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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. 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 hydro power magazines.

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

JEL Codes: Q4; L9

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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 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. Norway with its large amounts of hydro power 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 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. Benitez et al. (2008) uses an optimisation model with parameters estimated with data from Alberta, Canada. Studies of the Nordic market also exist. Førsund 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. Matevosyan et al. (2007) study the potential for wind power and hydro power 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 hydro power. Periods with strong winds 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 when considering the interaction of wind power and hydro power 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 hydro power 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 hydro power area.
- Short term variations in wind power affect local prices and 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 term 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 hydro power magazines of their neighbors. 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 Denmarks 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 to Norway. The rationale is that days of net exports are more likely to be times of supple 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 .3 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 .15 MWh/h.

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 can not be shown to differ significantly between days when there are net exports and net imports. The short term 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 .5% in southern Norway on days with net exports from Denmark but only by .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 .40 MWh/h of hydro power production in the southern Norwegian price area. When discerning between periods of net exports to Norway and net imports to Denmark the respective estimates are -.46 and -.16 MWh/h. That the effect of wind power on southern Norwegian production is estimated to be higher than the effect on marginal exports to Norway may suggest a bias in these results. One plausible explanation is that Danish wind power is correlated with wind power in other parts of northern Europe that have physical connections to Norway.

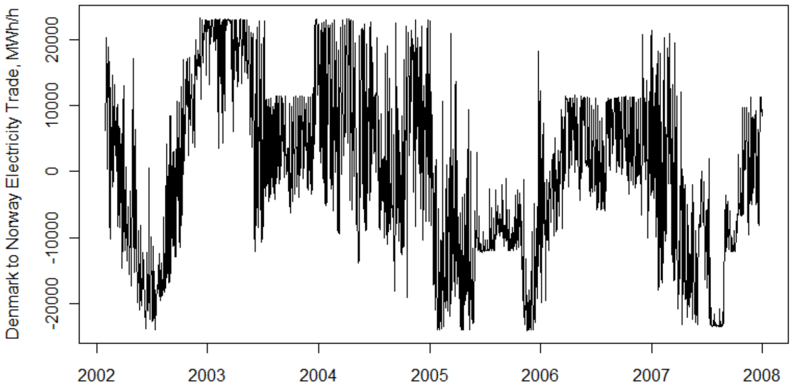

Figure 1 The pattern of trade between Norway varies both seasonally and yearly. Transmission constraints are visible as plateaus in both directions. Positive values represent net exports to Norway.

2 Data and Methodology

Data was assembled from several sources. Hourly price data as well as data on Norwegian hydro power production 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).

The data can be assumed to be of high quality and with up to eight years of daily data, the econometrics becomes easier as I can rely on asymptotics to obtain consistent and unbiased coefficient estimators and standard deviations. 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 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 general form of the distributed lag models I use throughout are as equation (1).

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

Here d_t represents the dependent variable being modelled - trade, prices or Norwegian production - and $wind_t$ represents the daily amount of wind power produced in Denmark. $\mathbf{X_t}$ 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 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. 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.

Vector Autoregressive (VAR) models are increasingly being used in the context of power markets (see for example Fell (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. 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 [1] 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

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[1] Nord Pool introduced negative prices on the 30th of November 2011, after my sampling period

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 summer 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 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 of the form of equation (2).

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

I_t represents net electricity trade between Norway and Denmark 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. $\mathbf{X_t}$ represents a vector of other exogenous regressors that are included in the regression. $\mathbf{I_{t-i}}$ represents the vector of autoregressive terms while $\epsilon_{\mathbf{t-i}}$ represents the vector of moving average terms. ϵ_t represents the contemporaneous error term.

The results for the regression are displayed in table 1.

Looking at the first column, the coefficient on the wind power term, labelled *wind*, is about .27 and is estimated with a relatively small standard error of .009. Since

	I	II	III
wind	0.269 (0.009)	0.276 (0.010)	n/a
win-ex	n/a	n/a	0.322 (0.010)
wind-im	n/a	n/a	.111 (0.012)
consum	n/a	-1.869 (0.515)	n/a
norTemp	n/a	-0.302 (0.061)	n/a
constant	-5.463 (2.432)	2.824 (3.121)	-4.832 (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 1. Effect of wind power on trade. A one megawatt-hour per hour (mWh/h) increase in wind power is shown to increase net exports by about .30 mWh/h and to reduce net imports by about .1 mWh/h.

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, .27 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 hydro power area.

In the second column I add terms for Norwegian consumption, labeled *consum*, and temperature in Norway, *norTemp*. 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 discussion around the battery effect suggests that the net direction of trade should be important. In the third column I estimate the effect of wind power on marginal trade during 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 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.

This result is in line with the idea that Denmark will export when it is difficult for the 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 hydro power area.

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 noted 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 hydro power 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 can not 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

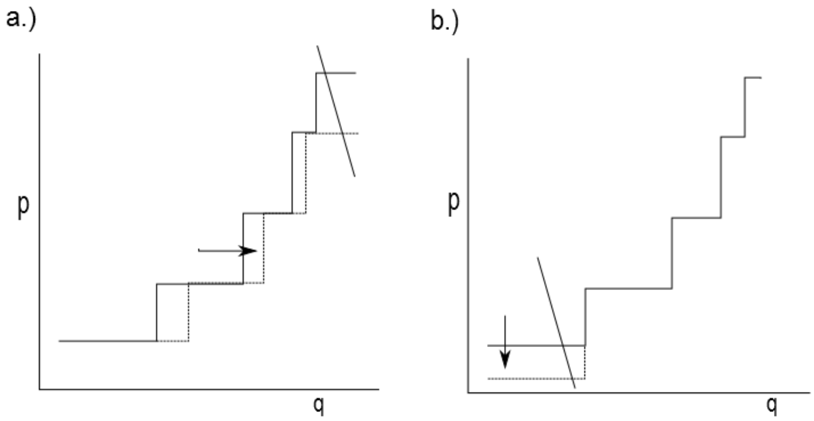

Figure 2. Panel a. shows the effect on prices of wind power shifting the supply curve. Panel b. shows the effect of wind power being able to underbid prices at the baseload level.

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. Two theoretically distinct effects can be identified. The first can be called a supply effect, illustrated in panel a of figure 2, where wind power can be seen to shift 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 high-load times.

The alternative way that wind power can affect local prices is by way of its low marginal costs, illustrated in panel b of figure 3.4. Here, wind power can be seen as underbidding other forms of base-load generation. The general effect would be to lower base load prices. Of course, in reality, both mechanisms are likely at play simultaneously. Results from Mauritzen (2010) suggest that the supply effect dominates and that wind power both reduces average prices and daily price variation.

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 hydro power 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 they also 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 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 hydro power dominated system. In periods with heavy winds and net exports to Norway,

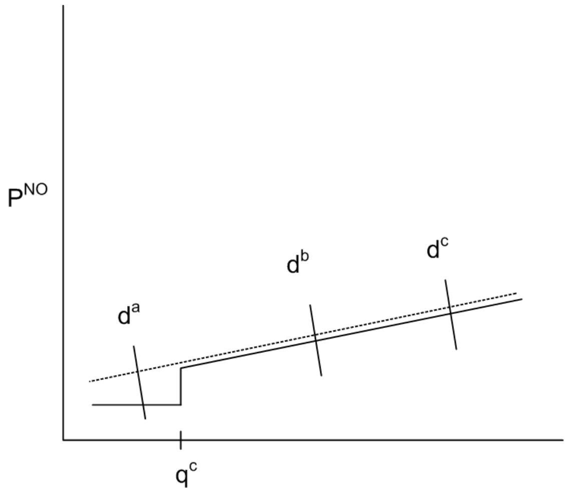

Figure 3. The short run effect on Norwegian prices of Danish wind power is likely to be slight due to capacity constraints and the dominance of hydro power in Norway

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 hydro power 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 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.

The illustration is of course an extreme oversimplification. Optimal hydro power 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 hydro power 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 Denmark west, Denmark east, and southern Norway. The model is described in equation (3), below.

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

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 to Norway or net imports to Denmark in that day. $\mathbf{C_t}$ 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. $\mathbf{P_{t-i}}$ 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 ($2^{-.08} \approx .95$), but only a .5 % reduction in Norway in periods with net exports to Norway and .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

	I	II	III	IV	V	VI
		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 parenthesis
2841 Observations

Table 2. Effect of wind power on Danish and Norwegian prices. A doubling of wind power in Denmark is shown to decrease prices in southern Norway by on average .5% as compared to approximately 5% in western Denmark and 2% in eastern Denmark

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 3.2.

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 can not be shown to be significantly different from zero, as was suggested.

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
2641 Observations

Table 3. Effect of wind power on Norwegian price variation. Wind power generated in Denmark can not be shown to affect intraday price variation in Norway.

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 production in Norwegian hydro power. In particular, periods of high wind power production in Denmark should supplant hydro power production in southern 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 hydro power.

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

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

Here $\Delta NOProd_t$ represents the first-difference of total production in the southern Norwegian price area per day. Since nearly 99 percent of production in Norway comes from hydro power, this can be considered a good proxy for total production of hydro power in southern 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. $\mathbf{X_t}$ represents a vector of other explanatory variables. $\mathbf{\Delta NOProd_{t-i}}$ represents a vector of autoregressive terms while $\epsilon_{\mathbf{t-i}}$ represents a vector of moving average terms. ϵ_t represents the contemporaneous error term. γ_i, σ, α, and β represents 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-difference 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 hydro power will also likely be short term and will be preserved by a first-differencing.

I show the results of the regression in table 4 below.

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

	I	II	III	IV
wind_t	-.39	-.48	-.38	n/a
	(0.05)	(0.03)	(0.021)	n/a
wind_{t-1}	0.11	.059	.01	.02
	(.05)	(.03)	(.02)	(.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	.98
	n/a	n/a	(.03)	(.028)
NOTemp	n/a	n/a	467	177
	n/a	n/a	(180)	(175)
cons	-26	n/a	n/a	n/a
	(294)	n/a	n/a	n/a
ar				
1	.050	.41	.22	.70
2	n/a	.13	.17	-.14
7	0.469	-.33	.97	.98
ma				
1	n/a	-.49	-.44	-.93
2	n/a	.-.33	-.36	.07
7	n/a	-.87	-.80	-.81
AIC	n/a	46364	46256	46258

Standard errors in parenthesis
2158 Observations

Table 4. Effect of wind power on Norwegian production. A marginal MWh/h of wind power production in Denmark is associated with approximately .4 MWh/h of reduced power production in Norwegian hydro power production. This suggests a strong battery effect between the two countries.

simplest of distributed lag models. I include a single autoregressive term as well as the wind power term and a lagged wind power term. The coefficient on the wind power term is estimated to be -.39. Since both southern Norwegian production and Danish wind production are in MWh/h units, this coefficient can be interpreted to mean that for ever MWh of wind power produced, production is reduced by .39 in Norwegian hydro power 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 modelling 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 -.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 -.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 to Norway 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 at periods of net export to Norway. In periods of net export, the coefficient is estimated to be -.46 where it is only -.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 can not 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 hydro power magazines.

The estimated coefficient of approximately .40 for the effect of Danish wind power on Norwegian hydro power production should however be seen as an upper bound. If wind power in Denmark is correlated with, for example, wind power in Sweden, then the estimated effect of Danish wind power will be biased upward. The fact that the effect of wind power on marginal exports to Norway was estimated to be approximately .30 gives some evidence for the existence of such a bias.

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 hydro power plants. The magnitude of that effect is dependent on the net direction of trade. Green and Vasilakos note that 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 suggests 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 hydro power plants. At these times, the estimates suggest that an extra MWh/h of wind power can lead to .30 MWh/h of increased exports and as much as a .40 MWh/h of reduced production in Norwegian hydro power production.

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 suggests that wind power does slightly affect prices in southern Norway in the short run. But unlike in the local Danish market wind power can not be shown to affect the daily distribution of prices. This slight price effect likely comes from a slackening of the hydro power producers supply constraint.

Though the interaction of wind power in Denmark and hydro power 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 hydro power 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 hydro power heavy neighbors. to a certain extent, this study supports that point. When wind power can not supplant local production, power can be exported and stored in the hydro power 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 is of course a question that requires a careful cost-benefit analysis.

5 Appendix: Affect of wind power 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 4. The price series are likely stationary, but as a robustness check I first-difference the variables and run regressions. The estimated coefficients are not significantly affected.

References

Amundsen, E. S. and L. Bergman (2006, September). Why has the nordic electricity market worked so well? *Utilities Policy 14*(3), 148–157.

Belanger, C. and L. Gagnon (2002, November). Adding wind energy to hydropower. *Energy Policy 30*(14), 12791284.

Benitez, L. E., P. C. Benitez, and G. C. van Kooten (2008, July). The economics of wind power with energy storage. *Energy Economics 30*(4), 1973–1989.

Bernanke, B. S. (1986, February). Alternative explanations of the Money-Income correlation. *National Bureau of Economic Research Working Paper Series No. 1842*.

Costa, A., A. Crespo, J. Navarro, G. Lizcano, H. Madsen, and E. Feitosa (2008, August). A review on the young history of the wind power short-term prediction. *Renewable and Sustainable Energy Reviews 12*(6), 1725–1744.

Danish Energy Agency (ENS) (2010). Energistatistik 2010. `http://www.ens.dk/da-DK/Info/TalOgKort/Statistik\_og\_noegletal/Aarsstatistik/Documents/Energistatistik\_2010.pdf`.

Fell, H. G. (2010, August). EU-ETS and Nordic Electricity: A CVAR Approach. *The Energy Journal 31*(2).

Forewind (2011). *Dogger Bank - Forewind*. `http://www.forewind.co.uk/dogger-bank/`.

Førsund, F. and L. Hjalmarsson (2010, May). Renewable energy expansion and the value of balance regulation power. Technical report, Göteborg University, Department of Economics. `http://ideas.repec.org/p/hhs/gunwpe/0441.html`.

Foyn, J. F. (2009, February). Nordpool electricity prices. Correspondence.

Green, R. and N. Vasilakos (2012). Storing Wind for a Rainy Day : What Kind of Electricity Does Denmark Export ? *The Energy Journal 33*(3).

Greene, W. H. (2002, September). *Econometric Analysis* (5th ed.). Prentice Hall.

Hjalmarsson, E. (2000). Nord pool: A power market without market power. `http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.4.8509`.

International Energy Agency (2009). Technology roadmap wind energy. Technical report. `http://www.iea.org/papers/2009/Wind\_Roadmap.pdf`.

Matevosyan, J., M. Olsson, and L. Söder (2007). Short Term Hydro Power Planning Coordinated with Wind Power in Areas with Congestion Problems. *Wind Energy Journal 10*(3), 1–11.

Mauritzen, J. (2010, December). What happens when its windy in denmark? an empirical analysis of wind power on price volatility in the nordic electricity market. *SSRN eLibrary*. `http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1754931`.

Newbery, D. (2010, July). Market design for a large share of wind power. *Energy Policy 38*(7), 3131–3134.

Newey, W. and K. West (1987). A Simple , Positive Semi-Definite , Heteroskedasticity and Autocorrelation Consistent Covariance Matrix. *Econometrica: Journal of the Econometric Society 55*(3), 703–708.

NOWAI (2010). *National Offshore Wind Association of Ireland - Making renewables Ireland's primary power source.* `http://www.nowireland.ie/`.

Rud, L. (2009, September). *Essays on Electricity Markets.* Ph. D. thesis, NHH Norwegian School of Economics, Bergen.

The Economist (2006, July). Where the wind blows. `http://www.economist.com/node/9539765`.

Twomey, P. and K. Neuhoff (2010). Wind power and market power in competitive markets. *Energy Policy 38*(7), 3198–3210.

Weigt, H. and C. V. Hirschhausen (2008, November). Price formation and market power in the German wholesale electricity market in 2006. *Energy Policy 36*(11), 4227–4234.

Weron, R. (2006, December). *Modeling and Forecasting Electricity Loads and Prices: A Statistical Approach.* Wiley.