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

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It is well established within both the economics and power system engineering literature that hydropower can act as a complement to large amounts of intermittent energy. In particular hydropower can act as a "battery" where large amounts of wind power are installed. In this paper I use simple distributed lag models with data from Denmark and Norway. I find that increased wind power in Denmark causes increased marginal exports to Norway and that this effect is larger during periods of net exports when it is difficult to displace local production. Increased wind power can also be shown to slightly reduce prices in southern Norway in the short-run. Finally, I estimate that as much as 40 percent of wind power produced in Denmark is stored in Norwegian hydropower magazines.

Keywords: Wind Power, Hydropower, Nordic Electricity Market, Empirical, Time Series

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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 (International Energy Agency, 2009). 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 hydropower plants with magazines which are able to quickly and cheaply adjust their production

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while storing energy in the form of water in their magazines. Norway with its large amounts of hydropower has been referred to as the "battery" (The Economist, 2006) of Europe, especially as several large off-shore wind power projects are being proposed off Great Britain, Ireland and other areas of northern Europe (see Forewind (2011) or NOWAI (2010)).

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. As of 2011, wind power makes up about 25% of rated generation capacity in Denmark, though its share of actual electricity produced is approximately 20% due to the intermittancy of wind. The remainder of capacity in Denmark comes nearly exclusively from thermal plants powered by coal, natural gas, and increasingly waste and biomass. Notably combined heat and power plants, which produce both electricity and district heating made up more than 60% of all thermal production in 2010 (Danish Energy Agency (ENS), 2010).

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 between Norway and for example the planned wind farms in Dogger Bank in the North Sea.

Wind and hydropower'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) explore the amount of added hydropower that would be needed to serve as an adequate backup to a proposed large wind power installation in Quebec. Benitez et al. (2008) uses an optimization model with parameters estimated with data from Alberta, Canada. Studies of the Nordic market also exist. Førsund and Hjalmarsson (2010) analyze the effect that a build-out of wind power in the Nordic market would have on the price of providing regulation power—primarily hydropower. Matevosyan et al. (2007) study the potential for wind power and hydropower interaction in Sweden.

Designing a market to ensure the correct signals for development and operation of intermittent energy is also an emerging area of research. Newbery (2010) gives a short overview. But at a basic level, the spot market should give the correct price signals for an interaction between wind power and hydropower. Periods with strong winds are likely to press down prices, providing an incentive for hydropower 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 uphill into the magazines). When wind power production is low, prices are likely to increase, providing an incentive for hydropower producers to then increase production.

But when considering the interaction of wind power and hydropower that is geographically separated, transmission constraints play a significant role. My starting point is Green and Vasilakos (2012), who lay out a model of wind power production and power trade with two areas: one dominated by hydropower while the other, representing Denmark, has both wind and thermal capacity. The model explicitly accounts for transmission constraints and leads to several testable implications:

- Wind power production should optimally lead to increased export to the hydropower area.
- Short term variations in wind power affect local prices and these effects are magnified when there is transmission congestion.

In addition to laying out a theoretical model, the authors take a descriptive look at price and trade data between Denmark and its neighbors and carry out regressions of the short-run effect on local prices of wind power production. The authors note a high short-run correlation between wind power and exports. At a daily level they note that Denmark exports at off-peak times and argue that this is evidence for the "storage" of Danish electricity in the hydropower magazines of neighboring countries. In their regressions they confirm that wind power is associated with a reduction in prices in the local price area and this price effect is magnified when there is transmission congestion.

My methods and results are largely complementary. However I diverge in several key respects. Instead of a static regression model, I use a simple dynamic distributed lag model where wind power is used as an exogenous regressor. With this model I use the strong autocorrelation 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. By explicitly accounting for autocorrelation, using daily-average prices and given the exogenous nature of wind power, I claim that my coefficients can be given a causal interpretation.

I also narrow my focus to the interaction between Denmark and Norway, rather than looking at the effects of trade to all of Denmark's neighbors. I focus on Norway at the exclusion of the rest of the Nordic market and other European connections because nearly all of Norwegian energy production comes from hydro production, most of which in turn comes from plants that have storage magazines.

Where Green and Vasilakos show that wind power's effect on local prices differs when there is transmission congestion, I take the approach of comparing days of net exports and imports from Denmark. The rationale is that days of net exports are more likely to be times of surplus energy supply in Denmark and that extra wind power will not easily replace domestic supply. Extra wind power is not likely to curtail production from combined heat and power plants during cold winter days for example. It is during these times that the battery effect can be expected to be strongest. Marginal wind power production is more likely to lead to increased exports to be stored in Norwegian reservoirs.

I find that in periods of net exports a marginal increase of 1 megawatt-hour per hour (MWh/h) of wind power leads to approximately 0.6 MWh/h higher exports to Norway. However, in days with net imports to Denmark from Norway, the marginal effect of an extra 1 MWh/h of wind power production is only to reduce net imports by about 0.3 MWh/h. These estimates include electricity flows that pass through Sweden. A striking result of the analysis is that most of the marginal exports of electricity to Sweden due to Danish wind power will be re-exported to Norway. The predominance of relatively inflexible nuclear power in southern Sweden is likely the reason for this result.

I also estimate the elasticity of both local Danish prices and Norwegian prices to wind power production. I estimate that a doubling of wind power production on average leads to a 5.5% decrease of prices in western Denmark and a 2% decrease in eastern Denmark. Surprisingly this effect cannot be shown to differ significantly between days when there are net exports and net imports. The short-run effect that wind power has on Norwegian prices is significantly smaller but is shown to differ depending on the net direction of trade. A doubling of wind power will tend to reduce prices by 0.5% in southern Norway on days with net exports from Denmark but only by 0.3% on days with net imports to Denmark.

Finally, I estimate that a 1 MWh/h increase in Danish wind power is associated with a decrease of approximately 0.4 MWh/h of hydropower production in Norway. When discerning between periods of net exports to Norway and net imports to Denmark the respective estimates are −0.46 and −0.16 MWh/h.

2. DATA AND METHODOLOGY

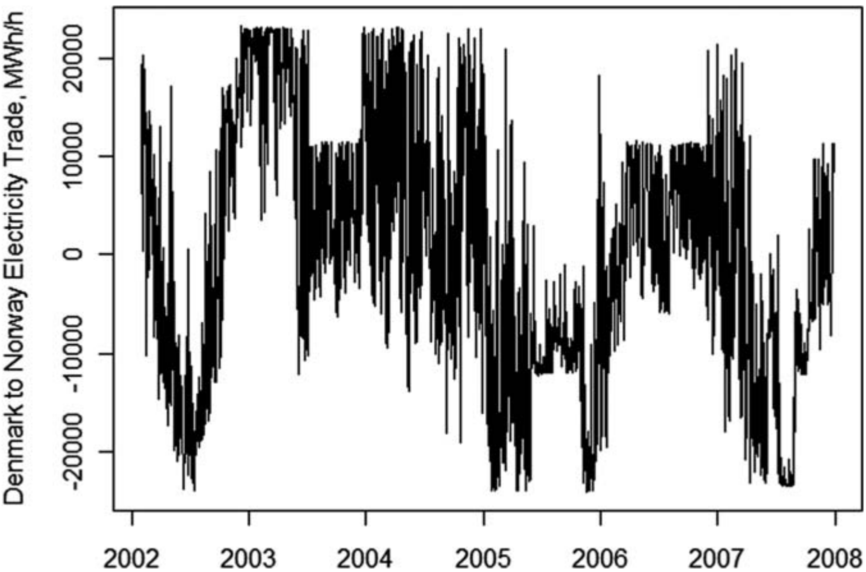
Data was assembled from several sources. Hourly price data as well as data on Norwegian hydropower production and electricity trade was obtained from Nord Pool (Foyn, 2009). Data on daily wind energy production from both eastern and western Denmark was obtained from the website of the Danish transmission system operator, Energinet (wwww.energinet.dk).

The data can be assumed to be of high quality and with six years of daily data, the econometrics becomes easier as I can rely on asymptotics to obtain consistent and unbiased coefficient estimators and standard errors. In particular, Newey-West standard errors will converge asymptotically to the correct standard errors in the presence of heteroskedasticity and autocorrelation (Newey and West, 1987).

Figure 1 shows the time series of direct trade between Denmark and Norway.

The figure clearly 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—seen as the sharp ceilings and floors in the figure. The figure does not include electricity trade between Denmark and

Figure 1: Direct Electricity Trade from Denmark to Norway



Norway that flows through Sweden, though that is accounted for in the analysis in section 3.1.

The general form of the distributed lag models I use throughout are as equation (1).

$$d_t = \sigma wind_t + \delta \boldsymbol{X_t} + \alpha_1 d_{t-1} + \alpha_2 d_{t-2} + \beta_1 \epsilon_{t-1} + \beta_2 \epsilon_{t-2} + \epsilon_t \qquad (1)$$

Here d_t represents the dependent variable being modeled—trade, prices or Norwegian production—and $wind_t$ represents the daily amount of wind power produced in Denmark. $\boldsymbol{X_t}$ is a vector of other variables, described below. These are often not 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 above model I arbitrarily include autoregressive (ar) 1 and 2 terms (d_{t-1}..) and moving average (ma) 1 and 2 terms (ϵ_{t-1}..) solely for the purpose of illustration.

The actual specifications I use in the regressions are arrived at by a process of using Wald tests, charts of autocorrelation and partial autocorrelation functions as well as comparisons 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. In practice several different specifications 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.

Vector Autoregressive (VAR) models are increasingly being used in the context of power markets (see for example Fell (2010)), especially when analyzing 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. Such single equation models may give biased results if wind power is not truly exogenous to the price and trade variables. I will discuss areas of possible endogeneity, but in the end argue that for measuring short-run effects the estimated coefficients can be interpreted as causal.

Wind power will be exogenous in the sense that production is likely not sensitive to price. Wind power is produced when it is windy and a negligible marginal cost of production means that producers have little incentive to reduce production even at times of very low price.

Two possible exceptions to the exogeneity of wind to prices should at least be mentioned. First, the system operator may order some wind off-line due to balancing concerns which might also be reflected in price. This is likely a minor factor. Nord Pool runs separate balancing markets and frequency regulation. Prices in the Denmark area do occasionally drop to zero, an effective price floor in the Nord Pool market in the period studied, but this is a relatively rare occurrence and is unlikely to affect the estimation.

The second possible concern is the exercise of market power. A large producer with a range of generation technologies including substantial wind power may have an incentive to reduce wind power in order to benefit from higher overall prices. Despite a high market concentration of generation in Denmark, most studies of the Danish and Nordic market have failed to detect evidence of market power (see for example Amundsen and Bergman (2006) and Hjalmarsson (2000)).

Another consideration is the possibility that wind power is correlated with variations in the consumption of electricity. The estimated coefficient on wind power may then be biased. I try to control for such effects. Seasonal effects—a tendency for there to be more wind power during the winter for example—is controlled for implicitly through the distributed lag terms in the model. With the inclusion of such dynamic terms the coefficient on wind power is only being estimated based on variations between days.

At a shorter time scale, averaged electricity prices and wind power tend to have a regular pattern of variation over a day. This could also lead to bias if using hourly data. I however use average daily data, so this will not be an issue. Still, consumption can change from day to day in ways which may still correlate with wind power. For example days with high amounts of wind could be correlated with generally poor weather, leading people to stay inside and use more electricity. I therefore include measures of consumption in the regressions, but they do not significantly affect the estimated coefficient on wind power.

When regressing prices, I log-transform the variables. This is primarily in order to give the coefficients a clear interpretation in terms of an elasticity. However, doing a log-transformation also implicitly assumes a constant-elasticity relationship between wind power and prices. This is unlikely to be fully true in reality. However it is likely a better approximation than assuming a linear relationship, which is implicitly what one does when not transforming in logarithms. Work by Weigt and Hirschhausen (2008) and Twomey and Neuhoff (2010) suggest that wind power has a greater-in-magnitude effect on prices at high load times. Thus the estimation of a logarithmic average is likely to be a better approximation than a simple linear approximation.

3. RESULTS

3.1 Effect of Wind Power on Trade

In this subsection I use distributed lag models with wind power as the exogenous regressor to explore the relationship between wind power and electricity trade between Denmark and Norway. The model is in the form of equation (2).

$$I_t = \gamma wind_t + \delta \boldsymbol{X_t} + \alpha \boldsymbol{I_{t-i}} + \epsilon_t \tag{2}$$

I_t represents net electricity trade flows from Denmark to Norway for every day t, in megawatt-hours per hour (MWh/h). A positive value means a net export to Norway and a negative value means a net import to Denmark.

$wind_t$ represents the amount of wind power produced in MWh/h that day from Danish wind turbines. $\boldsymbol{X_t}$ represents a vector of other exogenous regressors that are included in the regression. $\boldsymbol{I_{t-i}}$ represents the vector of autoregressive terms while ϵ_t represents the error term.

The results for the regression are displayed in Table 1.

Looking at the first column, the coefficient on the wind power term, labeled *wind*, is about 0.26 and is estimated with a relatively small standard error of 0.008. Since both the wind power term and the power trade term are in MWh/h units, one can interpret this to mean that for every MWh/h of wind power produced, 0.26 MWh/h more electricity is exported to Norway. This result is in line with both the predictions from Green and Vasilakos' model and their own empirical work. Periods with high amounts of wind power lead to increased marginal trade to the hydropower area.

However the estimate of 0.26 likely underestimates the total marginal trade to Norway caused by wind power. Electricity flowing through an alternating current (AC) transmission network cannot be directed and will flow in all available directions. Thus, electricity produced in Denmark and initially exported to Sweden may be consumed or stored in Norway. In columns II, III and IV I estimate the marginal trade to both Norway and Sweden from Denmark caused by wind power. In columns V and VI I in turn estimate the marginal imports to Norway from both Sweden and Denmark.

In the second column, the coefficient on the wind term is estimated to be about 0.6. This then can be interpreted to mean that for every MWh/h of wind

Table 1: Effect of Wind Power on Trade

	DK to NO	DK to NO and SE			DK and SE to NO	
	I	II	III	IV	V	VI
wind	0.26	0.60	0.63	n/a	0.54	n/a
	(0.008)	(0.02)	(0.02)		(0.02)	
wind-ex	n/a	n/a	n/a	0.69	n/a	0.62
				(0.02)		(0.02)
wind-im	n/a	n/a	n/a	0.44	n/a	0.29
				(0.02)		(0.03)
nor-consum	n/a	n/a	0.14	0.14	0.20	0.18
			(0.02)	(0.02)	(0.02)	(0.03)
dk-consum	n/a	n/a	−0.96	−0.91	−1.47	−1.42
			(0.04)	(0.04)	(0.06)	(0.06)
intercept	−4,602	−10,587	35,563	31,300	189,405	183,239
	(1,581)	(4,192)	(7,210)	(6,499)	(6,829)	(10,977)
ar						
1	0.58	0.61	0.61	0.62	0.77	0.76
2	0.001	0.05	0.07	0.07	−0.03	−0.02
3	0.04	0.05	0.08	0.07	0.08	0.06
4	0.05	0.01	0.05	0.06	−0.01	0.01
5	0.06	0.03	0.03	0.02	0.06	0.04
6	0.06	0.06	0.09	0.09	0.09	0.09
7	0.36	0.35	0.20	0.21	0.19	0.20
14	0.33	0.36	0.22	0.22	0.19	0.20
AIC	n/a	46,352	45,966	45,820	47,167	47,343

Standard errors in parenthesis.
2,867 observations.
AIC scores should only be compared between regressions of the same left-hand-side variable.

power produced, 0.6 MWh/h is exported to Norway or Sweden. In the third column I add terms for Norwegian consumption, labeled *nor-consum*, and Danish consumption, *dk-consum*. Smaller AIC scores indicate that the addition of these terms improves the fit of the regressions 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. The coefficients on the consumption terms should not be given a strict causal interpretation since consumption is endogenous with electricity trade. The consumption terms were included in this regression only to control for any possible correlation with the wind power term.

In column V the coefficient on the wind power term can be interpreted to mean that a 1 MWh/h marginal increase in Danish wind power leads to 0.54 MWh/h of extra imports to Norway from Denmark and Sweden. This is only slightly less than the estimated net exports to Norway and Sweden caused by wind power.

The discussion around the battery effect suggests that the net direction of trade should be important. In columns IV and VI I estimate the effect of wind power on marginal trade differentiated by days of net import and net export from Denmark. I interact the wind power term with an indicator variable (values of 0 and 1) for net exports from Denmark, *wind-ex*, and net imports to Denmark, *wind-im*. Column IV indicates that when there is a net export of electricity an extra 1 MWh/h of wind power leads to about 0.69 MWh/h of extra exports to Norway and Sweden. On the other hand, when there are net imports to Denmark in a day, 1 MWh/h of wind power leads only to 0.44 MWh/h less of net imports. Column VI in turn indicates that a marginal 1 MWh/h of wind power leads to 0.63 and 0.29 MWh/h of extra marginal trade to Norway from Denmark and Sweden during periods of net exports and net imports.

These results are in line with the idea that Denmark will export when it is difficult for wind power to supplant other local production. Periods of net import are likely peak periods where demand is partially met by gas turbines which can be easily turned off when extra wind power is produced. Periods of net export are more likely to be periods of base load production—primarily combined heat and power plants—which need to continue running in order to produce heat. Extra wind power production in these periods then leads to increased exports to the hydropower area.

The estimated coefficients on the Danish wind power term may have a slight upward bias in columns V and VI if Danish wind power is correlated with Swedish wind power. Unfortunately, I do not have a breakdown of Swedish production by source, so I can not directly check for this. However in my sampling period of between 2002 and 2008, Sweden had relatively little wind power. In 2002 it produced only 1/8 as much wind power as Denmark while it produced a little more than 1/5 as much as Denmark in 2007 (Energimyndigheten, 2012).

The striking aspect of these estimates is that the marginal trade from Denmark to Norway and Sweden caused by wind power is only slightly higher than the estimated trade to Norway from Sweden and Denmark. This is especially true during periods of net export from Denmark. The implication of this is that most of the marginal electricity trade to Sweden caused by Danish wind power is re-exported to Norway. The likely explanation has to do with the geographic distribution of Swedish power production. Somewhat less than half of all Swedish electricity production comes from hydropower, but this is overwhelmingly located in the more mountainous north of the country. Relatively inflexible nuclear power makes up most of the generation in southern Sweden. Furthermore, the north-south transmission net is often congested.

3.2. The Spot Market

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. Green and Vasilakos note that wind power presses down spot prices in Denmark and more so at times of congestion in the transmission net. Just as important is the effect that wind power has on prices in the hydropower market. In this subsection I estimate the short-run elasticity of wind power on prices in both Denmark and Norway.

Of course actual wind power does not directly affect prices in the day-ahead market because it cannot be scheduled. Instead it is forecasted wind power that producers bid on the market. The data that I have available is however realized wind power. A correct interpretation of the results I obtain then would be of the effect on spot market prices by forecasted wind power as approximated by actual wind power produced. If you interpret the variable of interest as expected wind power then the use of actual wind power inserts a measurement error component into the regression. Random measurement error can be shown to bias the estimated coefficient towards zero (Greene, 2002, p. 83). Rud (2009, Essay 5) has however pointed out that when a producer has access to both a real-time and day-ahead market they may have the incentive to underbid their expected level of production. This could lead to a systematic error term.

I do not see any good way to avoid this potential bias, but nor do I see it as being a major problem. The included variable of actual wind power produced is itself likely accurately measured and reported. Day-ahead forecasting of wind power production, while far from perfect, has improved substantially (Costa et al., 2008). Moreover, if a widespread and systematic underbidding occurred in the market it would likely be easily detectable and corrected by Nord Pool or the transmission system operator.

Consider first the effect that wind power can have on prices in its own (spot) price area, illustrated in Figure 2.

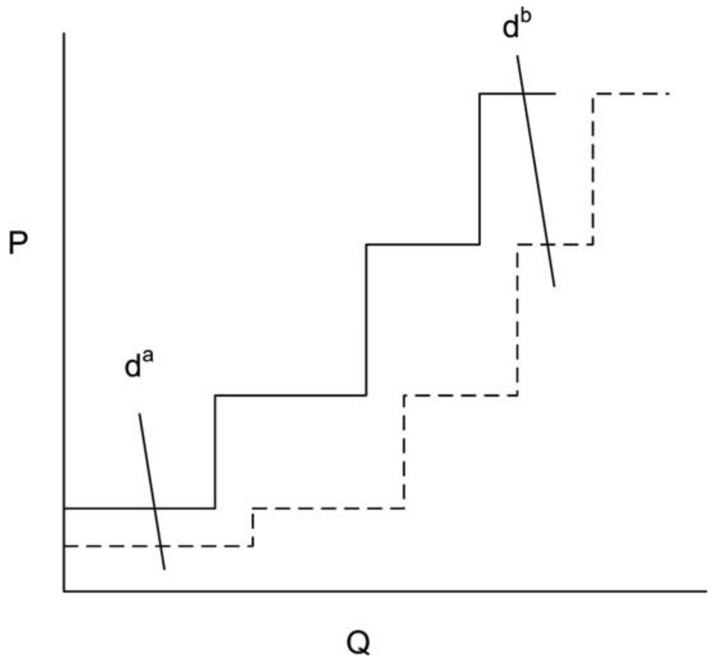
Wind power can be depicted as shifting the entire supply curve to the right. This implies reduced prices along the entire supply curve. But given that the high-load side of the supply curve tends to be steeper than the low-load, the price effect can be expected to be more pronounced at high-load times. Results from Mauritzen (2010) suggest that wind power both reduces average prices and daily price variation. By way of its low marginal costs, wind power can also reduce base-load prices at low demand times where it becomes the marginal producer, represented in the figure by the demand curve labeled d^a.

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 short-run effect on Norwegian prices to be significantly less pronounced than the effect on Danish prices.

I illustrate the idea in Figure 3.

The prices in my empirical model are average daily prices and thus they represent an average over different demand levels within a day, represented in the chart by the curves d^a, d^b and d^c. The curves are shown as being nearly

Figure 2: The Effect of Wind Power on Local Prices

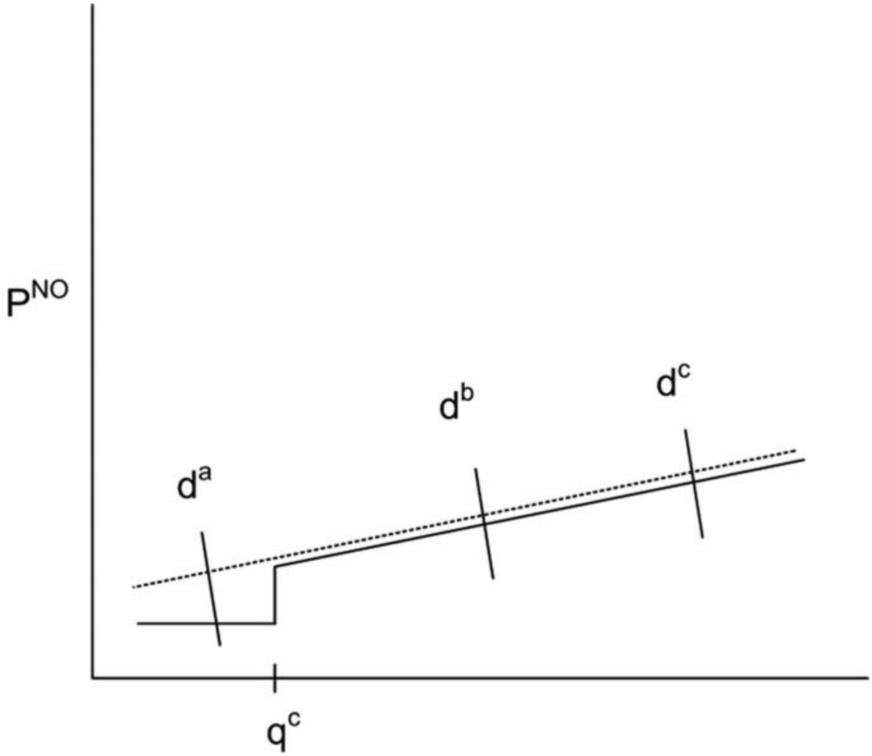


vertical, reflecting the highly inelastic nature of demand for electricity in the short-run.

The dotted line represents the Norwegian supply curve without imports. It is depicted as being relatively flat, reflecting the elastic supply curve of a hydropower dominated system. In periods with heavy winds and net exports to Norway, the model shows imported electricity 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 hydropower that is the price setter. 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 hydropower 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.

Figure 3: The Effect of Wind Power on the Export Hydropower Market



The illustration is of course an extreme oversimplification. Optimal hydropower scheduling is in itself a complex multi-period problem. But the illustration gets across the basic idea that an extra inflow of electricity into Norway from excess wind power produced in Denmark can be expected to decrease prices by relaxing the hydropower producers supply constraints. As Green and Vasilakos point out, the transmission constraints will tend to magnify the price effect on local Danish prices. The flip side is that transmission constraints will minimize the effect on Norwegian prices.

Another testable implication is that there will be either no effect on daily price variation in Norway or a slightly positive effect. This is because the effect on prices will likely be uniform across the supply curve. 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 is to significantly *decrease* daily price variation (Mauritzen, 2010).

To estimate the effects that wind power has on prices, I again use single equation distributed lag models where the dependent variables are prices in Den-

Table 2: Effect of Wind Power on Danish and Norwegian Prices

	Single Equation			SURE		
	I **dkw**	**II** **dke**	**III** **nor**	**IV** **dkw**	**V** **dke**	**VI** **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)
intercept	−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 parenthesis.
2,841 observations.

mark west, Denmark east, and southern Norway. The model is described in equation (3), below.

$$p_{t,a} = \gamma_x(wind_t * x_t) + \gamma_i(wind_t * i_t) + \zeta \boldsymbol{C_t} + \alpha \boldsymbol{P_{t-i}} + \epsilon_t \qquad (3)$$

In this equation, all variables are again in logs. $p_{t,a}$ represents the average daily prices in area a. $wind_t$ is again wind power produced. The wind power term is interacted with the dummy variables x_t and i_t which represent whether there were net exports from or net imports to Denmark in that day. $\boldsymbol{C_t}$ represents a vector of consumption variables for eastern and western Denmark and Norway. I include these to control for the possibility that wind power is correlated with daily changes in consumption, which in turn could bias the coefficient. $\boldsymbol{P_{t-i}}$ 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, p. 360)).

The results of the regression are displayed in Table 2.

Wind is shown to affect prices in Norway during periods of both net exports and imports. But the magnitude of this effect is 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 a 5% reduction of prices in western Denmark ($2^{-0.08} \approx 0.95$), but only a 0.5% reduction in Norway in periods with net exports from Denmark and 0.3% in periods with net imports to Denmark. A test for the equality of these two coefficients though fails to reject the null hypothesis of equal coefficients at the 5% level.

The results from running the SURE model are not radically different; however the point estimate of the effect of wind power on Norwegian prices is estimated to be the same in periods of net exports and net imports.

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 cannot reject the null at the 5% level (MacKinnon approximate p-value is 0.08). Likewise a test for the Denmark east price series with 20 lags also fails to reject the null at a 5% level.

Although a truly stationary price series might be expected to reject this null hypothesis at the 5% level once in twenty tests, 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 Table 5 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 2.

One important point is that the estimated effects above are averaged over times where transmission is both constrained and unconstrained. In a simplified sense, during hours with no transmission congestion, the prices in the Danish areas and Norwegian areas should be equal and therefore the price effect of wind power on the price areas should be equal. The reality is quite a bit more complicated as the area prices are determined based on the congestion and power flows between all the areas in the Nordic system and not just the bilateral congestion. More so, using daily data it is not possible to finely define constrained periods from unconstrained since there is substantial variation of power flows and congestion within the day.

Following Green and Vasilakos, I use price differences between areas as a rough proxy for congestion. As predicted, the effect of wind power on Danish prices during days of net export to Norway is smaller in magnitude when there is less congestion. But I fail to find a difference in the effect on Norwegian prices.

Finally, I do a 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 3. The coefficient on log daily wind power cannot be shown to be significantly different from zero, as was suggested.

3.3. Production

The most direct implication of the idea of the battery effect is that changes in wind power production in Denmark should lead to changes in pro-

Table 3: Effect of Wind Power on Norwegian Price Variation

	NO 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 parenthesis.
2,641 observations.

duction in Norwegian hydropower. In particular, periods of high wind power production in Denmark should supplant hydropower production in Norway, in effect storing the energy in the form of extra water in Norwegian magazines. In this subsection I estimate that as much as 40 percent of Danish wind power produced is "stored" in Norwegian hydropower.

I again use a distributed lag model with the general form of equation (4) below.

$$\Delta NOProd_t = \gamma_1 \Delta wind_t + \gamma_2 \Delta wind_{t-1} + \sigma \boldsymbol{\Delta X_t} + \alpha \boldsymbol{\Delta NOProd_{t-i}} + \beta \boldsymbol{\epsilon_{t-i}} + \epsilon_t \quad (4)$$

Here $\Delta NOProd_t$ represents the first-difference of total production in Norway per day. Since nearly 99 percent of production in Norway comes from hydropower, this can be considered a good proxy for total production of hydropower in Norway. $\Delta wind_t$ represents the first-difference of the contemporaneous amount of wind power produced in a day and $\Delta wind_{t-1}$ is a lagged term. $\boldsymbol{X_t}$ represents a vector of other explanatory variables. $\boldsymbol{\Delta NOProd_{t-i}}$ represents a vector of autoregressive terms while $\boldsymbol{\epsilon_{t-i}}$ represents a vector of moving average terms. ϵ_t represents the contemporaneous error term. γ_i, σ, α and β represent coefficients or vectors of coefficients to be estimated.

Norwegian production is highly seasonal. Household heating in Norway relies heavily on electricity, and production along with demand rise substantially during the winter. This strong seasonality makes it unlikely that the series is stationary and this is confirmed by running a Dickey-Fuller test. The first-differ-

Table 4: Effect of Wind Power on Norwegian Production

	I	II	III	IV
$wind_t$	−0.39	−0.48	−0.38	n/a
	(0.05)	(0.03)	(0.02)	n/a
$wind_{t-1}$	0.11	0.059	0.01	0.02
	(0.05)	(0.03)	(0.02)	(0.02)
wind-ex	n/a	n/a	n/a	−0.46
	n/a	n/a	n/a	(0.02)
wind-im	n/a	n/a	n/a	−0.16
	n/a	n/a	n/a	(0.03)
NOCons	n/a	n/a	1.08	0.98
	n/a	n/a	(0.03)	(0.03)
NOTemp	n/a	n/a	467	177
	n/a	n/a	(180)	(175)
intercept	−26	n/a	n/a	n/a
	(294)	n/a	n/a	n/a
ar				
1	0.05	0.41	0.22	0.70
2	n/a	0.13	.17	−.14
7	0.47	−0.33	0.97	0.98
ma				
1	n/a	−0.49	−0.44	−0.93
2	n/a	−0.33	−0.36	0.07
7	n/a	−0.87	−0.80	−0.81
AIC	n/a	46,364	46,256	46,258

Standard errors in parenthesis.
2,158 observations.

ence of the data can however be shown to be stationary. More so, first-differencing likely preserves much of the variation that I seek to capture. The wind power series is defined by high short-run variability that tends to dominate any seasonal trends. The effect that wind power has on hydropower will also likely be short-run and will be preserved by a first-differencing.

I show the results of the regression in Table 4.

The coefficient of interest is γ_1 on the contemporaneous wind power term. In the table this is labeled $wind_t$. In the first column I show the results from the simplest of distributed lag models. I include a single autoregressive term and a seasonal autoregressive term (ar 7) as well as the wind power term and a lagged wind power term. The coefficient on the wind power term is estimated to be −0.39. Since both Norwegian production and Danish wind production are in MWh/h units, this coefficient can be interpreted to mean that for every MWh/h of wind power produced, production is reduced by 0.39 in Norwegian hydropower plants. With production held back, extra water is preserved in the reservoir, in effect storing the energy.

The coefficient on the lagged wind power term should not be given any economic significance. It is included in the model to account for the fact that wind power tends to be autocorrelated and the positive and significant coefficient simply reflects this relationship and not any causal relationship between lagged wind power and production.

The simple AR(1) structure of the model is not adequate for modeling the dynamics of the series and the residuals from the regression are highly correlated. I therefore use Newey-West standard errors that are robust to autocorrelation.

In the second column I show the results of a regression where I try to more completely account for the dynamics of the first-differenced Norwegian production series. I find that including AR 1, 2 and 7 terms as well as MA 1,2 and 7 provides a relatively good fit as measured by a low AIC. Here the coefficient on the wind power term is estimated to be about -0.47.

In the third column I add variables for Norwegian consumption and Norwegian temperature. The rationale is again that the coefficient on wind power may be capturing some weather variable that affects both wind power and consumption and demand in Norway. The coefficient on wind power is reduced slightly, to approximately -0.39. But in general, all the estimates from the first three specifications are similar in magnitude.

In the fourth column I differentiate between times of net export from Denmark and periods with net imports to Denmark. As might be expected, the magnitude of the effect of Danish wind production on Norwegian production is considerably higher in periods of net export. In periods of net export, the coefficient is estimated to be -0.46 where it is only -0.16 in periods of import to Denmark. This mirrors the results from the regressions on the effect of wind power on marginal export to Norway. At times of plentiful base load production in Denmark, wind power cannot easily supplant local production and more power is exported. In turn flexible Norwegian production is reduced and energy is stored in the form of water in hydropower magazines.

4. DISCUSSION AND CONCLUSION

Wind power in Denmark clearly and significantly affects the pattern of trade between Denmark and Norway in the short run, with increased wind power having the effect of significantly increasing marginal exports and in turn reducing production in Norwegian hydropower plants. The magnitude of that effect is dependent on the net direction of trade. Green and Vasilakos note that at an annual level exports are most strongly correlated to the operation of thermal plants in Denmark, in particular combined heat and power plants. The results from this study suggest that there is a strong interaction effect. At times of plentiful base load production, like during winter days when combined heat and power plants run primarily to provide heat, extra wind power leads to increased net exports to Norway and a reduction of production in Norwegian hydropower plants. At these times, the estimates suggest that an extra MWh/h of wind power can lead to 0.6 MWh/h of increased exports and as much as 0.4 MWh/h of reduced production in Norwegian hydropower.

The mechanism by which this trade happens is through prices set in the Nordic electricity market. I estimate elasticities for the effect of wind power on the two Danish price areas, but I also investigate whether wind power can have an effect on southern Norwegian prices. My empirical models suggest that wind power does slightly affect prices in southern Norway in the short run. But unlike in the local Danish market wind power cannot be shown to affect the daily distribution of prices. This slight price effect likely comes from a slackening of the hydropower producers supply constraint.

Though the interaction of wind power in Denmark and hydropower in Norway appears to be strong, congestion in the transmission net between the countries is nonetheless a common occurrence and limits the interaction. Installing more transmission capacity would have the effect of decreasing the effect of wind power on prices in Denmark and increasing the effect on prices in Norway. In turn, the Norwegian hydropower producers would have an increased incentive to alter their production.

It has been argued that Denmark's large penetration of wind power is only possible due to its close proximity and large transmission connections to its hydropower heavy neighbors. To a certain extent, this study supports that point. When wind power cannot supplant local production, power can be exported and stored in the hydropower magazines of its neighbors. More so, the Nordic electricity market appears to provide the correct price signals for this interaction to occur. The ability to store excess wind power would clearly be an advantage for the planned wind power projects off the coast of Britain and northern Germany. Whether the benefit outweighs the cost of investing in the necessary expensive transmission infrastructure to connect these areas to hydropower areas is of course a question that requires a careful cost-benefit analysis.

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APPENDIX

The price series used in section 3.2 are likely stationary, but as a robustness check I first-difference the variables and run regressions. The results are shown in Table 5. The estimated coefficients are not significantly different from the estimates in Table 2.

Table 5: Effect of Wind Power on Prices, First-difference

	Denmark West	Denmark East	Norway South
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.
2,625 observations.

As an extension of section 3.2, I split days of net exports into periods where the Denmark east and Denmark west prices are close to the Norwegian price—within 0.3 Euro per MWh/h, under the assumption that this is a proxy for days with relatively little congestion. The results are shown in Table 6.

Table 6: Effect of Wind Power on Prices with Congestion

	Denmark West	Denmark East	Norway South
ln-wind-ex, not congested	−0.086	−0.035	−0.011
	(0.007)	(0.004)	(0.002)
ln-wind-ex, congested	−0.108	−0.042	−0.008
	(0.007)	(0.004)	(0.002)
ln-wind-im	−0.075	−0.025	−0.005
	(0.006)	(0.004)	(0.001)
ar			
1	0.350	0.631	1.14
2	0.154	0.039	−0.255
3	0.055	0.129	0.080
7	0.356	0.346	0.143
14	0.300	0.273	0.249

Standard errors in parenthesis.
2,625 observations.

The effect of wind power on Danish prices is estimated to be smaller in magnitude in days with less congestion. These results mirror those found by Green and Vasilakos. I fail to find a significant difference in the effect of Danish wind power on Norwegian prices between periods of more or less congestion however. These results should be taken with a grain of salt. The pattern of power flows and congestion across the Nordic system is complex. Furthermore, congestion is of course not exogenous to prices, so these results should only be seen as a rough splitting and averaging of effects and not given a too literal interpretation.