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Discussion paper

Dead Battery? Wind Power, The Spot Market, and Hydro Power Interaction in the Nordic Electricity Market

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Abstract

It is well established within both the economics and power system engineering literature that hydro power can act as a complement to large amounts of intermittent energy. In particular, hydro power can act as a "battery" where large amounts of wind power are installed. This paper attempts to extend that literature by describing the effects of cross-border wind and hydro power interaction in a day-ahead "spot" market. I use simple econometric distributed lag models with data from the Nordic electricity market and a sample of Norwegian hydro power plants with water storage magazines. I suggest that wind power mainly affects prices in the hydro power area by way of shifting the shadow value of water. The empirical results support this view.

Keywords: Wind Power, Hydro Power, Nordic Electricity Market, Empirical

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1. Introduction

Wind power has grown to be a significant source of electricity supply in Europe and increasingly in North America and Asia. its share of electricity production is likely to grow robustly in the coming decades. However, installing large amounts of intermittent energy generation presents serious risk to supply security. One proposed mitigater of this risk is to link areas with large amounts of wind power to areas with hydro power plants with magazines which are able to quickly and cheaply adjust their production while storing energy in the form of water in their magazines. In this context, Norway, with large amounts of hydro power has been referred to as the "battery" (Economist, 2006) of Europe, especially as large amounts of off-shore wind power are being proposed off Great Britain, Ireland and other areas of Northern Europe (see (Forewind, 2011) or (NOWAI, NOWAI)).

Wind and hydro power's complementarity has been noted in several contexts in both the economics and power systems engineering literature. Much of the literature consists of simulation studies. Belanger and Gagnon (2002) explores the amount of added hydro power that would be needed to serve as an adequate backup to a proposed large wind power installation in Quebec. Denault et al. (2009) studies the same power system, but is interested in the longer term issue of power generation diversification. Specifically, avoiding the risk of water shortfalls in a hydro dominated system. Studies of the Nordic market also exist. Foersund and Hjalmarsson (2010) analyse the effect that a build-out of wind power in the Nordic market would have on the price of providing regulation power - primarily hydro power.

My paper is perhaps most similar to Green et al. (2010), who lays out a model of Danish wind production and power trade with two areas: one dominated by hydro power while the other, representing Denmark, has both wind and thermal capacity. The model shows that the level of available hydro generation determines how much wind/thermal power is exported. They back-up the results from their model by taking a descriptive look at the data, noting that at yearly time scales, exports from Denmark are correlated with reservoir levels. At a daily level they note that Denmark exports at off-peak time and argue that this is evidence for the ”storage” of Danish electricity in the hydro power of their neighbours. The authors also note a high correlation between wind power and exports.

The day-ahead market run by Nordpool, called Elspot, is the largest and most active physical exchange market for power in the Nordic market. Electricity trade between Nordic countries, capacity constraints and the spot market are intricately linked. Yet, to my knowledge, no study of hydro and wind power interaction in the Nordic market has closely considered the role and effects of such interaction on the spot market. This article seeks to fill that hole.

In theory the spot market should give the correct price signals for such an interaction. Periods with high wind are likely to press down prices, providing an incentive for hydro power producers to cut production and store the energy in the form of water in their magazine (or in the case of magazines with pump-storage capabilities, actually pump water up hill into the magazines). When wind power production is low, prices are likely to increase, providing an incentive for hydro power producers to then increase production.

But, as I will show, transmission constraints limit the extent to which this interaction can occur, and serve to magnify wind powers effect on the local price area (Denmark) while minimizing them on the price area with hydro power (Norway).

The Nordic electricity market presents a good testing ground for the battery effect. Due to the early and heavy investment by Denmark, the Nordic electricity market is one of the few places with a relatively long history with significant amounts of wind power. The Nordic system is also a well developed market-based system with decentralized producers making bids in the wholesale "spot" market. Prices are the main tool to resolve transmission constraints and balance the system across regions and countries. In addition, the transmission capacity between Denmark and Norway is large and well within the scale of what has been proposed for between Norway and, for example, the planned wind farms in Dogger Bank in the North Sea.

In this paper I use an extensive dataset of hourly and daily data points from the Norwegian and Danish transmission system operators (TSO's), Nordpool - the central exchange, and hydro power plant magazine levels from a selection of 15 large plants located in southern Norway. I use simple and transparent distributed lag models with exogenous regressors. With these models, I use the strong auto-correlation in the data to control for factors that are not of direct interest. Put simply, I use to my advantage the principle that a good forecast of the electricity price tomorrow is the electricity price today.

Vector Autoregressive (VAR) models are increasingly being used in the context of power markets (see for example Fell (2008) or Andersson and Lillestol (2010), especially when analysing the interaction of several potentially endogenous series. However these models can often become complex and the results can be difficult to interpret (see for example Bernanke (1986)). I stick to the simpler single equation distributed lag models.

As preliminaries I test the direct relationship between wind power and power trade between Denmark and Norway. I also look to see if any direct correlation between Danish wind power and Norwegian reservoir levels can be detected. I then go on to the main component of the paper - the relationship between Danish wind power on Danish and Norwegian spot prices.

2. The Nordic Electricity Market

Deregulation of the Nordic electricity system towards a market-based system began in 1991 in Norway. By 1996 a Norwegian-Swedish power exchange was established and the joint trading exchange Nord Pool ASA was formed. Finland joined in 1998, western Denmark in 1999 and eastern Denmark in 2000. In later years, bidding areas have also been extended to Germany (Kontek area).

The Nordpool spot market - elspot - operates on a day-ahead basis [1]. Producers and consumers, either large direct-consumers or electricity retailers, provide bids [2] in the form of a supply and demand schedule for every hour of the following day. From these bids, Nordpool establishes an aggregate supply and a demand schedule from which an equilibrium system-price is established.

Significant transfer capacity exists between Denmark and Norway. A 1000 kv direct current (DC) cable runs between southern Norway and western Denmark and plans are for this connection to increase to 1600 kv by 2014. Large amounts of transfer capacity also exist between Denmark and Sweden as well as to Germany.

Though transfer capacities in the Nordic region are relatively large, transmission congestion is still a common occurrence. For this reason, several price-areas exist: two in Denmark (east and west), one for Sweden [3] and Finland each, and several in Norway [4]. When congestion occurs between areas, the price increases in the area receiving power and is reduced in the area sending power until equilibrium is met with the available transmission capacity. Thus, while a theoretic system price always exists, it is common that the different areas have different prices in

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[1] bidding starts at noon and is open 24 hours - thus bids can be sent between 12 and 36 hours in advance

[2] In trader jargon a sell bid is known as an "ask" while "bid" implies a supply side offer.

[3] as of November 2011, Sweden will also switch to having several price areas

[4] the exact number of price areas has depended on the level of congestion

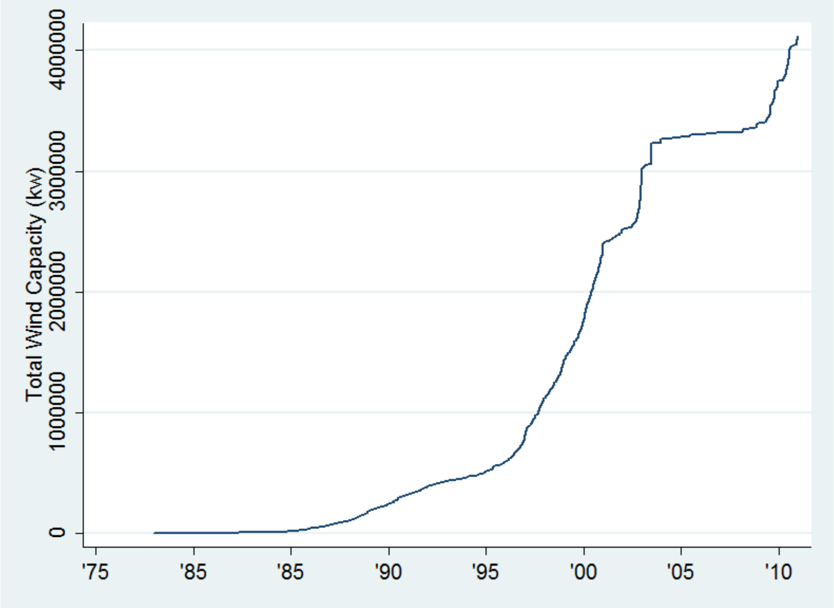

Figure 1. Shows the strong growth in Danish wind power capacity. By 2010, wind power provided approximately 20 % of the total electricity produced in Denmark

practice.

Denmark has a long history of using wind power, but the wide-scale use of wind-turbines to generate electricity for the grid trace back to the mid-1970's, when the Arab oil embargo and a subsequent dramatic increase in fossil fuel prices spurred investment in alternative forms of electricity generation. Denmark has since poured considerable resources into both research and development of wind-turbines. Equally important, Denmark has provided generous subsidies in order to build out capacity. Wind capacity growth was especially strong from the late 90's through about 2003 as figure 2 shows. A reduction of wind power feed-in tariffs in 2003 led to a levelling off of investment. Investment picked up again following a shift back towards higher subsidies in 2008.

3. Data and Methodology

Data was assembled from several sources. Hourly price data was obtained from Nordpool (Foyn, 2009). Data on daily wind energy production from both eastern and western Denmark was obtained from the website of the Danish transmission system operator, energinet (energinet.dk). Finally, the data (with a one year lag from the time of request) from individual hydro power plants was generously provided by the Norwegian Energy Directorate, NVE (Klausen, 2009).

The data can be assumed to be of high quality and with up to 8 years of daily data, the econometrics become easier as I can rely on asymptotics to obtain consistent and unbiased coefficient estimators and standard deviations. In particular, robust (White) standard errors will converge to the correct standard errors asympototically. Some serial correlation will still be present in the residuals, even after accounting for the dynamics in the regression model. Happily, White standard errors are also asymptotically consistent in the presence of serial correlation (Hamilton, 1994).

The data on water magazine levels consists of 15 individual daily time series from large water magazines in southern Norway. Table 1 gives an overview of these plants, ordered by the size of the magazines, in million cubic meters. From now on I will refer to the plants by the last digits of their ID number. Notice that I have differing sample sizes of the different magazines. For some I have data up to 2008, while others stop at February of 2007. For competition reasons, the data is made available with a one year lag, and it appears some with an even longer lag. All of the series date back to the beginning of the year 2000.

Figure 3 shows the level of magazine 113. The strong annual seasonality is readily apparent with a steady draw-down during the winter months and high inflows during the spring and summer snow melts. I attempt to at least partially deal

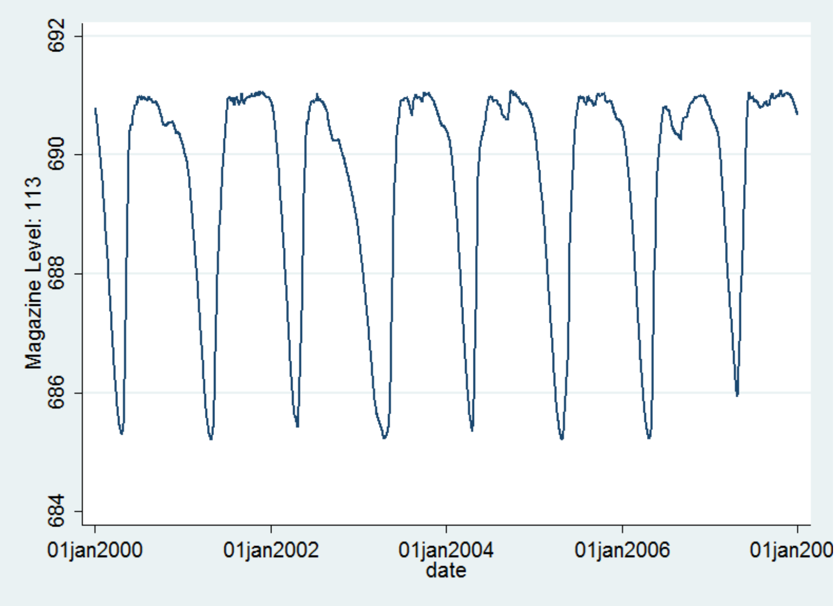

Figure 2. The level of magazine 113. The yearly seasonality in the data is apparent, caused by a pattern of spring and summer inflows and winter draw-down.

with this seasonality in the regression. I will use first differences of the data when running the regression. This helps make the series stationary, but a solid economic rationale also exists. I am interested in the water levels in that they provide information about hydro power electricity production. Production is primarily from the *flow* of water from the reservoir and can thus be approximated by a relative *change* in water levels.[5]

I also use energy imports/exports in some of the regressions. Figure 3 shows the large seasonal and yearly variation in this series. The measure also gives a clear visualization of the transmission capacity constraints between the two countries.

The general form of the distributed lag models I use throughout are as equation 1. Here d_t represents the dependent variable being modelled and ex_t represents the

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[5] production is also effected by the absolute level of the reservoir - but at the scale of daily changes in production, this plays only a minor role.

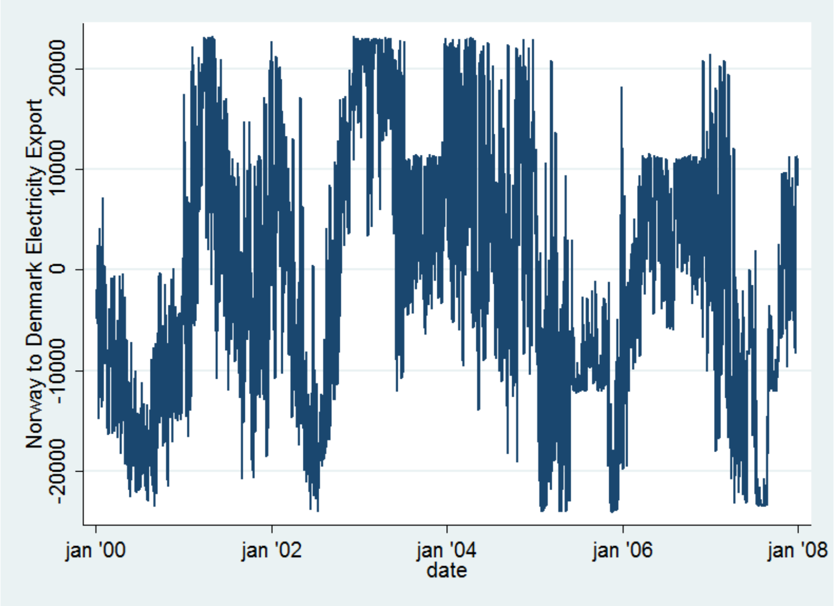

Figure 3. Shows the pattern of trade between Denmark and Norway. Transmission constraints are visible as time varying plateaus at the peak of trade in both directions.

exogenous variable being modelled. **x** represents a vector of other included control variables, though these are often not strictly necessary in such models since the autoregressive and moving average terms serve to control for much of the variation. Still they may be useful if there is uncertainty about interpretation. In the below model, I completely arbitrarily include autoregressive (ar) 1 and 2 terms (d_{t-1}..) and moving average (ma) 1 and 2 terms (ϵ_{t-1}...). The actual specification I use in the regressions is arrived at by a process of using wald tests, charts of auto-correlation and partial autocorrelation function as well as comparison of Akaike information criteria (AIC). Notably, I often include ar 6 and ar 7 terms which are often significant and represent weekly seasonality in the data (for example, when modelling price data).

$$d_t = \sigma ex_t + \delta \mathbf{x} + \alpha_1 d_{t-1} + \alpha_2 d_{t-2} + \beta_1 \epsilon_{t-1} + \beta_2 \epsilon_{t-2} + \epsilon_t \tag{1}$$

One intuitive way of interpreting such models is to interpret the coefficient on the exogenous variable, σ, as the marginal effect of that variable when the effect of recent values of the dependent variable have been controlled for.

In practice several different specification could be seen as giving a reasonable fit to such models. therefore, all of the results below have been tested to be robust to changes in specification.

4. Results

Subsection 4.1 and 4.2 present some preliminary results. First, I want to show the effect that wind power has on the trade flow of electricity between Denmark and Norway. I then follow by seeing if and to what extent there exists a direct relationship between Danish wind power production, and the change in magazine levels of the selection of Norwegian hydro power plant magazines. The main focus of the paper is however the role of the spot market and wind and hydro power generation. This is taken up in section 4.3.

4.1. Effect of Wind Power on Trade

Norwegian power production consists almost exclusively of hydro power. It could then plausibly be argued that the interaction between the intermittent wind energy in Denmark and Norwegian hydro power could be modelled by using electricity trade between Norway and Denmark as a proxy.

Here, I use distributed lag models with wind power as the exogenous regressor to test the relationship between wind power and electricity trade between Denmark and Norway. The model is of the form of equation 2 where I_t represents net electricity trade between Norway and Denmark for every day, t, in megawatt-hour/hour. W_t represents the amount of wind power produced in megawatt-hours per hour (mwh/h) that day from Danish wind turbines. $\mathbf{X}_t$ represents a vector of other exogenous regressors that are included in the regression. $\mathbf{I_{t-i}}$ represents the vector of autoregressive terms included in the regression while $\mathbf{\epsilon_{t-i}}$ represents the vector of moving average terms included in the regression. ϵ_t represents the contemporaneous error term.

$$I_t = \gamma W_t + \delta \mathbf{X_t} + \alpha \mathbf{I_{t-i}} + \beta \mathbf{\epsilon_{t-i}} + \epsilon_t \tag{2}$$

The results for the regression are displayed in table 2. I find that including ar 1,2,3,6 and 7 as well as ma 1,2 and 3 terms provides an adequate fit. Looking at the first column, the coefficient on the wind power term, labelled wind, is about .27, which is significantly different from zero at a 1% level. Since both the wind power term and the power trade term are in mwh/h units, one can interpret this to mean that for ever mwh/h of wind power produced, .27 mwh/h more electricity is exported to Norway.

In the second column I add terms for Norwegian consumption, labeled *consum*, and temperature in Norway, *norTemp*. One can see from comparing the AIC (smaller AIC indicate better fit) that these add to the fit of the model, but they do not substantially change the estimated coefficient on wind. This should ameliorate any concerns that the coefficient on the wind power term is capturing effects on trade from the demand side that may be correlated with wind speed. Norway, for example, still overwhelmingly uses electricity for heating, and cold weather could plausibly be correlated with wind conditions just south in Denmark.

The third column seeks to explore whether wind power's effect on marginal exports is correlated by the net direction of exports over a day. I interact the wind power term with an indicator variable (values of 0 and 1) for net exports to Norway, *wind-ex*, and net imports to Denmark, *wind-im*. The results indicate that when there is a net export of electricity to Norway, an extra 1 mwh/h of wind power leads to about .3 mwh/h of extra exports. On the other hand, when there are net imports to Denmark in a day, 1 mwh/h of wind power leads only to .1 mwh/h less of net imports

Table 2 here

The most likely explanation for this asymmetry is that the effect of wind power is non-linear in trade. Periods with large amounts of wind power will also be times with large amounts of export as the general amount of supply from Denmark increases. One could also say that wind power then ”causes” net exports of electricity from Denmark. On the other hand, periods with less wind power are correlated with net-imports and the effect, per mwh/h is less during these times.

This explanation also dovetails with the battery effect. Periods of excess supply in Denmark caused by large amounts of wind power lead to increased exports to Norway where the energy can be ”stored” in the form of hydro power.

But it is not conclusive evidence for this effect. Another possibility is, for example, that even with the current dominant role of hydro power in the Norwegian system, that extra wind power in Denmark does not substantially change the operation of the hydro power plants but instead shifts the total pattern of electricity trade and transmission. Norway imports more electricity from Denmark but less from Finland and Sweden.

4.2. Wind and Magazine Levels

In this section I attempt to establish if any direct relationship can be detected between the operation of Norwegian hydro power (with magazines) and wind power production in Denmark. I call this section preliminary because I do not attempt here to include an analysis of any of the market mechanism that lies behind the trade flows. In the following section, I look at the effects that wind power has on prices in the spot market, and use that to partly explain the results.

I test the relationship between wind and hydro power directly again by using simple distributed lag models, with wind as the exogenous regressor. I first transform the level data as in definition 3. I take the log of the magazine data (as well as of the wind power series) so that I can interpret the results as an elasticity. The minimum amount of water in the magazines in my sample period is well above completely empty. Thus I subtract away the minimum amount plus one (so as to avoid any numerical problems of taking a natural log of a value close to 0) for each of the series. This helps in interpretation, as the minimum amount observed in my 8 years of data becomes the reference amount when estimating the elasticity.

As mentioned earlier, I use the the first difference of the magazine level series. This makes the series stationary (A Dicker-fuller test confirms this), but there is also a clear economic rationale for doing this. I am using wind power as the exogenous regressor, and power produced is a flow. The corresponding flow of power from a hydro power plant is represented by a *change* in a magazine level.

In figure 4.2 I chart the first differenced series of the magazine level 130. Clearly, the series displays strong yearly seasonality with spring inflows a dominant component of the total variation. The smaller, day to day differences due to operation of the power plant, on the other hand, represents relatively minor part of total variation in the series.

$$l_{ti} \equiv ln(L_i - min(L_i) + 1) \tag{3}$$

Equation 4 shows the form of distributed lag model that is run for each magazine, i. $\Delta l_{t,i}$ represents the daily change in reservoir level in reservoir i. I find that two autoregressive terms and two moving average terms, the coefficients of which are

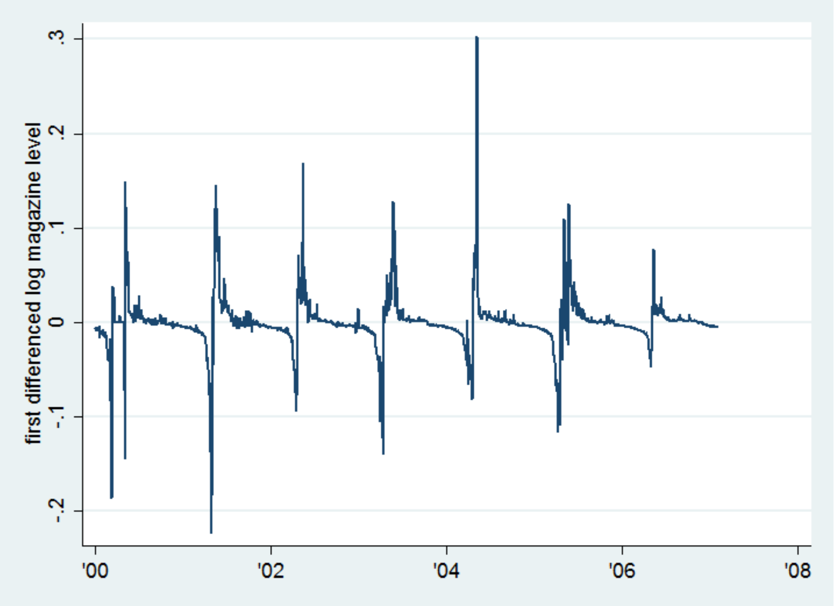

Figure 4. First difference of the level of magazine 130. The series is characterised by strong yearly seasonality caused by spring inflows.

represented as $\alpha_1, \alpha_2, \beta_1$, and β_2 provides adequate fit. The exogenous variable, wind power production, is represented by w_t and $\mathbf{X}$ represents a vector of other variables. s represents a dummy variable for the summer months of may through august. This is a very crude modelling of the seasonal nature of the data, but for my purposes it should be sufficient.[6]

$$\Delta l_{t,i} = \gamma w_t + \eta s + \zeta \mathbf{X} + \alpha_1 \Delta l_{t-1,i} + \alpha_2 \Delta l_{t-2,i} + \beta_1 \epsilon_{t-1} + \beta_2 \epsilon_{t-2} + \epsilon_t \tag{4}$$

In table 3 I show the results of the regression model on data from plant 130. I try several specifications of the model. In the first column, only the autoregressive and moving average terms and the summer dummy are included. In the second colum I add the wind power variable. The addition of wind power slightly increases the relative (to the number of coefficients) fit of the model, as indicated by the

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[6] A direct result of not modeling the seasonality is likely a relatively low R-squared. However, as long as the variation in wind is not significantly correlated with this seasonality it will not affect the validity of the results.

AIC. The estimated coefficient, is also of the expected sign. An increase in wind power is associated with relatively higher magazine levels. However, the estimated coefficient is not significantly different than zero at neither 5 percent level nor the 10 percent level.

In the third column, I show results from the regression where I add the log of consumption, which is shown to be significant and increases the fit of the model. In the fourth column I add variables for average temperature (across regions) and average rainfall. Surprisingly, they are not shown to be significant and *decrease* the fit of the model. In all specifications, the coefficient on wind power remains small and not significantly different from zero. The fact that the inclusion of wind power does increase the relative fit of the model may provide some evidence that there exists some relationship between wind power and changes in reservoir levels. The improvement in fit is however small, and it is at best weak evidence for any relationship.

table 3 here

In the appendix I report results of regressions run on the other 14 magazines. I again use an arma(2,2) specification and include terms for consumption and a dummy variable for the summer months. Without exception, no significant correlation between wind power generation on changes on magazine levels can be detected.

This test does not provide any evidence of a relationship between wind power and hydro power production. But neither does it provide strong evidence for an absence of any relationship. Changes in magazine levels are an imperfect measure of hydro power production. As noted, most of the variation in the series comes from seasonal factors dominated by spring and summer inflows. It may be that the small differences in magazine level caused by shifts in production are overwhelmed by these factors.

4.3. The Spot Market

The preliminaries have shown that wind power from Denmark affects the pattern of trade between Norway and Denmark in a non-symmetric manner. However, the last section fails to find any significant correlation between wind power production and hydro power production, as proxied by magazine levels. In the Nordic market both trade across borders and production are overwhelmingly scheduled by way of market mechanisms. The day ahead "spot" market is the largest of such markets for the physical trade of electricity. In this subsection, I look at the effect that wind power has on prices in the spot market in Denmark and Norway.

Of course, actual wind power does not directly affect prices in the day-ahead market because it can not be scheduled. Instead, it is forecasted wind power that producers bid on the market. The data that I have available is however actual realized wind power. However, assuming that the forecast errors are random, this shouldn't effect the consistency of the estimates.

Consider first the effect that wind power can have on prices in its own (spot) price area. Two theoretically distinct effects can be identified. The first can be called a supply effect, illustrated in panel a of figure 4.3, where wind power in effect shifts the entire aggregate supply curve to the right. This effect implies reduced prices along the entire supply curve. But given that the high-load side of the supply curve tends to be steeper than the low-load, the price effect can be expected to be more pronounced at peak load times.

The alternative way that wind power can affect prices is by way of its low marginal costs, illustrated in panel b of figure 4.3. Here, wind power can be seen as underbidding other forms of base-load generation. The general effect would be to

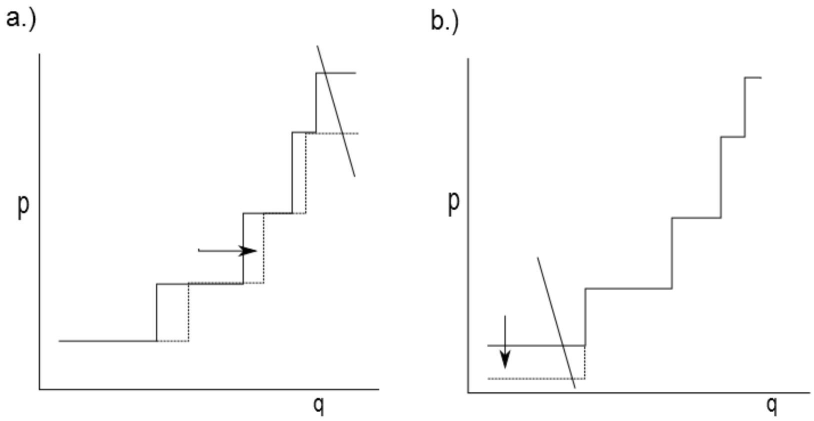

Figure 5. Panel a. shows the effect on prices of wind power shifting the supply curve. Panel b. shows the effect of wind power being able to underbid prices at the baseload level.

lower base load prices. Of course, in reality, both mechanisms are likely at play simultaneously. Empirical results suggest that the supply effect dominates and that wind power both reduces average prices and daily price variation (Mauritzen, 2010).

As discussed earlier, the Nordic market is made up of several price areas. When there is congestion in the transmission net between areas, prices are reduced in the area with excess production and increased in the area with excess demand until the expected flow of electricity meets the physical transfer capacity. These transmission constraints, as well as the ability of Norwegian hydropower producers to "store" energy, makes the likely effect on Norwegian prices to be significantly less pronounced than the effect on Danish prices.

I illustrate the idea in figure 4.3.

The prices in my empirical model are average daily prices, thus they also represent an average over different demand levels - represented in the chart by the curves D^a, D^b, and D^c. The curves are shown as being nearly vertical, reflecting the highly inelastic nature of demand for electricity in the short-run.

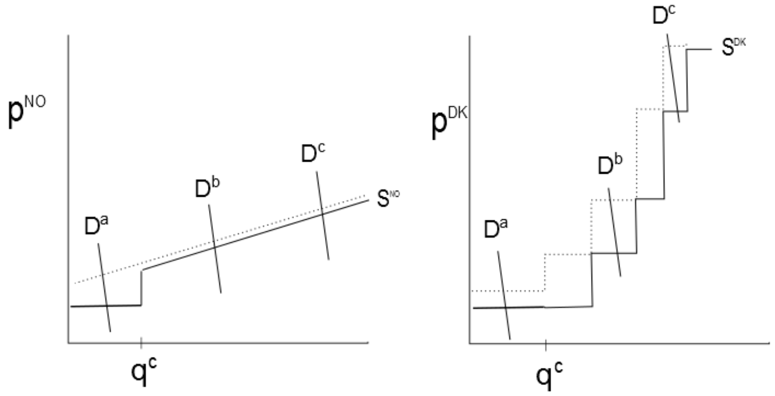

Figure 6. Compared to the effect on local Danish market (right panel), the effect on Norwegian prices is likely to be slight due to capacity constraints and the dominance of hydro power in Norway (left panel)

The left-hand side panel represents the effect that wind power has on prices in Norway. The dotted line represents the Norwegian supply curve without imports. It is depicted as being relatively flat, reflecting the elastic supply curve of a hydro power dominated system. In periods with heavy winds and net exports to Norway, the model shows wind power as the price setter as long as demand is below the transmission constraint, marked by q_c. If demand is higher than the transmission constraint, then it is the hydro power producers that are the price setters. Of course, demand would have to be exceptionally low for the imported (wind) power to be the price setter. Therefore, in practice, it will (almost) never be wind power that is the price-setter in the Norwegian market.

Wind power can still have an effect on prices, even if it is not the price setter - but only through an indirect supply effect. The marginal cost of hydro power is first and foremost dependent on the shadow value of water in the reservoirs. Hydro producers, having produced less during high wind periods, will have more water in their magazines. Increased water in the magazines means a loosening of their production constraints, and in turn the lowering of the shadow value of the water.

This in turn would lead to lower prices across their supply curve. The total average effect on prices will likely be slight however, as is depicted in the illustration.

By way of comparison, I again include an illustration of the expected effect on the local Danish market where wind power can expected to effect prices along the entire supply curve.

The first obvious testable implication from this rough model is that wind power will at best have only a slight negative effect on average prices in Norway compared to Denmark. Another testable implication is that there will be either no effect on daily price variation or a slightly positive effect. This is to due to that the effect on prices will likely be uniform across the supply curve in Norway. A possible exception is at times when the price is set by (imported) wind power. In contrast, the effect on daily price variation in Denmark, as demonstrated by , is to significantly *decrease* daily price variation (Mauritzen, 2010).

To estimate the effects that wind power has on prices, I use single equation distributed lag models where the dependent variables are prices in Denmark west, Denmark east, and southern Norway. The model is described in equation 5.

$$p_{t,a} = \gamma_x(w_t * x) + \gamma_i(w_t * i) + \zeta\mathbf{C_a} + \alpha\mathbf{P} + \epsilon_t \tag{5}$$

In this equation, all variables are again in logs. $p_{t,a}$ represents the average daily prices in area a. w_t is again wind power produced which is interacted with the dummy variables , x and i which represent whether there were net exports from Denmark to Norway or net exports from Norway to Denmark. $\mathbf{C_i}$ represents a vector of consumption variables - for eastern, western Denmark, and Norway. I include these to control for the possibility that wind power is correlated with, for example temperature, that in turn effects consumption and which in turn bias the coefficient. $\mathbf{P}$ represents a vector of autoregressive terms. ϵ_t represents the error term.

In the spot market, the area prices are determined simultaneously. Thus I also run a regression where I estimate the models simultaneously and allow for the error terms of each equation to be correlated with each other - a so called Seemingly Unrelated Regression (SURE) model (see Greene (2002)).

the results of the regression are displayed in table 4 below.

Wind, both during periods of net exports and imports, is shown to affect prices in Norway. But, as the simple model predicts, the magnitude of this affect is shown to be very small compared to the effect on the Danish price areas. Interpreting the coefficients as elasticities, a doubling of wind power will on average lead to on average a 8 percent reduction of prices in western Denmark, but only a .8 percent reduction in Norway in periods with net exports (to Norway) and .5 percent in periods with net imports (from Norway).

table 4 here

The results from running the SURE model are not radically different for the coefficients on wind power - suggesting an elasticity on Norwegian prices of -.9 percent for days of both net imports and exports. The coefficients on the consumption variables are not of direct importance. The variables were included to control for possible correlation between wind power and consumption. It is worth noting however how estimating the model by way of a SURE model radically changes these coefficients. Of course, prices and quantities are endogenous and this endogeneity bias in the consumption coefficients seems to be strengthened by allowing the error terms of the equations to be correlated with each other.

Electricity price series are known to not always be stationary (see Weron (2006)). In most of the specifications for the Dickey-Fuller tests, however, I am able to reject the null hypothesis of unit root(s). The exception is a test for the logged Norwegian price series with 13 lags. Here I can not reject the null at the 5 % level (MacKinnon approximate p-value is .08). Likewise a test for the Denmark East price series with 20 lags also fails to reject the null at a 5 % level.

As a robustness check to possible non-stationarity, I also run the regressions in first-difference format. I report the results of this regression in the appendix. It suffices to say that the estimated coefficients are nearly identical to the results of the line-by-line estimation in table 4.

I do a quick test of the implication on daily price variation as well by running a distributed lag model where the dependent variable is the standard deviation of the (24) hourly prices in the southern Norwegian price area. I report the result in table 6. The coefficient on log daily wind power can not be shown to be significantly different from zero, as the model suggests.

table 5 here

5. Discussion and Conclusion

The preliminaries in this article show that wind power in Denmark clearly and significantly affects the pattern of trade between Denmark and Norway - leading to an increase in exports. The magnitude of that effect is correlated with the net direction of trade. At the same time no correlation between wind power in Denmark and changes in Norwegian reservoir levels can be found.

The implications from my rough models of Danish wind power's effect on local versus Norwegian price is largely supported by the results from the econometric model. The conclusion is that while wind power does significantly alter the pattern of trade between Denmark and Norway, capacity constraints and presumably the storage effect of Norwegian hydro power plants mean that wind power has little effect on Norwegian spot prices or daily price variation.

Wind power should still, however, have some effect on hydro power production. The failure to detect any correlation between wind power and hydro power magazine can be seen to be puzzling. On the other hand, changes in magazine levels is only a proxy for production, and a rough one at that. The seasonal inflows dominate the variation in the series with daily production providing only a small residual of the variation. It is perhaps not that surprising that the relatively small changes in production due to wind power are difficult to detect in magazine level series.

This article also gives a hint of the challenges faced by the introduction of large scale wind, and other intermittent sources. Even with the large transfer capacities present between Norway and Denmark, significant congestion occurs. This congestion limits the extent to which hydro power and wind power can interact through the price mechanism. This has implications for investment and calculations of economic viability of large wind power investments as well as transmission investment.

This article has been mainly descriptive and exploratory. However, the results suggests several areas of more directed research. The use of magazine level data as a proxy for hydro power production leaves much to be desired. The variation in the series is dominated by seasonal inflow patterns - direct production data would be much preferred. With such data, one could with more precision see if any correlation exists between wind power and hydro power.

The article also notes a relationship between wind power production and trade between Norway and Denmark. This could also be extended to get a fuller picture of the effects on trade. Does wind power, for example, have a significant effect on trade between the other Nordic countries? Electricity transmission is a complex engineering problem and electricity does not flow in direct paths, but rather flows across all paths in a network. Looking at electricity trade between only Denmark and Norway then may be inadequate.

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Table 1: Selection of Hydro Power Magazines in Southern Norway

Plant ID	Plant Name	Mag. Size	# observations
012.130	Flvatn	204	2530
012.160	Ustevatn	210.7	2530
002.113	Aursunden	216	2922
012.128	Djup-Stolsvatn	219	2530
012.017	Dokkflayvatn	250	2530
002.138	Ossja	250.3	2922
002.164	Bygdin	335.8	2922
049.002	Svartevatn	398.9	2922
050.012	Sysenvatn	436.0	2922
012.006	Strandevatn	554	2530
016.197	Songavatn	639.4	2530
025.021	Roskreppfjord	684.1	2530
016.018	Masvatn	1064	2922
026.028	Svartevatn	1398.4	2530
021.056	Storvatn	1493	2922

Table 2: Effect of Wind Power on Exports

	a	b	c
wind	0.269	0.276	n/a
	[0.009]	[0.010]	
win-ex	n/a	n/a	0.322
			[0.010]
wind-im	n/a	n/a	.111
			[0.012]
consum	n/a	-1.869	n/a
		[0.515]	
norTemp	n/a	-0.302	n/a
		[0.061]	
constant	-5.463	2.824	-4.832
	[2.432]	[3.121]	[2.189]
ar			
1	0.312	0.372	0.346
2	-0.193	-0.298	-0.243
3	0.192	0.281	0.237
6	0.160	0.179	0.164
7	0.469	0.410	0.435
ma			
1	0.280	0.208	0.238
2	0.320	0.425	0.363
3	-0.009	-0.066	-0.055
AIC	17715.3	17656.6	17363.1

Standard errors in parenthesis

2867 Observations

Table 3: Effect of Wind on Change in Magazine Level 130

	a	b	c	d
ln-wind	n/a	1.65E-04	2.12E-04	3.64E-05
		[2.59E-04]	[2.26E-04]	[2.49E-04]
ln-consum	n/a	n/a	0.017	-1.87E-03
			[0.009]	[1.32E-03]
ln-temp	n/a	n/a	n/a	1.46E-04
				[5.99E-04]
ln-averRain	n/a	n/a	n/a	7.35E-05
				[1.38E-04]
summer	0.0174	0.017	-2.28E-03	0.019
	[0.00896]	[0.009]	[1.27E-03]	[0.010]
ar				
1	0.823	0.823	0.819	0.828
2	0.053	0.056	0.053	0.038
ma				
1	0.134	0.148	0.151	0.181
2	0.045	0.026	0.028	0.238
AIC	-14517.15	-14524.77	-14526.65	-12062.91

Standard errors in square brackets

2530 Observations

Table 4: Effect of Wind on Prices

	Sin. Eq.			SURE		
	dkw	dke	nor	dkw	dke	nor
ln-wind-ex	-0.081	-0.031	-0.008	-0.068	-0.030	-0.009
	[0.005]	[0.004]	[0.001]	[0.004]	[0.003]	[0.002]
ln-wind-im	-0.077	-0.028	-0.005	-0.066	-0.029	-0.009
	[0.006]	[0.004]	[0.002]	[0.004]	[0.003]	[0.002]
ln-DKWCons	0.850	0.614	0.023	1.088	0.735	0.278
	[0.147]	[0.179]	[0.011]	[0.080]	[0.059]	[0.034]
ln-DKECons	0.251	0.371	0.086	-0.594	-0.300	-0.165
	[0.213]	[0.122]	[0.077]	[0.111]	[0.082]	[0.050]
ln-NOCons	0.037	0.028	0.319	0.000	-0.019	0.010
	[0.021]	[0.018]	[0.111]	[0.016]	[0.013]	[0.008]
cons	-4.397	-3.780	0.334	-3.004	-2.925	-0.791
	[0.591]	[0.497]	[0.304]	[0.392]	[0.298]	[0.179]
ar						
1	0.312	0.571	0.940	0.330	0.487	0.851
2	0.165	0.036	-0.130	0.080	0.026	-0.112
3	0.089	0.120	0.106	0.105	0.103	0.122
6	0.082	0.069	0.015	0.066	0.082	0.039
7	0.181	0.117	0.071	0.153	0.149	0.069
14	0.125	0.062	-0.013	0.138	0.073	0.007

Standard errors in square brackets

2641 Observations

Table 5: Effect of Wind on Prices, first-difference

	dwt	det	nor
ln-wind-ex	-0.080	-0.030	-0.008
	[0.005]	[0.004]	[0.001]
ln-wind-im	-0.077	-0.027	-0.005
	[0.006]	[0.004]	[0.001]
ln-DKWCons	0.813	0.453	0.022
	[0.136]	[0.176]	[0.010]
ln-DKECons	0.293	0.449	0.082
	[0.208]	[0.120]	[0.076]
ln-NOCons	0.042	0.025	0.327
	[0.021]	[0.018]	[0.109]
cons	0.000	0.000	0.000
	[0.002]	[0.002]	[0.001]
ar			
1	-0.584	-0.360	-0.026
2	-0.354	-0.285	-0.154
3	-0.207	-0.160	-0.020
6	-0.043	-0.013	-0.042
7	0.052	0.119	0.049
14	0.065	0.057	0.112

Standard errors in parenthesis
2625 Observations

Table 6: Effect of Wind on Norwegian Price Variation

ln-windProd	-0.003
	[0.010]
Intercept	0.324
	[0.109]
ar	
1	0.517
2	0.024
3	0.080
4	0.016
7	0.093
ma	
6	0.074
7	0.156
14	0.142

Standard errors in square brackets

2641 Observations

Table 7: Effect of Wind and Price on Change in Magazine Levels

Plant ID	ln-wind	summer	ln-consum
ln-level130	2.12E-04	1.75E-02	-2.28E-03
	[2.26E-04]	[8.90E-03]	[1.27E-03]
ln-level160	-3.11E-04	2.75E-02	-2.77E-03
	[2.87E-04]	[8.15E-03]	[1.33E-03]
ln-level113	-4.08E-05	5.20E-03	-2.08E-04
	[1.09E-04]	[3.27E-03]	[4.71E-04]
ln-level128	1.01E-04	2.98E-03	-7.66E-04
	[1.43E-04]	[2.99E-03]	[8.21E-04]
ln-level17	-5.30E-04	1.25E-02	-2.81E-03
	[5.41E-04]	[1.86E-03]	[1.56E-03]
ln-level138	-1.74E-04	2.42E-03	-1.04E-03
	[1.79E-04]	[2.30E-03]	[7.53E-04]
ln-level164	1.78E-04	6.16E-03	4.01E-04
	[1.79E-04]	[1.63E-03]	[1.00E-03]
ln-level2	-1.77E-04	5.76E-03	-2.01E-03
	[5.77E-04]	[2.57E-03]	[9.05E-04]
ln-level12	3.89E-04	1.35E-02	-4.30E-03
	[3.61E-04]	[2.47E-03]	[1.40E-03]
ln-level6	1.53E-04	7.16E-03	-2.17E-03
	[2.39E-04]	[6.92E-03]	[1.48E-03]
ln-level197	1.41E-04	5.97E-03	-1.63E-03
	[2.15E-04]	[2.89E-03]	[9.99E-04]
ln-level21	6.56E-05	5.39E-03	-2.63E-03
	[2.15E-04]	[2.51E-03]	[5.38E-04]
ln-level18	-8.92E-05	5.89E-03	-3.12E-04
	[1.30E-04]	[3.46E-03]	[6.05E-04]
ln-level28	3.12E-04	9.28E-04	-2.06E-03
	[1.32E-04]	[2.20E-03]	[5.13E-04]
ln-level56	1.22E-04	2.84E-03	-7.81E-04
	[6.90E-05]	[1.18E-03]	[3.39E-04]

Standard errors in square brackets

Table 8: Effect of Wind on Prices, first-difference

	dwt	det	nor
ln-wind-ex	-0.080	-0.030	-0.008
	[0.005]	[0.004]	[0.001]
ln-wind-im	-0.077	-0.027	-0.005
	[0.006]	[0.004]	[0.001]
ln-DKWCons	0.813	0.453	0.022
	[0.136]	[0.176]	[0.010]
ln-DKECons	0.293	0.449	0.082
	[0.208]	[0.120]	[0.076]
ln-NOCons	0.042	0.025	0.327
	[0.021]	[0.018]	[0.109]
cons	0.000	0.000	0.000
	[0.002]	[0.002]	[0.001]
ar			
1	-0.584	-0.360	-0.026
2	-0.354	-0.285	-0.154
3	-0.207	-0.160	-0.020
6	-0.043	-0.013	-0.042
7	0.052	0.119	0.049
14	0.065	0.057	0.112

Standard errors in parenthesis
2625 Observations