.82	5.79	0.67	4.68	6.90	4.64	0.86	2.89	5.
SE Hydro	6.49	0.74	5.49	7.66	6.02	0.71	4.67	7.06	5.53	0.89	3.81	7.
SE RES	0.04	0.01	0.02	0.06	0.08	0.03	0.05	0.15	0.29	0.10	0.19	0.

Table 2 shows that roughly 97% of electricity generated in Norway is from hydropower. While constituting an insignificant supply (< 1%) of electricity there is hydropower in Denmark, although in comparison to Sweden and Norway, Denmark's topographical features are relatively flat (World Atlas, 2015) and therefore not conducive to the use of hydropower to generate electricity. From 2010 to 2015, production from combustible fuel sources decreased for all four countries, while each country increased its share of production from RES. From 2000 to 2015, the percentage increase of Denmark's annual mean share of RES was 242%. Although, the total contribution of electricity supplied from RES compared to the other fuel types was much smaller for Norway, Finland and Sweden, there was a substantial percentage increase from 2000 to 2015. For example, in 2000, the mean number of GWh produced from RES in Finland was 6 GWh, and by 2015 this number had increased to 220 GWh, indicating that the amount of electricity supplied from Finnish RES was roughly 35 times higher in 2015 than it was in 2000. From 2000 to 2015, electricity suppled from RES in Sweden was approximately 34 times higher and 26 times higher in Norway.

Figure 2 shows the annual sum of the electricity generation mix and consumption for the year 2015 only. The relative difference in total production and consumption was large, with Sweden and Norway with high production, although the population was only 2 times higher in Sweden and similar in Norway compared to Denmark. The difference was due to development of heavy industries in these countries. The main imbalance in total country production and consumption was in Sweden and Finland, with Sweden being a net seller.

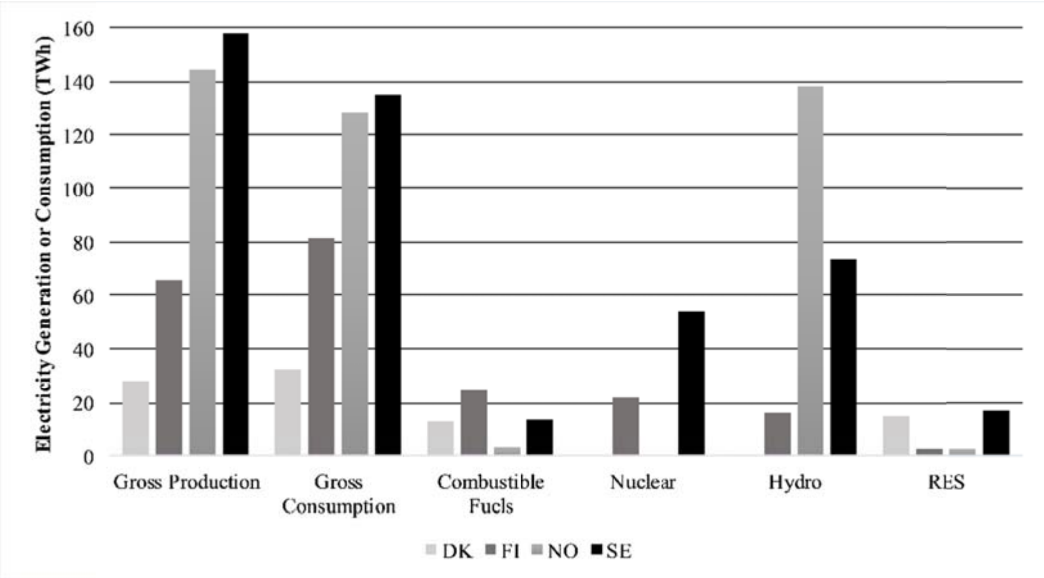

Figure 2 Annual sum of electricity generation mix and consumption in TWh in 2015.

National total gross consumption was calculated using hourly data from Nord Pool over the sixteen-year period by aggregating it to the monthly level to match the same temporal resolution of the IEA electricity supply variables. Table 2 shows that each country is growing in terms of consumption, although there was a slight decrease in 2015.

The physical constraints of the transmission system require a strong balance between supply and demand (Nord Pool, 2017b). As a result, there is a strong and positively correlated relationship between total demand and total production, as shown in Table 3. The table shows that there is only one correlation coefficient less than 0.6 and over half of the correlation coefficients are above 0.8. These high correlation coefficients show why it was not possible to insert all relative gross consumption variables into the respective model. This will be discussed in greater detail in the Methods section.

Table 3 Pearson's correlation coefficients for the Nordic countries' total supply and demand.

		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(1)	DK1 Gross Production	1.00							
(2)	FI Gross Production	0.74	1.00						
(3)	NO Gross Production	0.79	0.83	1.00					
(4)	SE Gross Production	0.83	0.86	0.96	1.00				
(5)	DK1 Gross Consumption	0.71	0.71	0.85	0.86	1.00			
(6)	FI Gross Consumption	0.74	0.86	0.88	0.88	0.81	1.00		
(7)	NO Gross Consumption	0.78	0.82	0.98	0.95	0.85	0.87	1.00	
(8)	SE Gross Consumption	0.66	0.76	0.79	0.80	0.58	0.67	0.79	1.00

Table 4 shows the Pearson's correlation coefficients between prices and all of the electricity supply variables. The coefficients show that there is an inverse relationship between the renewable energy sources, including hydro, and price (System price, DK1 Area price and F1 Area price), except for Norwegian hydropower. In their *ex-post* analysis of daily Spanish spot prices, Gelabert et al. (2011) also found a positive relationship, and explained this as because of the flexible nature of hydropower and its ability to store its energy in large reservoirs. Hence, unlike other renewable energy sources that have been shown to reduce market prices (see e.g., Clò et al., 2015; Cludius et al, 2014) but can also incur greater balancing costs due to their non-deterministic behavior (Koeppel and Korpås, 2008), hydropower, along with other conventional sources (Franco and Salza, 2011), may be dispatched in periods when demand is high, i.e., higher prices, creating a positive relationship between price and hydropower production.

Table 4 Pearson's correlation coefficients of monthly electricity supply levels.

		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
(1)	System Price	1.00											
(2)	DK1 Area Price	0.68	1.00										
(3)	FI Area Price	0.91	0.67	1.00									
(4)	DK1 Combust. Fuels	0.46	0.27	0.37	1.00								
(5)	DK1 Hydro	-0.10	-0.22	-0.17	0.15	1.00							
(6)	DK1 RES	-0.07	-0.34	-0.06	0.07	0.36	1.00						
(7)	FI Combust. Fuels	0.46	0.21	0.4	0.78	0.23	0.22	1.00					
(8)	FI Nuclear	0.01	-0.12	-0.07	0.26	0.11	0.13	0.10	1.00				
(9)	FI Hydro	-0.21	-0.24	-0.2	0.02	0.20	0.15	-0.02	-0.33	1.00			
(10)	FI RES	0.00	-0.05	-0.08	0.17	0.11	0.22	0.18	0.06	0.08	1.00		
(11)	NO Combust. Fuels	0.13	0.03	0.12	0.12	0.12	0.02	0.12	0.19	-0.01	0.05	1.00	
(12)	NO Hydro	0.18	0.00	0.22	0.68	0.31	0.29	0.6	0.28	0.21	0.13	0.09	1.00
(13)	NO RES	-0.09	-0.19	-0.14	0.21	0.18	0.41	0.23	0.22	0.16	0.61	0.13	0.21
(14)	SE Combust. Fuels	0.40	0.06	0.31	0.78	0.37	0.31	0.76	0.31	0.1	0.2	0.21	0.71
(15)	SE Nuclear	0.02	-0.16	-0.13	0.26	0.34	0.22	0.35	0.43	-0.11	0.08	0.15	0.17
(16)	SE Hydro	-0.13	-0.16	-0.07	0.26	0.27	0.15	0.28	-0.16	0.55	0.02	-0.01	0.43
(17)	SE RES	-0.06	-0.2	-0.10	0.11	0.18	0.57	0.2	0.14	0.07	0.69	0.07	0.14

Unlike other intermittent renewable energy sources, hydropower may store its energy in reservoirs and may be dispatched to r (Franco and Salza, 2011). Hence, hydropower may be used in periods of high demand, resulting in a positive correlation betw (Gelabert et al., 2011).

Cross comparing the three price series showed that the Finnish day-ahead spot is much more positively correlated to the system price (0.91) than the Danish price is (0.68). While not all the years are shown in Table 2, on average, Denmark's indigenous production was greater than its consumption until 2010. In 2011, this changed, and Denmark's annual consumption exceeded its indigenous production levels. Finland, compared to Denmark, has on average from 2000 to 2015 consumed more electricity than it produced. One plausible explanation for the difference in the correlation coefficients may be tied to Denmark's high penetration of wind energy, which can induce congestion for several reasons such as limitations in the grid, effects from nearby turbines, or environmental factors (EWEA, 2017). Therefore, even when there is cross-border energy flow into Denmark to level price differences between areas, there still exists a price difference due to its high penetration of wind power, reducing average prices (Cludius et al., 2014; Jonsson et al., 2010; Woo et al., 2010). Furthermore, when there is not enough transmission capacity, this limits the flow of energy and price differences persist.

2.1 Methods

In all, three linear regression models were built, using the price series (SP, DK1, and FI) as the dependent variables. To control for the temporal fixed effects, every model included seasonal indicators ($s = 1, \ldots, 3$). The seasons were defined as the following: 1) winter: December, January, and February; 2) spring: March, April, and May; 3) summer: June, July, and August; 4) fall: September, October, and November. The season, fall, was omitted from the model to prevent perfect multicollinearity. In addition to the seasonal indicator variables, a yearly binary variable ($y = 1, \ldots, 11$) was created for each year, omitting the year 2000 to prevent perfect multicollinearity.

Table 5 shows at a national level which countries DK1 and FI trade within the day-ahead spot market. This table determined which supply and consumption variables entered which model. Since the Nordic system price is the unconstrained price all the electricity production, variables from each country were tested in the model. In the case of western Denmark, Finnish electricity supply variables were not used because western Denmark does not trade energy with Finland. However, the western Denmark model did include all of the different types of production variables for Denmark, Norway and Sweden.

Table 5 Elspot trading partners.

	SP	DK1	FI
Denmark	X	X	
Finland	X		X
Norway	X	X	
Sweden	X	X	X

After all of the variables were inserted into the regression model, the hypothesis of non-significant difference from zero was tested for each coefficient on each variable using an asymptotic t-test (Greene, 2003). The statistical efficiency of the estimated coefficients was enhanced by restricting coefficients to zero on variables that were not found significantly different from zero at the 0.05 level.

One transformation was made to two of the Danish electricity supply variables. From 2000-2015 hydropower in Denmark was almost negligible (see Table 2); however, rather than omitting this variable, a new variable DK RES was formed by adding together Danish hydropower and other Danish renewable energy sources. As discussed earlier, hydropower in comparison to other renewable energy sources such as wind and solar, has different characteristics, so while it does not contribute to greenhouse gases, its flexible ability to be dispatched when demand is high explains the positive correlation with prices. Combining these two categories of renewable variables into one is a limitation to the study and future research is recommended to study these separately.

Over the last few years, the Nordic market has grown through market coupling with other countries outside of the Nordic region. Finland exchanges energy with Sweden and Estonia. Since, within the time frame of this study, Finland and Estonia have been trading since April 2010, an indicator variable was created to test the effect of Finland's trade with Estonia. The binary indicator was given the value of 1 to represent this coupling, starting in April 2010, and zero before that (Nord Pool, 2016b). In the system price model, a binary variable was constructed to test the effect of coupling markets with the Central Western European energy market it was given the value of 1 to represent the coupling, starting in January 2010, and zero before that (European Energy Exchange, 2014). Finally, a binary indicator was used to test the effect of Denmark coupling using planned energy exchanges from Germany (DE) and given the value of 1 to represent the coupling, starting in November 2009, and zero before that (Nord Pool, 2016c).

Before inserting any time-series electricity production variables into the models, each variable was tested for the presence of a unit root. To perform this an Augmented Dickey Fuller test (ADF) was used (Dickey and Fuller, 1979). To determine the appropriate number of lags in the ADF test, the approach suggested by Schwert (1989) was followed by using the equation $\mathrm{int}[12(n/100)^{1/4}]$, where n is the number of observations. In each ADF test, a linear deterministic time trend was included. The null hypothesis of ADF is that there is a unit root, and a test value lower than its critical ADF table value suggests that there is a unit root. The results, which are shown in Table 6, indicated that all the variables had a unit root. To handle this, the approach used by Gelabert et al. (2011), when analyzing daily Spanish electricity prices by taking the first difference for all variables, was used. After the first difference was taken for each variable, the ADF test was performed a second time, using the same number of lags. Furthermore, as Wooldridge discusses (2010), taking the first difference removes the concern of a potential time-invariant endogenous relationship that may exist between the independent and dependent regressors.

Table 6 Augmented Dickey Fuller test statistics.

	ADF (in levels)	ADF (in first differences)
DK1 Price	-2.536	-5.014
FI Price	-2.938	-5.356
SP Price	-2.693	-5.482
DK Combustible Fuels	-2.311	-5.115
DK RES†	-1.241	-7.186
DK Gross Consumption	-4.979	-4.954
Finland Combustible Fuels	-3.132	-4.142
Finland Nuclear	-3.167	-7.04
Finland Hydro	-3.721	-4.228
Finland RES	5.07	-2.014
FI Gross Consumption	-2.258	-6.772
Norway Combustible Fuels	-2.126	-3.698
Norway Hydro	-4.26	-4.6
Norway RES	-0.734	-7.188
NO Gross Consumption	-3.399	-6.578
Sweden Combustible Fuels	-1.576	-5.177
Sweden Nuclear	-3.096	-5.39
Sweden Hydro	-3.038	-5.394
Sweden RES	3.792	-6.033
SE Gross Consumption	-3.191	-6.59

Notes: The reported statistics correspond to models that include a constant and 14 lags. A trend was included for both models. MacKinnon (1994) critical values for rejection of hypothesis of a unit root are -3.120 (10% confidence level), -3.410 (for 5% confidence level), and -3.960 (for 1% confidence level) A positive value indicates rejection of the null hypothesis. † The Danish hydropower and other renewable energy sources were combined to form one category.

Earlier studies (O'Mahoney and Denny, 2011; Tveten et al., 2013; Würzburg et al., 2013) have used robust linear regression models, meaning that the standard errors were estimated using the Huber-White sandwich estimators in order to handle minor problems about normality, heteroskedasticity, or some observations that exhibit large residuals, leverage or influence. To test whether a robust linear regression model was necessary, several diagnostics tests were run after each standard OLS regression. The Durbin-alternative test tests for serial correlation in the disturbances, but does not require that all the regressors be strictly exogenous (Durbin and Watson, 1950; Durbin, 1970). A Breusch-Pagen test was performed to test the assumption of homoskedastic residuals (Breusch and Pagen, 1979).

As Gelabert et al. (2011) discusses, one potential concern in the model specification is the correlation that may exist between the independent regressors. Hence, the variance inflation factor (VIF) was calculated for each model. A VIF greater than 10 suggests that multicollinearity is high (Craney et al., 2002; Kutner et al., 2004). As presented in the results (see Table 7), the system price model had the greatest mean VIF of 4.33. The final test performed was the Ramsey (1969) specification-test, which tested for omitted variables (see Table 7).

Table 7 Diagnostic regression results.

	Regressors	N	Durbin-alternative test	Breusch-Pagan/Cook-Weisberg test	Ramsey test	Mean VIF
	(excluding constant)		Pr.>X^2	Pr.>X^2	Pr.>X^2	
SP	6	191	0.327	0.0004	0.004	4.33
DK	4	191	0.196	0.09	0.209	1.12
FI	8	191	0.496	0.306	0.601	2.27

The decision not to include importing and exporting volumes was intentional, so that the model would not suffer from endogeneity since the Nordic regions export and import with one another. It would also have led to double counting, since gross national production volumes were used rather than net volumes calculated by subtracting exports from gross production.

In each linear regression model, the unobserved error term, ε_t is assumed to be identically and independently distributed normally with 0 mean and variance σ^2.

3 Results and discussion

Table 6 reports the ADF test results for the price, electricity supply variables, and national demand covariates. The findings showed that Norwegian hydropower was the only independent electricity production variable that permitted the rejection of the null hypothesis at the significance level of 99%, with the variable stationary without transformation into the first difference. However, once all dependent and independent variables were transformed by taking the first difference, only electrical production by Finish renewable energy sources could not reject the null hypothesis at the 95% confidence level.

The results from the diagnostic tests are shown in Table 7. According to the results for the Ramsey (1969) test, the system price model suffered from omitted variables. Accepting this result, it was decided not to alter the system price model and acknowledge its possible shortcomings. This finding is important by showing that there may be a higher degree of difficulty when modelling the market clearing price versus area prices in the Nordic market. Given that the estimated coefficients could be biased in the system price model due to omitted variables, a marginal analysis was only conducted on the Danish and Finnish models.

Table 8 presents the estimation results for the three models: western Denmark (DK1); Finland (FI); and the Nordic market clearing price (SP). Comparatively, the range of explained variability across the three models according to the adjusted *R*-squared was in a similar range for Finland (0.47), and SP (0.43). However, in the case of western Denmark (DK1), only 29.3% of the variability was explained by the set of covariates.

Table 8 Linear regression results for sixteen-year analysis of the Nordic market clearing price (SP), western Denmark's (DK1) area price, and the Finnish (FI) area price.

	SP	DK1	FI
ΔDK Combustible Fuels		6.065*** (0.937)	
ΔDK RES†	-8.016*** (1.795)	-8.322*** (1.614)	
ΔFI Combustible Fuels	4.442*** (1.172)		4.980*** (0.975)
ΔFI Nuclear			-3.650* (1.756)
ΔFI Hydro			-6.950** (2.326)
ΔNO Hydro	-2.046*** (0.589)		
ΔSE Combustible Fuels			9.396*** (2.676)
ΔSE Nuclear	-2.312*** (0.591)	-1.809*** (0.442)	-2.576*** (0.489)
ΔSE Hydro	-3.766*** (0.617)	-1.626*** (0.456)	-1.449* (0.560)
ΔSE Demand	3.744*** (0.990)		
Spring			3.019** (1.098)
Summer			3.498*** (1.020)
Constant	-0.00142 (0.349)	-0.0139 (0.339)	-1.827** (0.560)
Observations	191	191	191
R-squared	0.434	0.293	0.470
Adjusted R-squared	0.416	0.278	0.446

* Indicates *p<0.05, **p<0.01, ***p<0.001. Standard error in parentheses. Year-specific indicator variables omitted for brevity. The symbol † is used to indicate that Denmark's electricity from hydropower was added to its other renewable energy source variable.

Exploring the signs of the different estimated coefficients that remained in the models, the results showed that when there was a one TWh increase in monthly generation using combustible fuels from any country this always led to a positive increase in the predicted marginal monthly spot prices. Furthermore, as shown in the Finnish model, where electricity produced from combustible fuels from both Finland and Sweden remained statistically significant at the 95%

confidence level, the results showed that the average marginal effect for Sweden was two times larger (9.39 EUR/MWh) than for Finland (4.98 EUR/MWh). This result is logical because, over the sixteen years, Finland has almost always (98.98%) been a net importer. This finding also shows the magnitude in which different energy sources used for electricity production can impact its "connected" neighbors.

In this analysis, there were four energy sources represented, and while Denmark does not have any nuclear power plants, the estimated coefficients for Swedish hydroelectric energy (-1.63) and Swedish nuclear energy (-1.81) were significant at the 99% confidence level in the Danish model. Since there were four types of energy source variables, in the Danish model, all four are represented either by Denmark or another country Denmark exchanges energy with in the spot market.

Exploring the results more specifically, and employing the delta method (Rice, 1994), selected marginal changes were calculated. As mentioned, Sweden is expected to reduce its nuclear capacity by 2.7 GW by 2020. The expected impact of these nuclear power plant closures is mixed. Some experts predict that if these nuclear reactors go offline there will be a minimal impact (ICIS, 2015), while Energi Danmark, an energy trading company, has warned that the Nordic system price would increase somewhere between €1.0 – €4.0/MWh (ICIS, 2015).

To explore this further, Table 9 shows the marginal annual average change (EUR/MWh) in western Denmark and Finland's spot price when there is a 1 TWh increase or decrease in Swedish nuclear energy per month. This corresponds to about half of the capacity (~1.35 GW) that is planned to go offline in 2020, assuming 100% uptime and usage. As expected, there is an inverse relationship between production levels and prices. Nonetheless, whether there is an increase or decrease in production levels, Finland's average annual spot prices experience larger changes than western Denmark's price. For example, looking at 2002 in Table 9, holding all else constant, when Sweden decreased its nuclear energy by 1 TWh per month, the average annual spot price in Finland increased 6.19 EUR/MWh. For western Denmark, the increase in the average annual price was roughly three times less (2.13 EUR/MWh). This finding supports Energi Danmark's estimates (ICIS, 2015) and it goes further by showing that the effect of closure is not equal for all the countries. Furthermore, there were seven years (2000, 2003, 2004, 2005, 2011, 2013, and 2015) when the marginal effect created when Sweden increased its supply was greater than the marginal effect of its reducing nuclear power production for Finland and Denmark (see Table 9). Overall, there was no obvious trend that emerged, although the absolute marginal difference was higher for Finland in the earlier years. There were four years (2005, 2006, 2013 and 2014), when the absolute marginal difference was almost the same for Finland and Denmark, showing that the absolute average marginal change in price will be roughly the same when there is either a 1 TWh increase in Swedish nuclear energy or a 1 TWh decrease in Swedish nuclear energy. Furthermore, the absolute difference in these years between Finland's and Sweden's differences was less than 0.50 EUR/MWh.

Table 9 The annual average marginal change in the Danish (DK1) and Finnish (FI) spot prices when ther decrease in Swedish nuclear energy (SE) production per month.

	FI					DK1			
	FI	-ΔSE Nuc.		+ ΔSE Nuc.		DK1	-ΔSE Nuc.		+ ΔSE Nuc.
	Avg. Pr.	Marginal Δ	*t*-stat.	Marginal Δ	*t*-stat/	Avg. Pr.	Marginal Δ	*t*-stat.	Marginal Δ
	EUR/MWh					EUR/MWh			
2000	23.1	2.46	2.77	-4.74	-4.91	25.5	1.22	2.00	-1.86
2001	33.5	4.87	5.12	-2.33	-2.57	34.8	2.06	3.19	-1.02
2002	38.2	6.19	6.06	-1.01	-1.12	35.8	2.13	3.22	-0.95
2003	48.2	1.59	1.77	-5.61	-5.65	45.8	0.88	1.42	-2.20
2004	37.9	2.93	3.26	-4.27	-4.51	39.4	1.46	2.35	-1.62
2005	40.0	3.56	3.87	-3.64	-3.93	49.0	1.33	2.16	-1.75
2006	60.4	3.36	3.71	-3.84	-4.15	55.0	1.64	2.57	-1.44
2007	37.3	4.37	4.68	-2.83	-3.12	39.9	2.00	3.2	-1.08
2008	57.5	3.18	3.50	-4.02	-4.26	63.8	1.67	2.69	-1.41
2009	42.3	4.85	5.05	-2.35	-2.59	41.6	1.26	2.03	-1.82
2010	63.2	4.44	4.73	-2.76	-3.06	53.0	1.83	2.85	-1.25
2011	51.5	1.25	1.42	-5.95	-5.89	50.0	0.35	0.56	-2.73
2012	37.8	4.27	4.57	-2.93	-3.25	37.5	1.87	2.99	-1.21
2013	42.5	3.25	3.59	-3.95	-4.17	39.2	1.26	1.93	-1.82
2014	36.3	3.45	3.79	-3.75	-4.07	31.0	1.70	2.75	-1.38
2015	29.7	2.77	3.05	-4.43	-4.67	22.9	1.02	1.61	-2.07

All price series have been converted to real 2015 euros.

Table 10 shows the effects of increasing or decreasing electricity generation from renewable energy sources in Denmark and Finland. In both the Danish and Finish models, electricity produced from RES had an inverse relationship with price (Table 10), which supports earlier studies that have shown increased electricity generation from renewable energy sources, such as wind, will lead to a reduction in electricity market prices (Sensfuss et al., 2008; Würzburg et al., 2013). However, this effect may be transient due to increased interconnection (Ketterer, 2014), when policy is designed under incorrect assumptions (Nelson et al, 2015) or the structure of the wholesale market splits the electricity price into different products (Felder, 2011).

Table 10 The annual average marginal change in the Danish spot price when there is a 1 TWh increase or decrease in Danish RES energy per month and the annual average marginal change in the Finnish spot price when there is a 1 TWh increase and decrease in Finnish RES energy per month.

	DK1					FI				
	DK1	-ΔDK RES		+ ΔDK RES		FI	-ΔFI RES		+ ΔFI RES	
	Avg. Pr.	Marginal Δ	*t*-stat.	Marginal Δ	*t*-stat.	Avg. Pr.	Marginal Δ	*t*-statistic	Marginal Δ	*t*-stat.
	EUR/MWh					EUR/MWh				
2000	25.5	7.96	4.24	-8.45	-4.57	23.1	7.33	1.97	-8.54	-2.38
2001	34.8	8.62	4.59	-7.79	-4.21	33.5	8.69	2.39	-7.19	-1.97
2002	35.8	8.85	4.75	-7.56	-4.04	38.2	10.27	2.87	-5.60	-1.5
2003	45.8	7.72	4.09	-8.69	-4.73	48.2	6.08	1.65	-9.79	-2.7
2004	39.4	8.08	4.28	-8.33	-4.53	37.9	7.58	2.04	-8.29	-2.31
2005	49.0	8.07	4.3	-8.34	-4.51	40.0	7.88	2.14	-7.99	-2.21
2006	55.0	8.53	4.57	-7.88	-4.24	60.4	7.96	2.18	-7.91	-2.17
2007	39.9	8.37	4.47	-8.04	-4.34	37.3	8.58	2.37	-7.29	-1.98
2008	63.8	8.48	4.55	-7.93	-4.25	57.5	8.18	2.20	-7.69	-2.14
2009	41.6	8.08	4.31	-8.33	-4.50	42.3	9.07	2.46	-6.80	-1.88
2010	53.0	8.39	4.45	-8.02	-4.36	63.2	8.36	2.30	-7.51	-2.05
2011	50.0	7.39	3.91	-9.02	-4.9	51.5	5.68	1.53	-10.19	-2.83
2012	37.5	8.30	4.41	-8.11	-4.4	37.8	8.42	2.30	-7.45	-2.05
2013	39.2	8.35	4.48	-8.06	-4.32	42.5	7.52	2.11	-8.35	-2.24
2014	31.0	8.23	4.38	-8.18	-4.43	36.3	7.85	2.13	-8.02	-2.22
2015	22.9	8.08	4.32	-8.33	-4.49	29.7	7.67	2.10	-8.20	-2.25

† The Danish hydropower and other renewable energy sources were combined to form one category. All prices have been converted to real 2015 euros.

Another key result shown in both Table 9 and Table 10 is that the lowest marginal effect on the average annual price when there was a decrease in supply corresponds to 2011. Furthermore, this applied to Swedish nuclear energy, Danish renewable energy sources, and Finnish renewable energy sources. For example, as Table 10 shows, when there was a 1 TWh decrease in DK RES, the annual average marginal change in the Danish spot price, of 7.39 EUR/MWh. In the years after 2011, this value began to increase again. This result also applies to the Finnish model. Prior to 2011, when there was a 1 TWh decrease in Finnish nuclear energy, the annual average marginal change in the Finnish spot price was on average an increase in the Finnish spot price of around 8.18 EUR/MWh. In 2011, the marginal effect was almost 3 EUR/MWh less, but climbed again in 2012. In 2011 the Nordic market became fully interconnected with the Central Western European market (European Energy Exchange, 2014).

4 Conclusion

The integration of European electricity markets has long been viewed as an option to increase energy security by expanding the geographical boundaries of the transmission system and allowing more producers into the market. While earlier research had come to the overall conclusion that the benefits of market integration outweigh the cost of not integrating electricity markets (see e.g. Hobbs et al., 2005; Küpper et al., 2009; Malaguzzi, 2009; Zani et al., 2010), it had also become apparent that unilateral decisions can have a rippling effect in an integrated market. More evidence of disconnect between regional and national policies may arise as the adoption of the United Nations Framework Convention on Climate Change Paris Agreement goes into effect, which sets the basis as: "Agreeing to uphold and promote regional and international cooperation in order to mobilize stronger and more ambitious climate action by all Parties and non-Party stakeholders, including civil society, the private sector, financial institutions, cities and other subnational authorities, local communities and indigenous peoples" (UNFCCC/COP21, 2015). Therefore, it will be pertinent for policy makers to make dynamic, regional policies to ensure that the same thing does not happen as occurred in Australia, for example, where fixed environmental targets muddled investments (Nelson et al., 2015).

While countries must coordinate to a higher degree, there needs to be more standardization in published data. An aim of this research was to perform a multinational study that evaluated market integration by specifically looking at how changes in the different types of fuels used to generate electricity can impact day-ahead prices for different countries, using accessible data. A primary benefit of using data from Nord Pool and the IEA was that the data covered a relatively lengthy period of 16 years (2000-2015).

This analysis showed that using the Nordic electricity supply variables, temporal indicators, gross consumption, and market integration variables was not enough to model the Nordic system price without the system price model suffering from omitted variables bias. However, for the Danish (DK1) and Finnish price models, these four categories of variables sufficed. In addition, this study confirmed the negative effect of increased generation from renewable energy sources on electricity prices. Cludius et al. (2014) showed that electricity prices in Germany were reduced between 6-10 EUR/MWh, and while Ketterer (2014) also found that increased wind power led to lower market electricity prices, prices began to exhibit more volatility (see also Riesz et al., 2016). While the marginal effect was not as large as the results of Cludius et al. (2014), Caralis et al. (2016) showed that the effect can vary due to project specific characteristics such as water depth, size of projects, distance from shore and grid availability.

While electricity produced from renewable energy sources costs less than electricity produced from conventional energy sources, the intermittency creates volatility and uncertainty in prices. As a result, this can skew the amount of capital required for investment in the transmission system, while also pushing out conventional thermal sources. Conventional sources continue to play a key role in mitigating the variability of intermittent renewable energy sources (Hittinger et al., 2010; Traber and Kemfert, 2011) until the issue of storability (outside of hydro reservoirs) is resolved. However, Gelabert et al. (2011) emphasized that the effect of low prices created by higher shares of renewable energy sources (RES) may be temporary, since this will slow investment, which in turn restricts supply. These findings are highly relevant, because in the analysis presented here, choices to increase wind power could impact investment decisions in Sweden, for example.

Another key lesson that emerged from this analysis is that not all changes were equal. This was shown by Swedish nuclear power, where it had a greater impact on Finland's average marginal spot price than Denmark's. Therefore, one might see in future years that, as market integration increases by increased transmission capacity across national borders, these effects will become larger because a nation may decrease its total capacity since it can either export or import electricity. In doing this, it places itself at the greater mercy of other nations' energy targets and policies. Therefore, while interconnectivity can lead to a decrease in average spot prices, it also may make one nation more vulnerable to higher prices, especially in the case where the country is a net importer, such as Finland. We suggest that as long as markets become more integrated, it becomes more important to develop regional energy targets, shifting the power away from national actors. Acting independently will potentially diminish the benefits and strain international relationships.

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References

Blindheim, B. (2013). Implementation of wind power in the Norwegian market; The reason why some of the best wind resources in Europe were not utilised by 2010. *Energy Policy*, *58*, 337-346.

Borenstein, S., Bushnell, J., & Stoft, S., (1997). *The Competitive Effects of Transmission Capacity in a Deregulated Electricity Industry* (No. w6293). National Bureau of Economic Research.

Borenstein, S. (2002). The trouble with electricity markets: Understanding California's restructuring disaster. *The Journal of Economic Perspectives*, *16*(1), 191-211.

Breusch, T. S., & Pagan, A. R. (1979). A simple test for heteroscedasticity and random coefficient variation. *Econometrica: Journal of the Econometric Society*, 1287-1294.

Bunn, D. W., & Gianfreda, A. (2010). Integration and shock transmissions across European electricity forward markets. *Energy Economics*, 32(2), 278-291.

Caralis, G., Chaviaropoulos, P., Albacete, V. R., Diakoulaki, D., Kotroni, V., Lagouvardos, K., & Rados, K. (2016). Lessons learnt from the evaluation of the feed-in tariff scheme for offshore wind farms in Greece using a Monte Carlo approach. *Journal of Wind Engineering and Industrial Aerodynamics*, 157, 63-75.

Clò, S., Cataldi, A., & Zoppoli, P. (2015). The merit-order effect in the Italian power market: The impact of solar and wind generation on national wholesale electricity prices. *Energy Policy*, *77*, 79-88.

Cludius, J., Hermann, H., Matthes, F. C., & Graichen, V. (2014). The merit order effect of wind and photovoltaic electricity generation in Germany 2008–2016: Estimation and distributional implications. *Energy Economics*, 44, 302-313.

Craney, Trevor A., and James G. Surles, (2002): Model-dependent variance inflation factor cutoff values. *Quality Engineering 14*, no. 3 391-403.

De La Torre, S., Conejo, A. J., & Contreras, J. (2008). Transmission expansion planning in electricity markets. *Power Systems, IEEE Transactions on*, *23*(1), 238-248.

Dickey, D. A., & Fuller, W. A. (1979). Distribution of the estimators for autoregressive time series with a unit root. *Journal of the American Statistical Association*, *74*(366a), 427-431.

Durbin, J. (1970). Testing for serial correlation in least-squares regression when some of the regressors are lagged dependent variables. *Econometrica: Journal of the Econometric Society*, 410-421.

Durbin, J., & Watson, G. S. (1950). Testing for serial correlation in least squares regression: I. *Biometrika*, *37*(3/4), 409-428.

European Commission, (2014). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Progress towards completing the Internal Energy Market.* https://ec.europa.eu/energy/sites/ener/files/publication/iem_web_0.pdf. (Accessed October 10, 2016.)

European Energy Exchange, (2014). Press release: January 17, 2011. *Next Decisive Step Towards a Single European Electricity Market*.

http://static.epexspot.com/document/12058/20110117_Final_ITVC%20Launch_step2.pdf (Accessed March 7, 2017).

European Parliament and of the Council, (1996) Council Directive 96/92/EC concerning common rules for the internal market in electricity. *Official Journal L* 027, 30/01/1997 P. 0020 – 0029. http://data.europa.eu/eli/dir/1996/92/oj

European Parliament and of the Council, (2009). *Regulation (EC) No. 714/2009* Conditions for access to the network for cross-border exchanges in electricity and repealing Regulation (EC) No 1228/2003 (2009). http://data.europa.eu/eli/reg/2009/714/oj

European Parliament and of the Council, (2011). Regulation (EU) No. 1227/2011 (REMIT), *Official Journal of the European Union*, Article 2 (7), L326 (December 08, 2011), p. 7.

[dataset]Eurostat, (2016). HCIP (2015=100): *Denmark – Electricity.* http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=prc_hicp_midx&lang=en. (Accessed August 30, 2016).

European Wind Energy Association (EWEA), (2017). *Curtailments*. https://www.wind-energy-the-facts.org/curtailments-7.html. Accessed February 28, 2017.

European Network of Transmission System Operators for Electricity (ENTSO-E), (2015). P5 – *Policy 5: Emergency Operations.* https://www.entsoe.eu/Documents/Publications/SOC/Continental_Europe/oh/20150916_Policy_5_Approved_by_ENTSO-E_RG_CE_Plenary.pdf. Accessed May 31, 2017.

Escribano, A., Ignacio Peña, J., & Villaplana, P. (2011). Modelling electricity prices: International evidence. *Oxford Bulletin of Economics and Statistics*, *73*(5), 622-650.

Fanone, E., Gamba, A., & Prokopczuk, M. (2013). The case of negative day-ahead electricity prices. *Energy Economics*, 35, 22-34.

Felder, F. A. (2011). Examining electricity price suppression due to renewable resources and other grid investments. *The Electricity Journal*, *24*(4), 34-46.

Finnish Energy Agency, (2016). Hourly Electricity Supply Data. http://energia.fi/en/statistics-and-publications/electricity-statistics/hourly-electricity-data. (Accessed October 10, 2016).

Franco, A., & Salza, P. (2011). Strategies for optimal penetration of intermittent renewables in complex energy systems based on techno-operational objectives. *Renewable Energy*, *36*(2), 743-753.

Gelabert, L., Labandeira, X., & Linares, P. (2011). An ex-post analysis of the effect of renewables and cogeneration on Spanish electricity prices. *Energy Economics*, *33*, S59-S65.

Greene, W. H. (2003). *Econometric analysis*. Pearson Education India.

Helm, D. (2014). The European framework for energy and climate policies. *Energy Policy*, *64*, 29-35.

Hobbs, B. F., Rijkers, F. A., & Boots, M. G. (2005). The More Cooperation, The More Competition? A Cournot Analysis of the Benefits of Electric Market Coupling. *Energy Journal*, 26(4).

Hittinger, E., Whitacre, J. F., & Apt, J. (2010). Compensating for wind variability using co-located natural gas generation and energy storage. *Energy Systems*, *1*(4), 417-439.

Huisman, R., & Mahieu, R. (2003). Regime jumps in electricity prices. *Energy Economics*, *25*(5), 425-434.

ICIS, (2015). *Nuclear Power Absorbs Nuclear Closures – Traders.* http://www.icis.com/resources/news/2015/10/30/9938305/nordic-power-market-absorbs-nuclear-closures-traders/.(Accessed November 13, 2015).

[dataset]International Energy Agency (IEA) (2015a), OECD - Monthly net electricity supply, *IEA Electricity Information Statistics* (database). DOI: http://dx.doi.org/10.1787/data-00456-en (Accessed on 16 October 2015).

International Energy Agency (IEA), (2015b). *Energy Policies of IEA Countries: Spain 2015 Review*. https://www.iea.org/publications/freepublications/publication/IDR_Spain2015.pdf (Accessed February 5, 2017).

International Energy Agency (IEA), (2016a). *IEA Wind: Member Country Activities for Spain.* http://www.ieawind.org/countries/spain.html. (Accessed October 10, 2016).

International Energy Agency (IEA), (2016b). *France: Electricity supply and Heat.* http://www.iea.org/statistics/statisticssearch/report/?year=2014&country=FRANCE&product=ElectricityandHeat. (Accessed October 10, 2016).

International Energy Agency (IEA), (2016d). *Norway: Electricity and Heat in 2010.* http://www.iea.org/statistics/statisticssearch/report/?country=NORWAY&product=electricityandheat&year=2010 (Accessed October 13, 2016).

International Energy Agency (IEA), (2016e). *Norway: Electricity and Heat in 2014.* http://www.iea.org/statistics/statisticssearch/report/?country=NORWAY&product=electricityandheat&year=2014 (Accessed October 13, 2016).

International Energy Agency (IEA), (2016f). *Sweden: Electricity and Heat in 2010.* http://www.iea.org/statistics/statisticssearch/report/?country=SWEDEN&product=electricityandheat&year=2010. (Accessed October 13, 2016).

International Energy Agency (IEA), (2016g). *Sweden: Electricity and Heat in 2014.* http://www.iea.org/statistics/statisticssearch/report/?country=SWEDEN&product=electricityandheat&year=2010. (Accessed October 13, 2016).

International Energy Agency (IEA), (2016h). *Electricity Information*. 2016 ed. http://wds.iea.org/wds/pdf/Ele_documentation.pdf. (Accessed November 15, 2016).

Janczura, J., & Weron, R. (2010). An empirical comparison of alternate regime-switching models for electricity spot prices. *Energy Economics, 32*(5), 1059-1073.

Jónsson, T., Pinson, P., & Madsen, H. (2010). On the market impact of wind energy forecasts. *Energy Economics*, *32*(2), 313-320.

Ketterer, J. C. (2014). The impact of wind power generation on the electricity price in Germany. *Energy Economics*, 44, 270-280.

Koeppel, G., & Korpås, M. (2008). Improving the network infeed accuracy of non-dispatchable generators with energy storage devices. *Electric Power Systems Research*, *78*(12), 2024-2036.

Kutner, M. H.; Nachtsheim, C. J.; Neter, J. (2004). *Applied Linear Regression Models (4th ed.).* McGraw-Hill Irwin.

Küpper, G., Delarue, E., Delvaux, B., Meeus, L., Bekaert, D., Willems, B., & Belmans, R. (2009). Does more international transmission capacity increase competition in the Belgian electricity market? *The Electricity Journal*, 22(1), 21-36.

MacKinnon, J. G. 1994. Approximate asymptotic distribution functions for unit-root and cointegration tests. *Journal of Business and Economic Statistics,* 12, 167–176.

Malaguzzi Valeri, L. (2009). Welfare and competition effects of electricity interconnection between Ireland and Great Britain. *Energy Policy*, 37(11), 4679-4688.

Mitchell, C., Bauknecht, D., & Connor, P. M. (2006). Effectiveness through risk reduction: A comparison of the renewable obligation in England and Wales and the feed-in system in Germany. *Energy Policy*, *34*(3), 297-305.

Nelson, T., Reid, C., & McNeill, J. (2015). Energy-only markets and renewable energy targets: Complementary policy or policy collision? *Economic Analysis and Policy*, *46*, 25-42.

[dataset]Nord Pool, (2016a). Historical Market Data. Available at: http://www.nordpoolspot.com/historical-market-data/. (Accessed October 10, 2016).

Nord Pool, (2016b). No. 16/2010 – *Estlink Capacity Owners Support the Opening of the Estlink Bidding Area*. http://www.nordpoolspot.com/message-center-ontainer/nordicbaltic/exchange-message-list/2010/03/No-162010-NPS---Estlink-capacity-owners-support-the-opening-of-the-Estlink-bidding-area/. (Accessed September 22, 2016).

Nord Pool, (2016c). No. 14/2005. *Successful Start of Nord Pool Spot's New Bidding Area – Kontek*. http://www.nordpoolspot.com/message-center-container/nordicbaltic/exchangemessage-list/2005/10/No142005-Successful-start-of-Nord-Pool-Spots-new-bidding-area---KONTEK/. (Accessed September 22, 2016).

Nord Pool, (2017a). *Bidding Areas*. http://www.nordpoolspot.com/How-does-it-work/Bidding-areas/ (Accessed February 6, 2017).

Nord Pool, (2017b). *The Nordic Electricity Exchange and the Nordic Model for a Liberalized Electricity Market*. http://www.nordpoolspot.com/globalassets/download-center/rulesand-regulations/the-nordic-electricity-exchange-and-the-nordic-model-for-a-liberalized-electricity-market.pdf (Accessed February 3, 2017).

Nordic Energy Regulators (Nord Reg), (2010). Harmonising the balancing market: Issues to be considered. *Report 5/2010*. http://www.nordicenergyregulators.org/wp-content/uploads/2013/02/NordREGreport5_2010_Balancing.pdf. (Accessed October 15, 2015).

Oliver, C., (2014). *Franco-Spanish Energy Spat tests EU*. https://www.ft.com/content/8e94079c-585f-11e4-b331-00144feab7de. (Accessed February 5, 2017).

O'Mahoney, A., & Denny, E. (2011). The merit order effect of wind generation on the Irish electricity market. https://mpra.ub.uni-muenchen.de/56043/1/USAEE%20Washington%20Paper.pdf. (Accessed on October 12, 2016).

Ramsey, J. B. (1969). Tests for specification errors in classical linear least squares regression analysis. *Journal of the Royal Statistical Society Series B*. 31 (2): 350–371.

Riesz, J., Gilmore, J., & MacGill, I. (2016). Assessing the viability of Energy-Only Markets with 100% Renewables. *Economics of Energy & Environmental Policy*, *5*(1).

Rice, John. (1994). *Mathematical Statistics and Data Analysis*. 2nd ed. Duxbury.

Schwert, G. W. 1989. Tests for unit roots: A Monte Carlo investigation. *Journal of Business and Economic Statistics* 2: 147–159.

Sensfuss, F., Ragwitz, M., & Genoese, M. (2008). The merit-order effect: A detailed analysis of the price effect of renewable electricity generation on spot market prices in Germany. *Energy Policy*, *36*(8), 3086-3094.

Shrestha, G. B., & Fonseka, P. A. J., (2004). Congestion-driven transmission expansion in competitive power markets. *Power Systems, IEEE Transactions on*, *19*(3), 1658-1665.

Singh, H., Hao, S., & Papalexopoulos, A. (1998). Transmission congestion management in competitive electricity markets. *IEEE Transactions on Power Systems*, *13*(2), 672-680.

Sioshansi, R., Denholm, P., Jenkin, T., & Weiss, J. (2009). Estimating the value of electricity storage in PJM: Arbitrage and some welfare effects. *Energy Economics*, *31*(2), 269-277.

Statistics Sweden, (2016). Monthly electricity supply. http://www.scb.se/en_/Finding-statistics/Statistics-by-subject-area/Energy/Energy-supply-and-use/Monthly-electricity-statistics/. (Accessed October 10, 2016).

Traber, T., & Kemfert, C. (2011). Gone with the wind? Electricity market prices and incentives to invest in thermal power plants under increasing wind energy supply. *Energy Economics*, *33*(2), 249-256.

Tveten, Å. G., Bolkesjø, T. F., Martinsen, T., & Hvarnes, H. (2013). Solar feed-in tariffs and the merit order effect: A study of the German electricity market. *Energy Policy*, 61, 761-770.

United Nations Framework Convention on Climate Change (UNFCCC), (2015). Conference of the Parties (COP) 21: Adoption of Paris Agreement: Proposal by President. https://unfccc.int/resource/docs/2015/cop21/eng/l09.pdf. Accessed May 31, 2017.

Wizelius, T. (2014). *Windpower Ownership in Sweden: Business Models and Motives*. Routledge.

Woo, C. K., Horowitz, I., Moore, J., & Pacheco, A. (2011). The impact of wind generation on the electricity spot-market price level and variance: The Texas experience. *Energy Policy*, *39*(7), 3939-3944.

Wooldridge, J. M. (2010). *Econometric analysis of cross section and panel data*. MIT press. pp. 279–291.

World Atlas, (2015). Denmark Geography. http://www.worldatlas.com/webimage/countrys/europe/denmark/dkland.htm. (Accessed November 30, 2015).

World Nuclear Organization, (2015). Nuclear Power in Sweden. http://www.world-nuclear.org/info/Country-Profiles/Countries-O-S/Sweden/. (Accessed November 19, 2015).

Würzburg, K., Labandeira, X., & Linares, P. (2013). Renewable generation and electricity prices: Taking stock and new evidence for Germany and Austria. *Energy Economics*, 40, S159-S171.

Zachmann, G. (2008). Electricity wholesale market prices in Europe: Convergence? *Energy Economics*, 30(4), 1659-1671.

Zani, A., Benini, M., Gelmini, A., Migliavacca, G., & Siface, D. (2012). Assessment of the impact on the Italian electricity market of a price coupling with neighboring countries. *Power Plants and Power Systems Control*. 8(1), 687-692.