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Wind power, network congestion and hydro resource utilisation in the Norwegian power market

by

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Wind power, network congestion and hydro resource utilisation in the Norwegian power market[1]

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Abstract: Capacity constraints in electricity networks can have important impacts on utilisation of new renewable energy capacity and incumbent generation resources. Neglect of such impacts in development of renewable energy resources can result in crowding-out of incumbent generation. This trade-off is particularly problematic if the incumbent generation also consists of renewable sources, such as hydropower in the Norwegian electricity system. This paper presents a numerical analysis of the current location of wind-power development plans in Northern Norway and their impacts on utilisation of hydropower. Policy simulations are conducted using a dynamic partial equilibrium model that is calibrated to reflect the structure of the Nordic power market. The paper draws conclusion and policy implications for integration of renewable energy resources in the Norwegian power market.

JEL classification: C61, L9, Q2, Q4

Keywords: Wind power; Hydropower; Electricity; Network congestion

[1] A first version was presented at the 7th IAEE European Energy Conference, Bergen, 2005. Trond Jensen and Cato Larsen were then employed by the Norwegian Water Resources and Energy Directorate (NVE), and Balbir Singh was working at the Institute for Research in Economics and Business Administration (SNF). The paper has been finalised under the SNF project “Efficient incentive mechanisms for introduction of renewable resources and development of transmission in deregulated power markets” financed by NFR (the Renergi programme).

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1. Introduction

Technological options for conversion of primary energy to electric power have never been as many as they are today. This is particularly true for environmentally friendly generation technologies that use renewable resources such biomass, geothermal, hydro, sun, wave and wind energy. Policy makers around the world are drawing ambitious targets for introduction of supplies from renewable technologies into the energy mix of the future. In Norway, introduction of renewable energy resources is being promoted as an important policy objective for meeting the future energy and environmental policy targets for the power sector. Wind power is emerging as one of the important renewable resources in this context. To facilitate the achievement of the policy objectives, various economic incentive mechanisms and policy measures have been used.

In Norway, the differences in wind power generation costs at alternate locations are quite small compared to the differences in transmission costs associated with integration of projects at alternate locations. So far, the incentive mechanisms have primarily focussed on stimulating new generation capacity with minimum attention being given to the transmission costs of integration of new capacity in the current system. These incentives have led to announcement of a number of wind power projects by the industry. However, an important characteristic of the announced projects is the mismatch between location of the new projects and the transmission capacity in the system. Focus of the public policy on stimulating generation has led to announcement of project plans that although profitable for the individual investor's point of view, may not necessarily be socially desirable given the transmission capacity situation in the Norwegian system.

It is the objective of this paper to analyse the interactions between location of wind power projects and network congestion and outline the efficiency trade-offs involved in policies that focus on generation capacity to promote introduction of wind-power in the Norwegian power market. The paper is divided into four sections. In Section two we provide background information related to introduction of wind power in Norway. In Section three we outline an optimisation formulation of an equilibrium model of a power market. In Section four we use a simulation model incorporating features outlined in Section three to analyse the interaction between location of wind power in Northern Norway and its impact on hydro resource utilisation in the region. Section five relates the results to the current empirical evidence about introducing wind power in the region and draws policy implications and conclusions of the analysis.

2. The Norwegian Power Market and Wind Power

Introduction of wind-power in Norway is being promoted as an important policy objective for meeting the future energy and environmental policy targets for the power sector. A recent assessment of the wind resources along the Norwegian coast covering an area of nearly 37682 km^2 indicates a production potential of approximately 480 TWh per year, although the effective production potential would be lower than this level. A government white paper (St.mld. nr. 29 (1998-99)) on the Norwegian energy policy identified a target for development of wind power capacity to the tune of only 3 TWh/year by 2010. The main challenge facing the policy makers is that at the prevailing market prices - which typically reflect the marginal costs in large-scale fossil power generation plants in the Nordic market - wind power is not cost competitive.[3] However, it is expected that competitiveness will improve in the future as the industry gains experience with the new technology. To reach this stage there is a need for incentive mechanisms to support wind power projects and this “infant industry” argument has provided the main motivation for design of the incentive mechanisms for introduction of wind power in the Norwegian electricity market.

Various incentive schemes have been introduced to support wind power in the Norwegian power market during the recent years. Initially, the focus was placed on promoting investment through reduction in capital costs and consequently an investment subsidy covering 25% of the investment costs was introduced in the Norwegian system. In addition, to expand the focus from investment to generation, a 50% rebate in electricity tax rates was also included, together with a proposal for a market for green-certificates to be introduced from 1st January 2007. More recently the green-certificates proposal was shelved and the government has now established a fund that will be used to support development of renewable technologies including wind power. The current proposal reaffirms the commitment of the Norwegian

[3] See also Skytte, K. (1999) and Morthorst, P. E. (2000) for a general discussion of competitiveness of wind power.

government to the development of renewable resources and the Norwegian Ministry of Oil and Energy OED is currently working on incentive mechanism to be supported by the new fund.

Figure 1 gives the status with regards to the size and geographic distribution of wind power projects in the pipeline in Norway. In principle there are many suitable location sites along the coast, however, as shown in Figure 1 majority of the current plans involve development of centralised generation in wind-power parks in Northern Norway; a region that already has surplus power and often faces binding transmission capacity constraints on the interconnections with the rest of the Nordic market. Figures 2 and 3 show the percentage of the time Northern Norway was partitioned[4] from Southern Norway as a separate price area during the period 1995-2004.

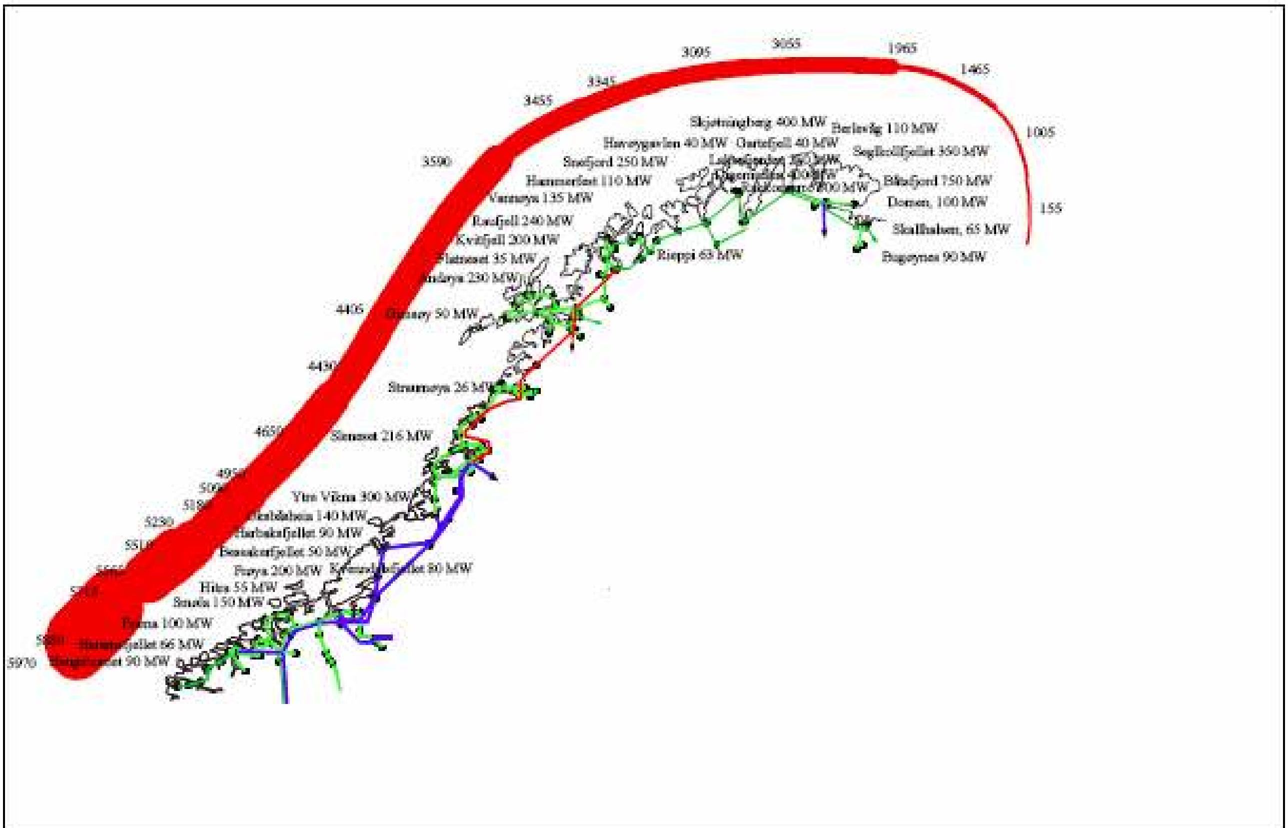

Figure 1. Geographic distribution of planned wind power generation in Norway
Note: The broad line gives the cumulative distribution from North to halfway South of Norway. All data in MW.
Source: "Nettkonsekvenser av ny vindkraft i Nord- og Midt-Norge ", Statnett (2003)

[4] Under the current market architecture, the Nordic market, Nord Pool, functions as a single integrated market as long as there is no congestion in the Nordic transmission network. Whenever there is network congestion, the market is partitioned geographically and each partition functions as a separate price area in the Nordic market. The geographic partitions of the market may vary on hourly basis. Northern Norway has been increasingly partitioned as a separate price area due to insufficient transmission connection with the rest of the Nordic Market. Northern Norway consists of the three counties Nordland, Troms and Finnmark.

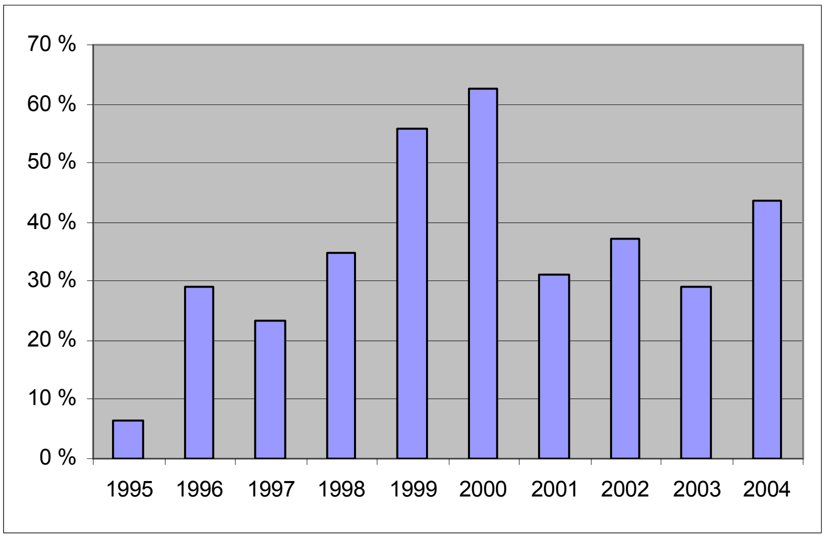

Figure 2.Percentage of time per year Northern Norway was a separate price area

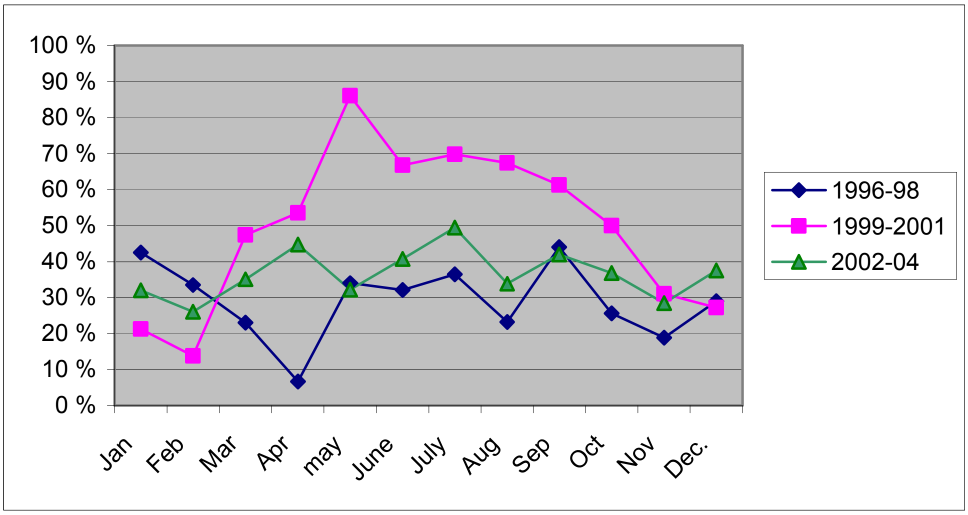

Figure 3: Percentage of hours Northern Norway was defined as a separate price area during the period 1996-2004. (Three year averages)

Figure 2 indicates that there has been a rapid increase in frequency of partitioning due to transmission constraints from 1995 to 2000, but then a downward shift in 2001 and a gradual increase again on the average to 2004. An important characteristic associated with partitioning is spillage of hydro inflows that occur when hydro storage capacity has been exhausted and transmission constraints are binding for export.

The normal pattern of water availability and storage in Norway is cyclical over the year. Inflows gradually increase during May to September due to the melting of snow while demand gradually falls during these summer months. Starting with the minimum storage level by the last week of March/beginning of April that marks the end of winter, the storage levels start rising as inflows increase and consumption falls during summer. It is particularly during this high inflow and low local demand period, that utilisation of hydro resources is crucially dependent on the availability of transmission capacity to the rest of the Nordic market to prevent overflow[5]. As shown in Figure 3, Northern Norway has been experiencing transmission constraints during the summer months. During 1999-2001 Northern Norway was a separate surplus production price area between 60-80 % of the time during the summer months. Development of new wind power resources in this region under the current circumstances would further constrain the utilisation of incumbent hydro resources, and can be expected to result in further increase in water spillage as new wind power is phased into the system. Understanding the interplay between utilisation of hydro and wind power is crucial for design of incentive mechanism for optimal location of wind power generation in the Norwegian power system.

3. A multi-period systems model

The Norwegian power system has been modelled by a number of authors as a multi-period optimisation formulation, including stochastic elements like inflows. The so called "Samkjørings" – model, a systems model outlined as early as in Hveding (1968), and its later refinements in Gjelsvik et al. (1992), is one of the most commonly used models in this context. The spatial structure in this system model is expressed by delimiting a number of areas that are connected by transmission lines with limited capacities. The system model is, firstly, solved for each area separately with aggregated generation and storage capacities for each type of power generation. In a second stage the areas are connected through calibration exercises to establish system-wide prices. Traditionally, the model was used for planning and coordination purposes by authorities, like the regulator NVE, however, subsequent to the establishment of the Nordic market Nord Pool the model has also been used by market actors for predicting the development of system market prices in the spot market. Many hydro power companies are actively using this type of model for operations planning purposes.

[5] The discussion assumes competitive behaviour on part of all the producers with hydro storage capacity.

To give a flavour of the main mechanism of concern in this paper of the multi-period system model, we present a highly stylised version of the model in this section in order to elucidate the interplay between utilisation of hydro and introduction of wind power in the Norwegian power system. Focussing on a single sub-area of the system, where wind power is to be introduced, and assuming the price formation in the rest of the system to be independent of the sub-area, the social planning model for the sub-area can be represented by the following simplified structure (Førsund, 2005, 2007).

$$
\begin{aligned}
& Max \sum_{t=1}^{T} \Big(\int_{z=0}^{x_t} p_t(z)dz + p_t^S e_t^{XI} \Big) \\
& s.t. \\
& x_t = e_t^H + e_t^W - e_t^{XI} \\
& -\bar{e}^{XI} \le e_t^{XI} \le \bar{e}^{XI} \\
& R_t \le R_{t-1} + w_t - e_t^H \\
& R_t \le \bar{R} \\
& e_t^W, p_t^S \text{ exogenous, } R_T \text{ free, } t = 1,..,T
\end{aligned}
\tag{1}
$$

The definition of variables and parameters are:

$$
\begin{aligned}
T &= \text{planning horizon} \\
x_t &= \text{total consumption} \\
p_t(x_t) &= \text{demand function} \\
p_t^S &= \text{system price} \\
e_t^H &= \text{hydropower} \\
e_t^W &= \text{wind power} \\
e_t^{XI} &= \text{export (positive), import (negative)} \\
\bar{e}^{XI} &= \text{transmission limit} \\
R_t &= \text{water in reservoir at the end of the period} \\
w_t &= \text{inflow during the period} \\
\bar{R} &= \text{reservoir capacity}
\end{aligned}
$$

The system, exclusive of the sub-area, is represented by exogenous price p_t^S. There is a transmission link between the sub-area and the rest of the system with a given capacity, $\bar{e}^{XI}$. In the sub-area there are both wind power and hydro power. For ease of exposition no upper production constraint is explicitly introduced for the two technologies, but there is a reservoir constraint for hydro. In addition, we also neglect transmission losses. The objective in this model is to maximise the sum of producer and consumer surplus plus net trade income. In the above formulation we assume that there are no variable costs associated with generation of hydro or wind power. The consumer and producer surplus terms therefore simplify to the area under the demand curve. The last term in the objective function represents revenues from trade with the rest of the system. The term is positive in case of exports and negative in case of imports. This term ensures that for an optimal solution the divergence between area prices and system prices will be as small as allowed by the optimal solution. Without constraints on transmission the area prices will become identical to the system prices.

Due to the possibility of storing water the problem is dynamic. A qualitative discussion of feasible solutions will bring out the interaction between wind and hydro when transmission to the rest of the system is constrained. The first constraint in our formulation is the energy balance for the area we are looking at. It has to hold with equality. The second constraint expresses the transmission capacity that is the same in absolute value for imports and exports. The third constraint captures the dynamics of the system showing the net accumulation of water in the reservoir. The last constraint is the limited reservoir capacity.

The Lagrangian for problem (1) when the energy balance is inserted for consumption is:

$$
\begin{aligned}
L = & \sum_{t=1}^{T} \Big(\int_{z=0}^{e_t^H + e_t^W - e_t^{XI}} p_t(z)dz + p_t^S e_t^{XI} \Big) \\
& - \sum_{t=1}^{T} \lambda_t (R_t - R_{t-1} - w_t + e_t^H) \\
& - \sum_{t=1}^{T} \gamma_t (R_t - \overline{R}) \\
& - \sum_{t=1}^{T} \alpha_t (e_t^{XI} - \overline{e}^{XI}) \\
& - \sum_{t=1}^{T} \beta_t (-e_t^{XI} - \overline{e}^{XI})
\end{aligned}
\tag{2}
$$

The Kuhn - Tucker conditions are:

$$
\begin{aligned}
& \frac{\partial L}{\partial e_t^H} = p_t(e_t^H + e_t^W - e_t^{XI}) - \lambda_t \le 0 \quad (= 0 \text{ for } e_t^H \ge 0) \\
& \frac{\partial L}{\partial e_t^{XI}} = -p_t(e_t^H + e_t^W - e_t^{XI}) + p_t^S - \alpha_t + \beta_t = 0 \\
& \frac{\partial L}{\partial R_t} = -\lambda_t + \lambda_{t+1} - \gamma_t \le 0 \quad (= 0 \text{ for } R_t \ge 0) \\
& \lambda_t \ge 0 \ (= 0 \text{ for } R_t < R_{t-1} + w_t - e_t^H) \\
& \gamma_t \ge 0 \ (= 0 \text{ for } R_t < \overline{R}) \\
& \alpha_t \ge 0 \ (= 0 \text{ for } e_t^{XI} < \overline{e}^{XI}) \ (e_t^{XI} > 0) \\
& \beta_t \ge 0 \ (= 0 \text{ for } -e_t^{XI} < \overline{e}^{XI}) \ (e_t^{XI} < 0)
\end{aligned}
\tag{3}
$$

Let us assume that hydropower is always produced in the area implying that the first condition in (3) holds with equality. If the trade constraint is not binding, both the shadow prices on this constraint will be zero, and we have that the period price will be equal to the system price. We may have export or import. If the optimal solution is export at full capacity the area price will typically be less than the system price, and if the optimal solution is import at full capacity the area price will typically be higher than the system price:

$$\begin{aligned} p_t(e_t^H + e_t^W - e_t^{XI}) &= p_t^S - \alpha_t \text{ (export)} \\ p_t(e_t^H + e_t^W - e_t^{XI}) &= p_t^S + \beta_t \text{ (import)} \end{aligned} \tag{4}$$

The exogenous wind power will influence the optimal solution for hydro production and trade through the effect on demand.

Figure 4 illustrates the impact of restricted trade and introduction of wind power on the area prices and utilization of hydro. Only two periods are considered, t and t +1. The total available hydropower is AD, where AC is the inflow in period 1, CD inflow in period 2 and the reservoir capacity is BC. Wind power is introduced by extending the axis left of A for period t to $A^{/}$ and to the right of D for period t +1 to $D^{/}$. Furthermore, we assume that there is more wind during period t +1 ("day/winter") as compared to period t ("night/summer").

To introduce interaction with the rest of the system define $p_{t+1}{}^{S}$ as the exogenous system price during period t +1 and $p_{\mathrm{t}}{}^{\mathrm{S}}$ as the system price for period t, assuming that the system price for period t is lower than the system price for period t+1. Period t may be the last period before an upward shift in the system price that may occur when the reservoirs are full in the system sometime during late summer or in the autumn. For simplicity the system price for period t +2 is assumed to be the same as for period t +1 (it has to be greater than the area price for period t +1 for the illustration to function). The transmission constraint $\overline{e}^{XI}$ limits trade possibilities with the rest of the system.

The total energy at disposal in period t is wind $A^{/}A$ plus hydro AC. In period t it is optimal to store the maximum amount of water BC and transfer to period t +1 since the system price is higher. But since the storage capacity is limited some water will also have to be used in period t; the amount AB is locked in to use in this period. In order not to spill neither wind nor hydro power the maximal amount, $A^{/}A^{//}$ is exported, using all wind power plus $AA^{//}$ of water for export and consuming $A^{//}B$ in the area. The residual demand curve for period t is anchored at the wall up from $A^{//}$, drawn with a solid line and determined by full export in period t. The

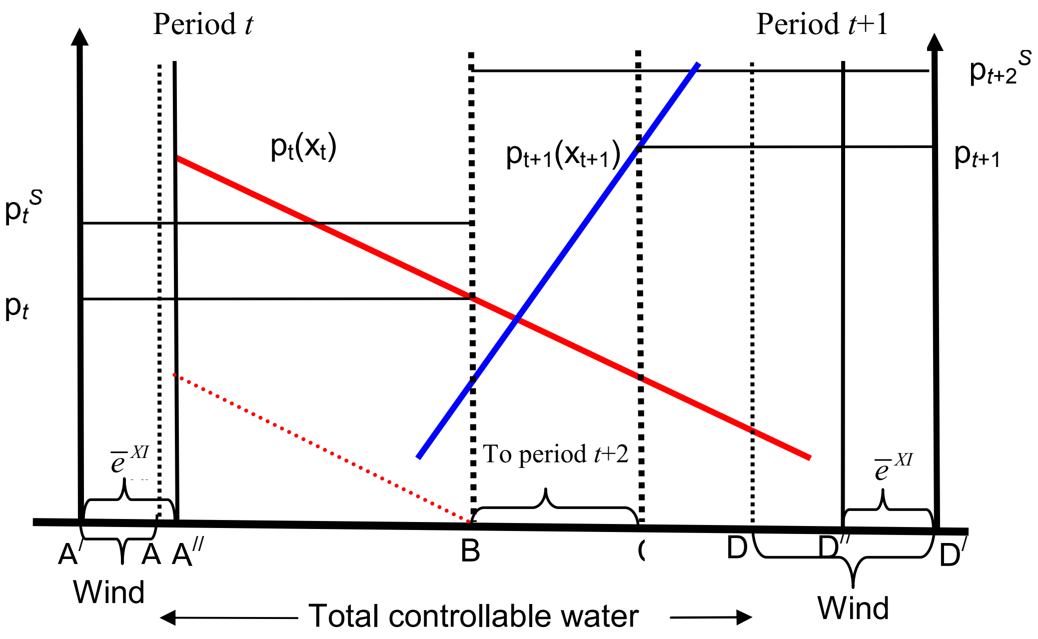

Figure 4. Price formation with wind and hydro power

period t price will then be lower than the system price and determined by the intersection of the demand curve and the limit of the reservoir line up from B.

In period t +1 BD of hydropower is available plus the wind power DD$^{/}$. Consuming the whole amount will result in an area price much lower than the system price. In fact, both exporting maximally and transferring the maximal amount of water, BC, to period t +2 still makes the area price lower than the system price for periods t +1 and t +2. The residual demand curve for period t +1 is anchored at the wall up from D$^{//}$ taking maximal export into account, and then the area price is found as the intersection of the demand curve and the reservoir limit up from C. The use of water in period t +1 is exactly the inflow of the period since this is locked in, due to the fact that the maximum amount BC is passed from period t to period t +1 and then to period t +2. All wind power is accommodated in period t +1. However, if either inflows or wind resources are greater than the levels assumed in Figure 4, prices will fall further and spillage would occur once prices fall to zero. Such a situation is indicated in period 1 by the dotted demand curve through B. A location of the demand curve further to the left will result in spilling of water in period t. In practice, prices would seldom fall to zero due to rigidities in pricing or limited demand flexibility and locking in of water at individual hydro plants, resulting in spillage even at positive prices as is indicated by current spillage statistics for Northern Norway.

4. Simulations: Introduction of Renewable Energy

This section presents the simulation results using the “Samkjørings” – model, briefly introduced in the previous section, to understand the impacts of introduction of wind power in Northern Norway. Northern Norway is in the model simulation limited to the two counties Troms and Finnmark. However, for ease we will continue to use the name Northern Norway. To assess the impacts of introduction of wind power we examine two scenarios, in addition to a base case that assumes business as usual with no new capacity in the system. The two scenarios are simulated assuming two different levels of wind power capacity; alternative 1 that assumes a realisation of somewhat more than half of the existing plans of 4594 GWh, namely 2500 GWh, and a more conservative alternative 2 that assumes realisation of only a third of the existing plans - 1500 GWh of new capacity. Furthermore, the alternatives represent the most favourable pattern over the year for wind power production, where we assume that new wind power capacity utilisation is positively correlated with variation in load over the year. Thus the levels 1500 and 2500 GWh represent the yearly energy output based on installed wind capacity applying the wind factors over the year deterministically. The two interconnections from Northern Norway to the Nordic market in the model are the Finland inter-connector with 50 MW export capacity and 70 MW import capacity, and the Troms interconnection with a capacity of 150 MW in both directions. The results shown are averages for each week when the meteorological observations on inflows and temperature for the period 1941 – 2000 have been used in a serial simulation.

Hydropower generation

Figure 5 illustrates the impact on hydropower generation of introduction of wind power in Northern Norway. As can be seen in the figure, an important impact of introduction of wind power on hydro utilisation is a shift in the pattern of hydropower generation over the year. Essentially, the change involves crowding out of hydropower generation during the winter weeks when wind power production is at its highest level. The hydropower that is crowded out is accommodated through changes in four variables: hydro generation, prices, storage and spillage of water. Increase in hydropower production during some spring weeks for the 1500 GWh alternative 2 is one outcome that accommodates the hydropower that is crowded out due

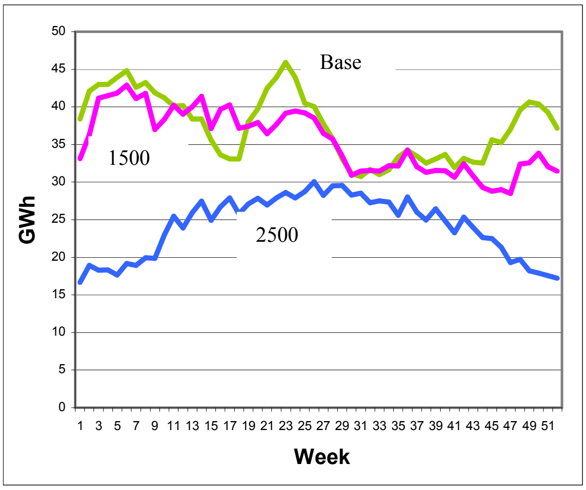

Figure 5. Impact on hydropower production of introducing wind power

to the introduction of wind power. For the 2500 GWh alternative 1 use of water for current production is reduced for all weeks, especially for the winter period.

Prices

The shift in production is a result of the changes in prices that takes place due to introduction of wind power. Figure 6 illustrates the average prices levels under the three alternative scenarios. The introduction of wind power has two types of impacts; a general fall in power prices and a change in the time path of prices over the year. The size and pattern of these impacts is crucially dependent on the quantity of wind power that is introduced in the system. Prices are driven down to the postulated marginal costs of wind power during some summer weeks for the highest wind power alternative.

Storage

Figure 7 illustrates the impacts on storage due to introduction of wind power in Northern Norway. Change in price structure is also associated with a change in inter-temporal storage in the region. In the case of alternative 1, with realisation of more than half of the wind power plans, the storage impact is quite significant. The reservoir is only run down somewhat in late winter weeks, and otherwise is kept at maximum level, corresponding to the situation illustrated in Figure 4 for periods t and $t+1$.

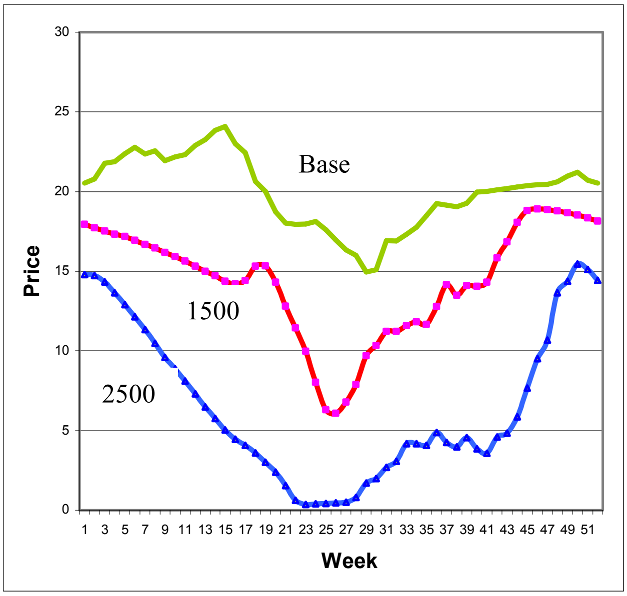

Figure 6. Price impacts of introduction of wind power in Northern Norway (Øre/KWh)

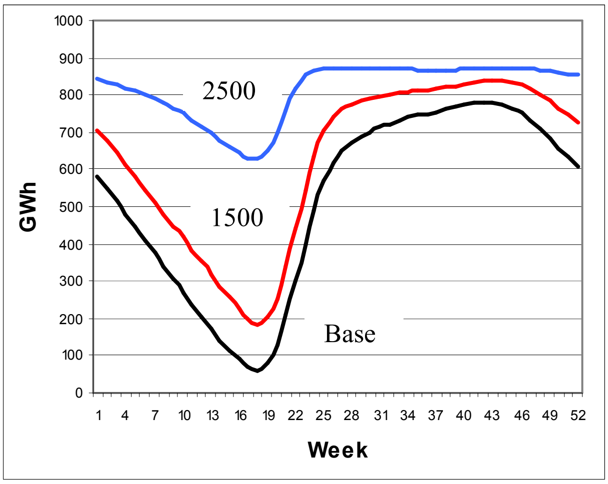

Figure 7. The impacts on storage due to introduction of wind power in Northern Norway

Spillage of Water

In addition to the above changes, an important consequence of introduction of wind power is observed through changes in spillage of water in Northern Norway. With current installed hydro generation and transmission capacity, Northern Norway is a surplus supply region and there is already spillage of water during the high-inflow and low demand periods during summer months. Introduction of new wind power in the absence of expansion in transmission capacity can be expected to result in an increase in spillage.

Figure 8 illustrates the spillage of water due to introduction of wind power in Northern Norway. Effects on spillage are also crucially dependent on the quantity of new wind power capacity that is introduced in the region. With realisation of only a third of the current plans, alternative 2; there is no significant increase in spillage as new wind power is accommodated through changes in prices and storage. However, realisation of alternative 1 will result in an significant increase in spillage of water. Average annual spillage under the base scenario is 411 GWh, which increases by over 170% to 1112 GWh with realisation of half of the current plans.

Variation in spillage is quite significant around the average levels and reaches peak levels during wet years characterised by high inflows and low demand (due to higher temperature). Figure 9 illustrates the variation in spillage based on the hydro inflow series for preceding 60 years. The very small spillage at the zero percentile in week 24 means that even at the most dry alternative there is spillage. The median inflow situation corresponds to spillage of 100 GWh as the maximum for a week (week 23), whereas the average spillage is higher as shown in Figure 8 due to the distribution of absolute inflows.

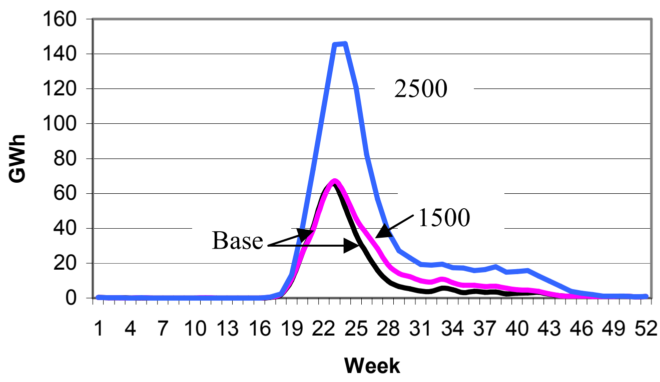

Figure 8. Spillage of water due to introduction of wind power in Northern Norway

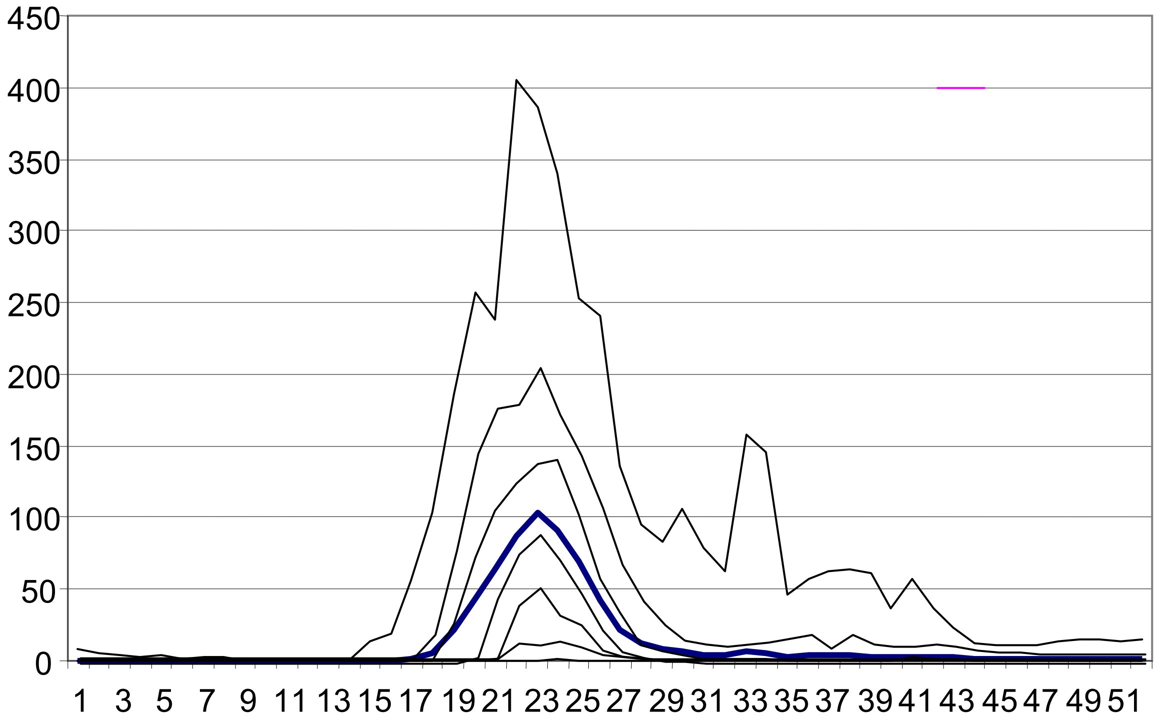

Figure 9. Variation in spillage of water due to introduction of 2500 GWh wind power in Northern Norway (GWh). Percentiles and median (thick line)

Transmission Capacity

Needless to say, introduction of new wind power in a surplus area such as Northern Norway will result in increased capacity utilisation on the transmission links to the rest of the Nordic Market. The two interconnections to the Nordic market in the model are the Finland interconnector with 50 MW export capacity and 70 MW import capacity, and the Troms interconnection with a capacity of at 150 MW. As can be observed in figures 11.1-2, the interconnection between Finnmark and Finland will be chronically congested as a consequence of new wind power production in the North. In general, the direction of trade on the interconnections will shift towards greater exports; the actual impact depending on the quantity of wind power that is introduced in the system and hydro inflows. In case of full realisation of current plans, the interconnections will essentially function as export links, while in case of the conservative scenario with realisation of one third of the plans there would still be some imports, however less than in the base scenario. Figure 11.3 illustrates the impacts on average capacity utilisation of the Finnmark–Troms interconnection under the three scenarios; base, 1500 GWh, and 2500 GWh.

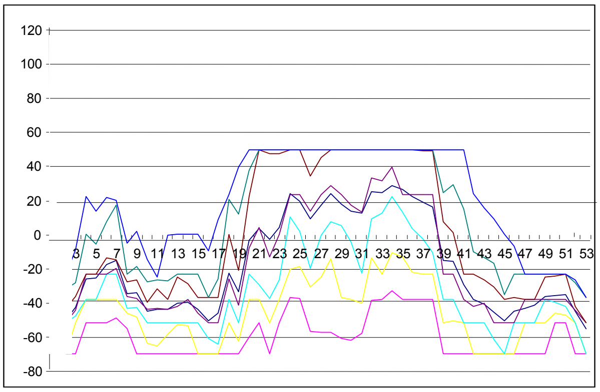

Figure 11.1 Capacity utilisation on Finnmark-Finland interconnection Percentiles Base Scenario

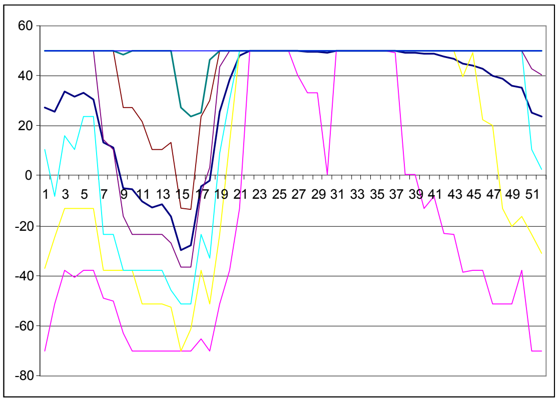

Figure 11.2 Capacity utilisation on Finnmark-Finland interconnection due to introduction of wind power in Northern Norway. Percentiles 2500 GWh wind power

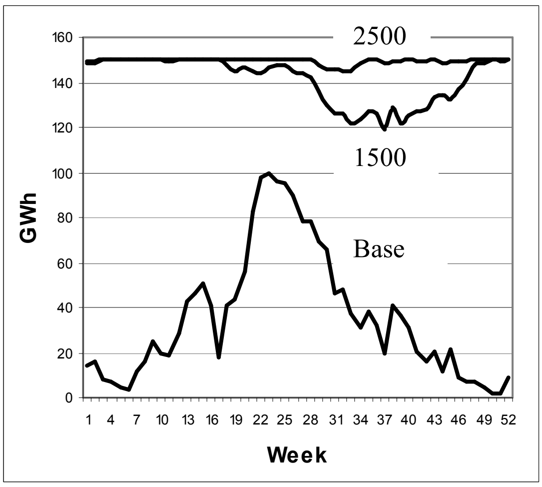

Figure 11.3. Average capacity utilisation on the Finnmark-Troms Interconnection due to introduction of wind power in Northern Norway

5. Policy Implications and conclusions

Analysis of the introduction of wind power reveals important impacts on prices and hydro utilisation in Northern Norway. In principle, the size and direction of the impacts is dependent on the quantity of wind power that is introduced into the system. The main impacts are a reduction in area prices together with changes in hydro resource utilisation. Of particular interest in this context, is an increase in spillage of water. The actual size of the spillage would vary depending on the hydro inflows and quantity of wind power that is phased into the system. In the analysis in this paper we ignore the impacts that would result from the uncertainty in availability of wind power resources and assume that availability of wind power is positively correlated with the local demand. The actual variations under uncertainty may therefore be greater. An important assumption in the analysis is that transmission connection capacity to the rest of the Nordic Market through Finland, and the Troms interconnection is held constant at the current levels.

Results in this paper are also supported by the recent empirical results from a study by the grid operator (Statnett, 2003). The study indicates that in cases where the existing grid capacity is sufficient, introduction of wind-power does not raise any special problems. In Northern Norway, this applies to wind-power projects that can be connected to the current 420 kV line in the region. These projects account for around 400 MW or around 30% of current plans. Uplift of power from the rest of the projects will result in high congestion costs and steep rise in transmission losses both with respect to transport within the region and exchange of power from Northern Norway with rest of the Norwegian and the Nordic power market. As expected, increase in congestion and related costs depends on the pattern for phasing in of new capacity, not only within Northern Norway, but also outside this region given the meshed structure of the grid.

For example, an additional phasing in of 150 MW of wind-power capacity at 132 kV level results in binding thermal constraints in the existing net and increase in transmission losses. Marginal transmission losses gradually increase to nearly 45% by the time 400 MW of additional wind-power is introduced in the existing net. Increase in addition to this level results in serious capacity problems and increased risk of voltage collapse in the net.

Furthermore, Statnett estimates indicate that there will be an increase in hydro spillage as a consequence of an increase in wind-power deliveries in the region. This occurs particularly during the summer season when hydro inflows are at the maximum and storage capacity is exhausted.

To assure reliable and stable uplift of wind-power from the current planned projects Statnett estimates a need for a new 420 kV line involving a total investment of 1,6 billion Norwegian Kroner. In addition, there will be a need for new investments in interconnection capacity with rest of the Nordic market to reduce congestion costs, and hydro-overflows resulting from crowding-out of hydropower by wind-power. Various alternatives have been evaluated for reducing congestion across the regions. This includes both connections between Northern Norway and Central Norway and cross-border connections to Finland and Sweden.

Efficiency in introduction of new wind power capacity calls for internalisation of transmission costs in the location decisions of the wind power generators. In a market based system such as in the Nordic market, the two main economic signals facing the generators are the transmission use-of-system charges and the locational electricity prices. In the context of location decisions, it is the expectations about the future levels of these signals that are relevant.

The relevant issue with respect to the transmission use-of-system charges is that establishment of new capacity impacts on transmission costs. In the context of wind power in Northern Norway, the impacts involve increase in costs for the transmission operator (higher levels of transmission losses, out-of merit generation, and transmission investment) and wastage of hydro resources. Statnett estimates indicate that wind power generation costs at alternate locations range between 28-30 øre/KWh with the lowest (highest) figure representing location in Northern Norway (Central Norway). On the other hand transmission costs of integrating new capacity in Norway range between 1-9 øre/KWh, with Northern Norway (Central Norway) representing the higher (lowest) estimates in this range. There is no doubt that location in Northern Norway is preferable on grounds of production efficiency. However, this advantage does not compensate for the transmission cost difference associated with location in the North. In the worst case, location in the North may involve a total cost of 37øre/KWh as compared to the cheapest location in Central Norway with production cost of 31øre/KWh. Geographic differentiation in transmission use-of-system charges that reflects the expected costs associated with integration of wind power, would provide an important signal for location decisions. Recognising that there has been a general reluctance in Norway towards use of transmission use-of-system charges to guide location decisions, a new transmission tariff on energy was introduced in January 2007. The new transmission charge is based on a weekly average of marginal losses at each node incurred by using the central transmission network. Previously the charge was updated six times per year only. The charge is calculated as the product of the marginal loss evaluated at the system price and the total volume of energy. A detailed projection of network flows is undertaken every week in order to signal the level of transmission charge before the actors make their decisions on volume of energy flows.

As regards the locational electricity price signals, the analyses in the paper indicate that introduction of wind power in Northern Norway will lead to a fall in electricity prices in the region. However, with large degree of socialisation of transmission costs in the past it is not surprising that the signals of expected fall in electricity price have not been able to provide efficient signals to guide location of new wind power capacity in the Norwegian electricity system. The new transmission energy charge should give much better locational signals.

Economic and environmental efficiency of the introduction of renewable energy generation in a market-based power sector with limited network capacity is crucially dependent on the location of these resources in relation to the capacity constraints in the network. Coordination between the development of renewable generation resources and network expansion is important to assure internalisation of network impacts of the new developments. Neglect of such impacts risks location of facilities that are difficult to justify both in economic and not the least in environmental terms. In the context of development of wind power in Northern Norway, it is unlikely that current development plans are based on careful evaluation of the network costs and environmental benefits of these developments. Optimal location of new capacity calls for coordination between generation and transmission[6]. In the context of wind-power development in Norway, possibilities for coordination between generation and network capacity investment decisions have been limited; both through the medium of licensing mandate of NVE and due to a lack of internalisation of transmission costs associated with

[6] Coordination does not necessarily imply centralisation, as was the case in traditional vertically integrated systems.

establishment of new capacity. Inefficient location not only impacts on transmission costs, but also involves an increased risk for crowding-out of hydropower and consequently a reduction in positive environmental impacts of introducing wind power. There is an urgent need to evaluate the costs and benefits of wind power before large resources are committed in development of network capacity.

Infant industry argument for supporting wind power is an issue related to correcting for the temporary lack of competitiveness of wind power vis-à-vis other technologies. In the long run it is expected that competitiveness of wind power would improve and reduce the need for public support. However, infant industry argument does not justify non-optimal location of wind power. The government has established a fund that is expected to give a return of around 800 Million NOK per year, a part of which would be used for supporting the development of renewable energy including wind power. What will be the return in terms of KWh of renewable energy per NOK of public support from the fund is crucially dependent on location of the projects supported by the fund, and need for effective location signals is crucial in this context.

References

Førsund, F. R., 2005. Hydropower economics. Memorandum 30/2005, Department of Economics, University of Oslo.

Førsund, F. R., 2007. *Hydropower economics*. International Series in Operations Research & Management Science , Vol. 112. Springer Science+Business Media, LLC.

Gjelsvik, A., Røtting, T. A., Røynstrand, J., 1992. Long-term scheduling of hydro-thermal power systems, in Broch, Lysne (Eds): *Hydropower 92*. Rotterdam: Balkema, pp. 539-546.

Hveding, V., 1968. Digital simulation techniques in power system planning. *Economics of Planning* 8 (2), 118-139.

Morthorst, P.E., 2000. Capacity Development and Profitability of Wind Turbines. *Energy Policy* 27, 779-787.

Skytte, K., 1999. Market Imperfections on the Power Market in Northern Europe, A Survey Paper. *Energy Policy* 27, 25-32.

Statnett, 2003. Wind-power in Northern Norway, consequences for the central grid (in Norwegian). UA-Note 03-19, Division for Development and Investment, Oslo.

St.meld. nr. 29 (1998-99). Om energipolitikken [The energy policy]. Ministry for Oil and Energy.