Energy resource planning;
Integrating wind power

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1 Background

Among renewable energy alternatives, wind power has proven to be a competitive alternative and a valuable contribution to energy systems. Further expansion of hydro power in Norway are becoming less desirable, both economically and environmentally. Norway is now becoming a net importer of electricity, if the electricity demand continues to increase. Norway's energy policy is to be self-sufficient with electricity exclusively based on *renewable* energy resources. This calls for alternatives in addition to hydro power, of which wind power shows to be the most promising [9] .

Wind power in combination with hydro power

Wind power and hydro power posses characteristics that are partly complementary. Hydro power (as the case for Norway) must be supported by water storage to fit with the demand. Norway consumes about 112 TWh of electricity per year. The water storage capacity is about 83 TWh, measured as the energy amount that can be produced when the water storage is filled [12] . This storage capacity is necessary in order to supply the energy demand during winter, when the consumption is at its peak. While hydro power shows a seasonal variation, wind power is intermittent over short periods, yet have a seasonal variation. Unlike hydro power, the production fits well with the yearly demand curve, and might reduce the need for water storage when combined with hydro power, allowing a better management of the water storage [2] . The dispersed population along the coast, also makes the electricity transmission system quite expensive. Energy losses in transmission are on average 10 percent of the total electricity production, from producer to consumer [1] .

2 Problem formulation

Integrating wind power affects the electricity system in different ways. Some of the technical aspects are:

- The need for water storage and its management
- Transmission losses in the power grid
- Reliability
- Power quality

Water storage management is more of interest to the principally hydroelectric energy systems, like the ones in Canada and Norway.

The purpose of this paper, is to quantify wind power's influence on transmission losses in the power grid, thereby consider whether this parameter is significant for economy and location of future wind power projects.

If changes in transmission losses are significant, this parameter should be included in wind power planning. the case of Norway, transmission losses are reflected in the transmission cost term (see figure 7) - and can be both positive and negative, according to the regulations by NVE[1] [13] . In order to estimate changes in transmission losses, we will have to simulate the power flow in the electricity grid, as transmission losses depend on power flow, grid layout, power production and consumption pattern.

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[1] NVE: Norwegian Water Resources and Energy Administration

Nord-Trøndelag elektrisitetsverk (*Nord-Trøndelag electricity company, hereafter written as* ***NTE***) was chosen as a case-study for this purpose. Like many Norwegian and Scandinavian utilities, NTE uses *Netbas*[2] as a simulation tool for their power grid. As the only utility company in Norway, they also have experience of operating wind turbines.

3 NTE's power grid

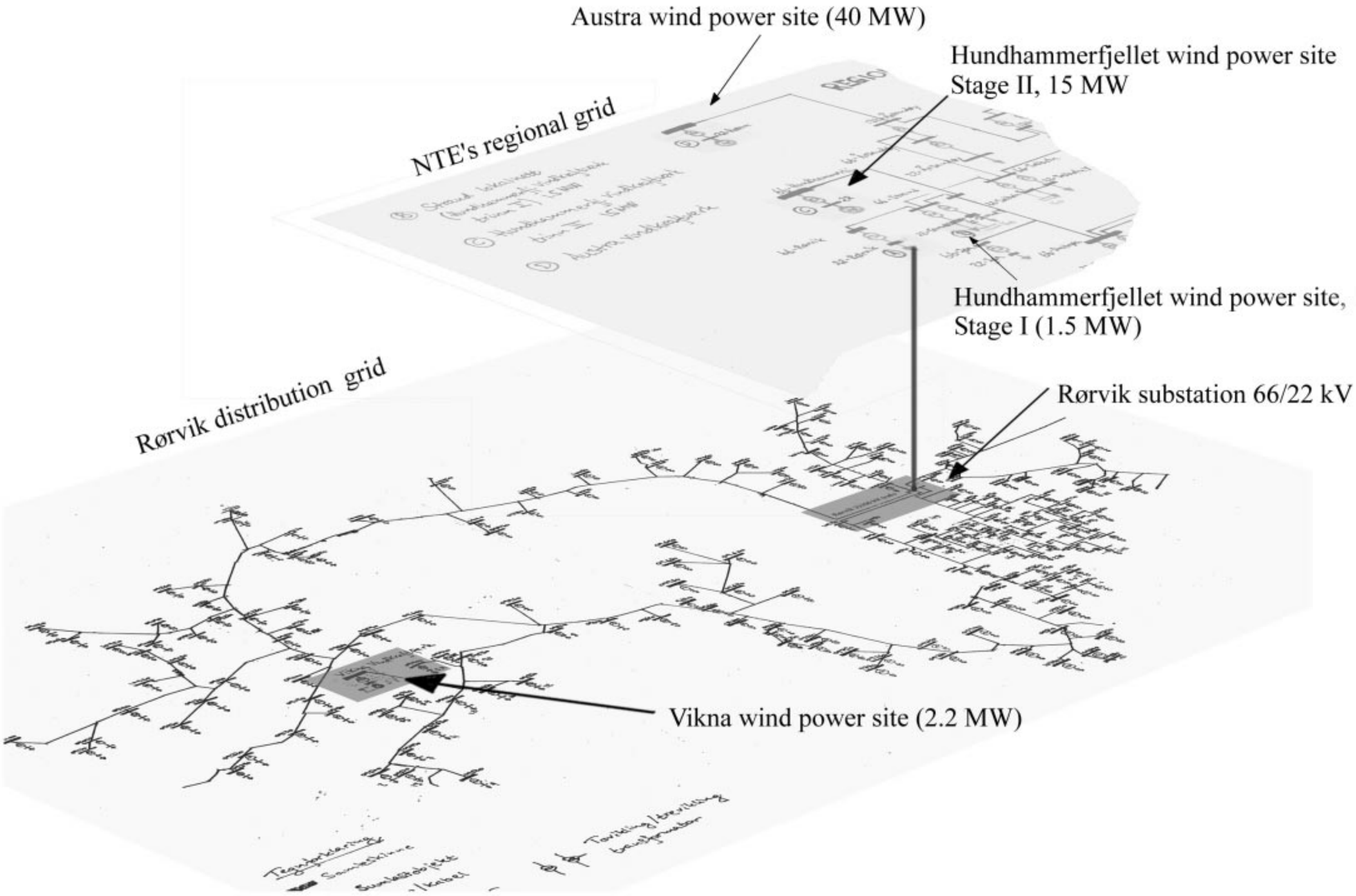

Figure 1 Rørvik distribution grid (22 kV level), is connected to NTE's regional grid as shown on the figure. The location of the various wind power projects are also denoted on the figure.

The transmission system is divided into *the main grid* (132, 300, 420 kV), *the regional grid* (66,132 kV) and *the distribution grid (22 kV).* NTE operates the regional and distribution grids in Nord-Trøndelag, while Statnett operates the main grid, Rørvik distribution grid is one of several distribution grids connected to the regional grid. In the Netbas simulation model, each distribution grid is represented as a single load object in the regional grid, see figure 1 and the corresponding figure 2. The four different wind power project locations are shown on in the figure. Vikna wind power site is located in Rørvik distribution grid (denoted (A) on figure 2), and Hundhammerfjellet wind power site stage I (HH1) is located in Strand distribution grid (denoted (B) on figure 2). Hundhammerfjellet wind power site stage II (HH2) and Austra wind power site (denoted (C) and (D) on figure 2) are both directly connected to the regional grid due to their size. Also note the location of the hydro power generating units, namely Kolsvik and Salsbruket. Kolsvik is also a connection point to *the main grid.* A power flow simulation revealed that Kolsvik mainly supplied this area of the regional grid. Integrating wind power in the distribution grids Rørvik and

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[2] Netbas is a tool for maintenance, documentation, management, and simulation of power grids. For more information, see Appendix and also http://www.powel.no

Strand and thereby reduce the need for power transmission along the 72 km distance Kolsvik-Årsandøy-Salbotn-Strand-Rørvik, and thereby reduce the transmission losses as well. The simulation model that NTE uses contain all the data of the components in the regional grid (see Appendix). Table 1 below show some key figures of the grids used in the simulations.

Grid	Max. Power [MW]	Energy flow [GWh/y]	Transmission loss [%]
Rørvik, distribution	12.0	68	2.2
Strand, distribution	4.1	23	2.1
NTE, regional	1000	6400	4.4

Table 1 Simulation results, NTE transmission system

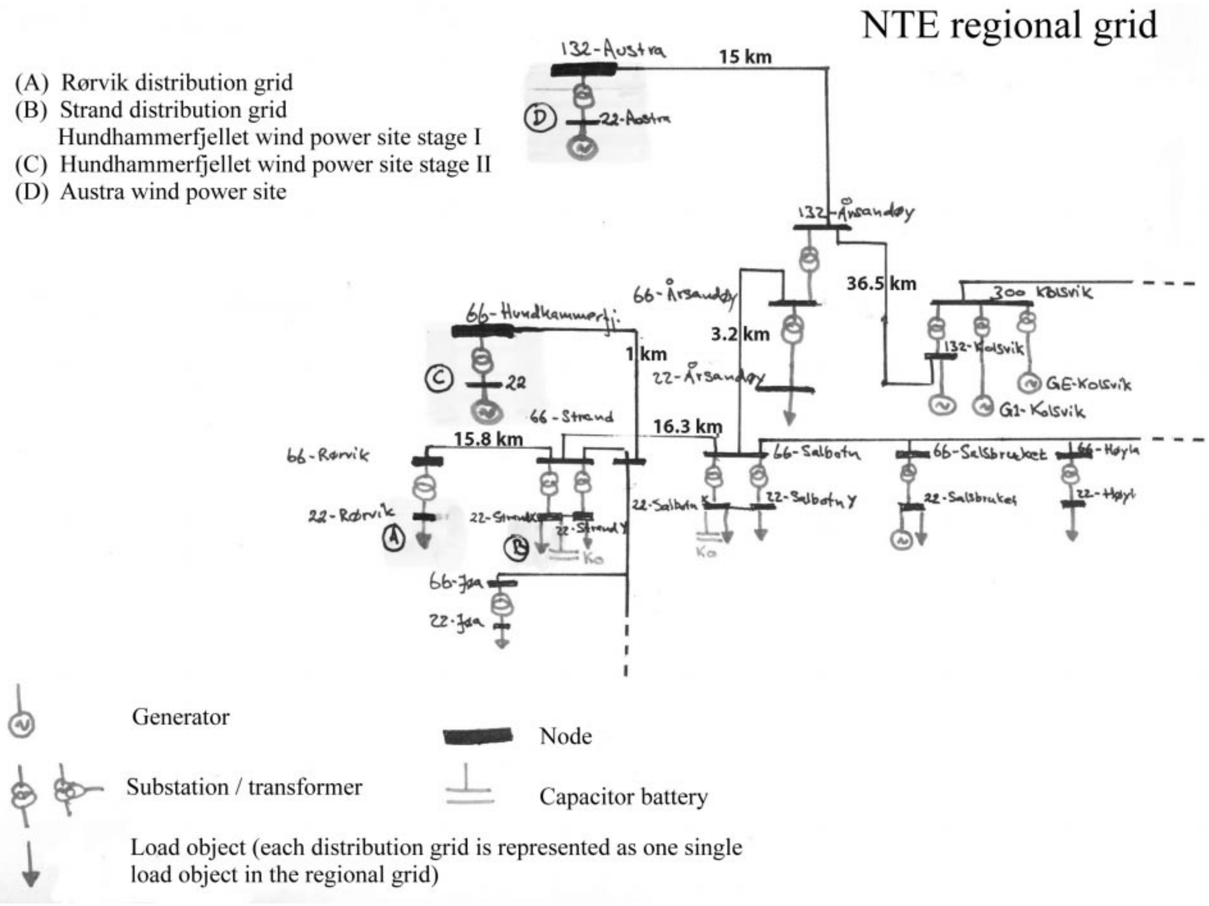

Figure 2 An outline of NTE's regional electricity grid. Strand, denoted (B), is a distribution grid like Rørvik. The figure shows the location of the four selected cases of wind power projects.

4 Theory and program tools

The simulation are performed using Netbas simulation tool. For more information about Netbas and the simulation models, see "Appendix" on page 12. The following section contains an example of transmission loss reduction in one cable segment, to exemplify the mechanism of transmission losses.

Transmission losses in a cable segment

The power loss L for a cable segment can be described as [5] :

$$L = kP^2 \text{ [W]} \tag{1}$$

$$\text{where} \quad k = \frac{Rl}{U^2}(1 + \tan^2\phi) \tag{2}$$

L is the transmission loss [W] along the cable segment, P is the power load [kW]. R represents resistance in [Ohm/km], l cable length [km], ϕ = phase angle [rad] between active and reactive power and U the voltage level [kV]

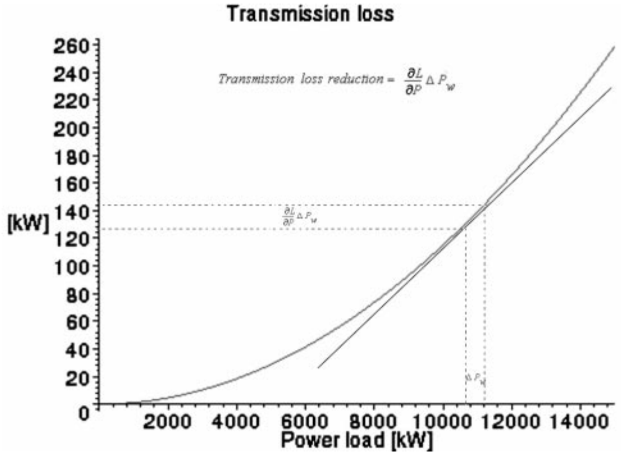

Figure 3 Transmission loss as a function of power load along the Rørvik-Strand cable

If we assume the *energy* production from the wind power sites to be small compared to the power load along the cable segment, the loss reduction caused by wind power can be linearized to:

$$LR = MLR \cdot \Delta P_w \tag{3}$$

Where the *marginal loss reduction*, $MLR = \frac{\partial L}{\partial P}$.
As the integration of wind power affects the power flow in the entire grid, the *transmission loss reduction* caused by integrating wind power is thus.

$$\text{Transmission loss reduction} = \sum_{t=0}^{T}\sum_{i=1}^{n} LR_{i,t} \text{ [kWh]} \tag{4}$$

along the cable segments *i=1..n* in the regional grid during a time period *T* of one year with time steps, *t* of 1 hour. The data listed in table 2 shows the state of the cable segment Rørvik-Strand at 12^{00} in January. figure 3 is plotted with these data for the Rørvik-Strand cable.

Data, cable segment, Rørvik-Strand	
R	0.28 Ohm/km
l	15.8 km
ϕ	0.349 rad
U	66 kV

Table 2 Data for the cable Rørvik-Strand.

The *marginal loss reduction* along this cable segment was at this instant 2.4% per kWh of wind power. Adding up the *transmission loss reductions* along the cable segments along the distance from Rørvik to Kolsvik could potentially reduce the transmission losses significantly. This is what we will do in the following sections.

5 Method

Netbas provides functions for estimating energy losses in the power grid, but the wind power model in Netbas did not take into consideration the seasonal variation of wind power, nor its intermittent power production[3]. However, wind power can be modelled as *"negative consumers"*, because wind power possesses many characteristics similar to consumer loads [2] . The analogy is based upon the following similarities:

- The production is small scale, (less than 10 MW);
- Wind power sites are located at the end of the power grid, near the consumer (in the distribution grid)
- Its yearly power production curve is positively correlated with the demand curve [8] [9] .

This makes it possible to draw upon Netbas extensive simulation tools using the load object model. The approach in order to quantify wind power's influence on transmission losses in the grid was as follows:

- Model wind power sites as "negative consumers" in the grid
- Simulate the selected cases for wind power sites and their influence on the power flow in the grid using NETBAS. The power flow is simulated over a year, and compared to the reference case, that is NTE without wind power.

The different case studies are listed in table 3 below:

Case No.	Site	Size [MW]	Grid	Description
1	Vikna	2.2	Distribution, Regional	Integrated in Rørvik distribution grid, see figure 1. This site has been up and running since 1991, and the wind power production curve from this site has been used for the other selected cases as well. The site consists of 5 Vestas turbines (3 x 400 + 2 x 500 kW)
2	HH1	1.65	Distribution, Regional	Hundhammerfjellet wind power site, stage 1. Integrated in Strand distribution grid, see figure 2. The site is under construction, with one Vestas 1.65 MW turbine
3	HH2	16.5	Regional	Stage 2 of Hundhammerfjellet wind power site will be directly connected to the regional grid due to its size. This case is an expansion of the first stage of HH1
4	Austra	40	Regional	Location Austra, approx. 15 km distance from Årsandøy. The site will be connected to a 132 kV transmission line.

Table 3 Simulation cases. The cases are compared to the reference case, a simulation without wind power. Only Vikna exist as a wind power site today, while HH1 is under construction. HH2 and Austra are future projects for wind power assessment by NTE in Nord-Trøndelag.

Due to their size and location, HH2 and Austra cannot be integrated in the distribution grid close to the consumer.

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[3] Until recently, there has been no need for advanced wind power models, as there's been only one wind power site in Norway. However, the situation has changed, and there are now a number of wind power projects that are under consideration (see http://www.nve.no/energiforvaltning/ressurs/vindkraft/vindkraft.html), and there is now a need for including wind power in the simulation tools.

These large scale wind power sites have more similarities to a centralized production unit rather than “negative consumers”, and are therefore not expected to reduce the transmission losses significantly. The simulation results were achieved by first disconnecting the wind power site and simulate a reference case, that is NTE without wind power production. The various wind power sites were then connected to the grid to simulate the change of the power flow when introducing the wind power site. For the regional grid simulations, Vikna wind power site was kept connected because Vikna wind power site already is a part of NTE’s power production.

6 The wind power model

Our first step was to establish a wind power model to be used in the Netbas simulation model. Using the load object in Netbas (representing consumer loads), we were able to model Vikna wind power site as a “negative consumer”. The data acquired for this was a yearly power production curve with time steps of one month and a power curve with a daily consumption pattern. This is how the consumer load in Netbas is modelled (see Appendix). While the monthly wind power production curve could be presented as “negative load”, there were no periodic behaviour on a daily basis for Vikna wind power site, as the wind power production over shorter time periods turned out to be stochastic Fourier analysis of the hourly wind power production in January was used to possibly identify periodic power production from wind power. The resulting periodogram showed no periodic behaviour of wind power production at shorter time intervals. The data basis was the hourly logged power measurements from each wind turbine during 1995 and 1996.

The time series for wind power were averaged monthly, represented by the dotted line in figure 4b)

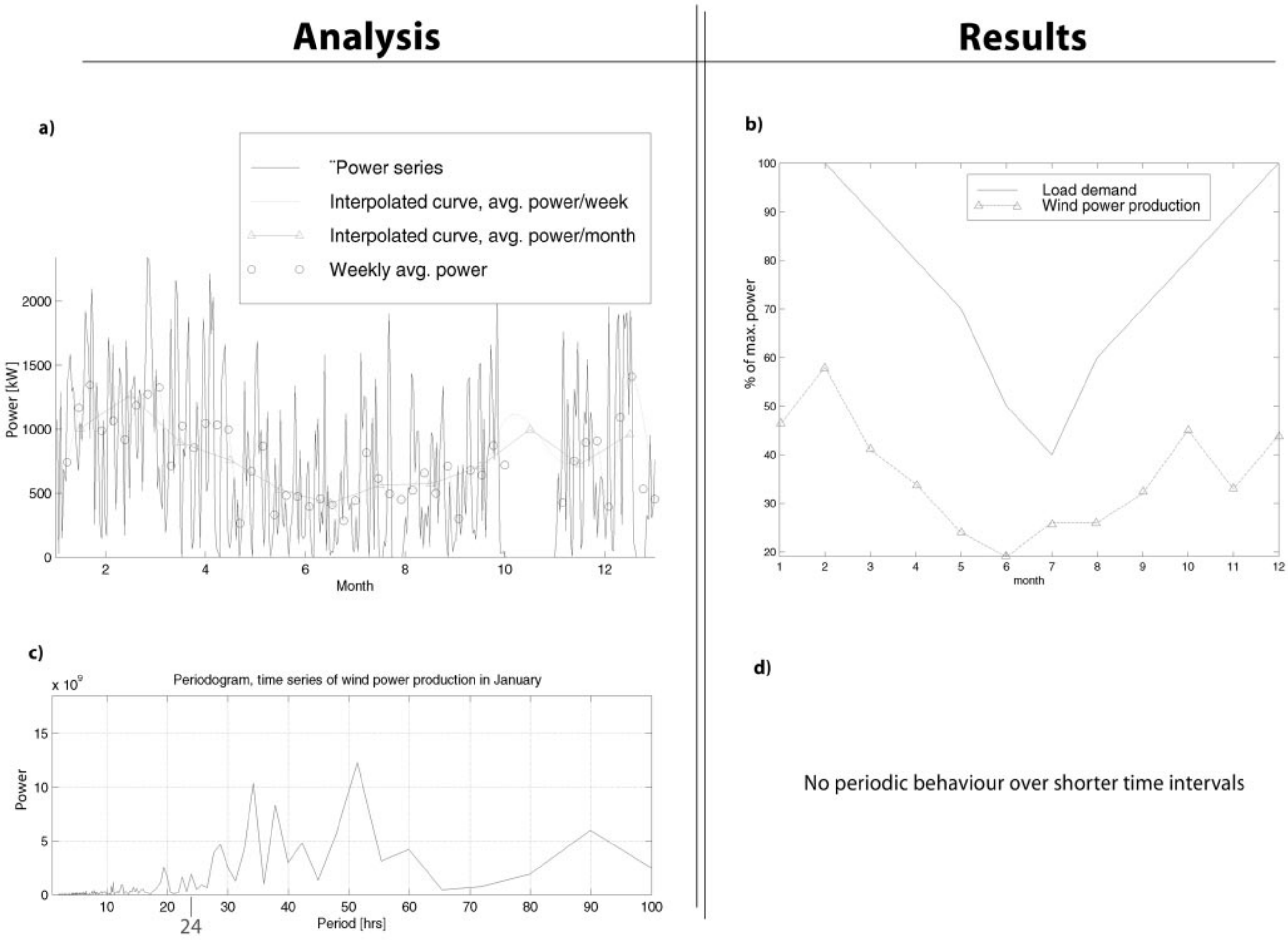


Figure 4 a) shows the wind power production curve (Measured data of October month is missing, and the wind power production was interpolated for this month). b) compares the yearly wind power production with the demand curve. c) Fourier analysis were used to check whether wind power production has a periodic behaviour over a day, similar to the demand curve. The periodogram is a plot of the fourier coefficients squared, whereas the x-axis is the time periods. The Fourier analysis was based on the wind power time series of January. The periodogram shows that there are no strong periodic behaviour at Vikna.

The results show that the energy production at Vikna is positively correlated with the demand curve over a year (see figure 4a). The wind power production curve from Vikna was also used to simulate the other wind power production sites. Although the wind conditions might be slightly different, the purpose in this paper is to estimate the transmission losses in the grid. For this purpose, the location of the site in the grid will be of more importance. The wind power production curve is represented as percent of max. capacity.

7 Simulation results

figure 5 shows the simulation result of the 4 selected cases described in the previous section. The transmission loss The transmission loss reductions are represented in percent of the wind energy production within the month. HH1

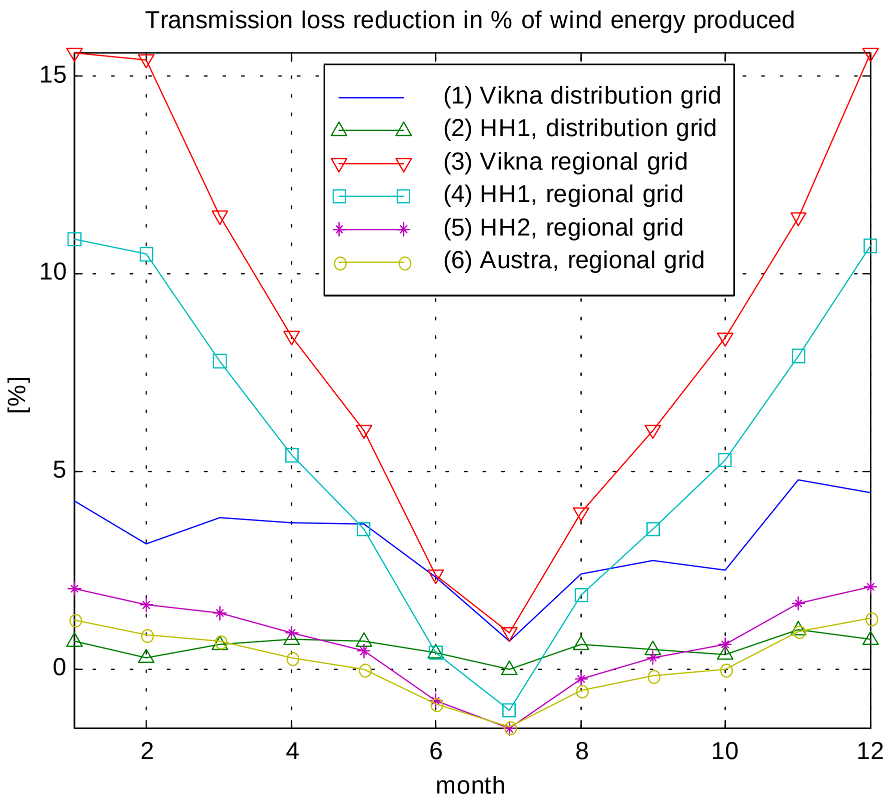


Figure 5 Simulation results - wind power's influence on transmission losses

and Austra did not have a significant impact on the transmission losses, while the wind power sites integrated into the distribution grids reduced the transmission losses significantly per kWh. figure 6 compare the results on a yearly basis.

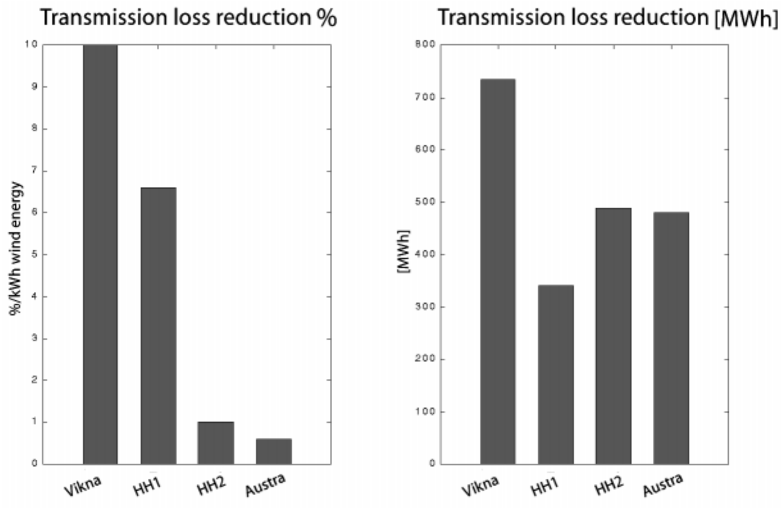


Figure 6 Simulation results, The left graph illustrates reduced energy losses in percentage of wind energy production for each project. The graph on the right, shows the energy loss reductions for each project in MWh.

8 Implications on the economy of wind power

Distributed energy production (such as wind power integrated into distribution grids) can reduce the transmission costs by reducing the need for transmission over long distances. Although the energy system in Norway is decentralised, with about 650 hydro power stations distributed all over the country and interconnected through the main grid, the population is also dispersed. The transmission system represents large investments to supply population

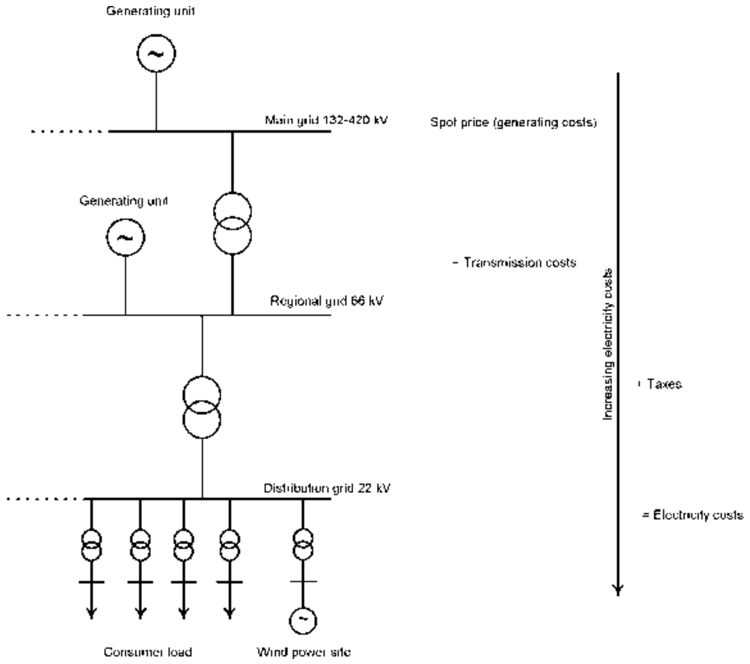


Figure 7 Transmission system; Not only the costs of generating comprise the electricity costs. The transmission costs are related to O & M, investments and administration and system services of power transmission. Distributed energy production is here represented in the distribution grid as a wind power site. Being closer to the consumer, distributed energy production reduce the need for power transmission over long distances, hence reducing the transmission costs.

in rural areas with power. In some of these cases, wind power could represent an alternative to increasing the transmission capacity in coastal areas. table 4 shows the electricity costs refererred to the end-user.

Electricity costs, example NTE 1998	ore/kWh
Spotprice / generating costs	13.30
Transmission costs	21.80
Taxes	17.84
Total	52.94

Table 4 Electricity costs, end-user (Source: Prices, NTE 1998)

The Norwegian electricity supply is a deregulated market; electricity production and distribution are distinguished. All the producers have access to the grid; the customers are free to choose their suppliers, and the costs of transmission is calculated according to NVE's guidelines to ensure an efficient power transmission. One of these cost terms is the energy term:

$$\text{Transmission cost reduction} = \sum_{t=0}^{T} E_{w,t} \cdot MLR_t \cdot SP_r \qquad (5)$$

where $E_{w,t}$ represents the wind energy produced, MLR_t is the *marginal loss reduction*, and SP_r represents the spot price at time step *t*, respectively.

The time step for the calculations are one month. Being a net consumer, any added energy production in Nord-Trøndelag results in reduced need for power transmission from the main grid. This means that wind power also reduce transmission losses in the above main grid (connected at Kolsvik).
The transmission loss estimates in the main grid are set for periods of 8 weeks in the main grid by the operator, Statnett. The transmission losses are referred to some selected nodes in the grid. The regional utility company, in our case NTE, pays the transmission costs for their use of the main grid. Vikna wind power site reduce these costs The costs are calculated for the main grid, the regional grid and the distribution grid. Statnett operate the main grid, while the utilities and distribution companies operate the regional and distribution grids. The marginal losses are estimated using power flow models for, while the spot price changes on an hourly basis.

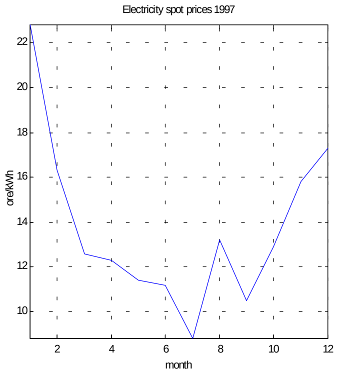


Figure 8 Spot prices Nordpool, 1997 (Source: Nordpool)

Note that the spot prices are much lower than the generating costs for wind power and hydro power projects in Norway that are estimated to be 22 and 25 øre/kWh for the time being. The spot price somewhat correlates with the demand although the expectations among the actors in the electricity market heavily influence the spot price. This is to the benefit of wind power which also correlates with the demand. Lets apply the *transmission cost reduction* formula ((5) on page 10) to Vikna wind power site using the spot price data from 1997 (figure 8), the wind power production curve (figure 4) and the marginal loss reduction curve (figure 5), The cost reduction for transmission of wind power is summarised in table 6

Transmission cost reductions, Vikna wind power site	ore/kWh
Main grid	0.4
Regional grid	1.54
Distribution gird	~0
Total	1.92

Table 5 Transmission cost reduction due to integration of Vikna wind power site

The results show avoided costs of 1.92 øre/kWh of wind power produced at Vikna. Compared to potentially new wind power sites at 25 øre/kWh in total energy costs, the cost reductions are significant for the location of wind power projects (about 7-8% energy cost reductions). The results indicate that transmission loss reduction as a parameter should be taken into consideration for future wind power planning, especially in coastal areas with long distances to the nearest generating units and a potential of significant transmission loss reduction

9 Discussion

One of the simplifications that has been made, was the modelling of the wind power production. The wind power production is averaged over a month, and the effects of wind powers fluctuating power production is therefore neglected. This was done due to limitations in the Netbas simulation program tool. However, the significance of this effect did not seem to alter the results significantly. A simulation of Rørvik distribution grid was performed, entering the hourly power production data of January month. Held against the previous simulation of monthly time steps, there was a slight change of the resulting transmission loss reduction. When keeping daily wind power energy production constant, the transmission loss reductions was reduced from 4.3 to 2.6% (see figure 5). Therefore transmission loss reductions in the distribution grids are likely to be insignificant because the effect of increasing power fluctuations increases the power losses, counterbalancing the effect of reducing transmission distances. In the regional grid however, this effect is not likely to be prominent, as the wind power production is small compared to the demand in the distribution grid. For the wind power sites directly connected to the regional grid, it may have a stronger impact, if this will increase the variations in the power flow. The transmission loss reduction for HH2 and Austra are therefore likely to be insignificant, or may in fact increase the transmission losses (note that HH2 and Austra increase the transmission losses during the summer months, see figure 5)

If we relate the results to the location in the grid, Vikna seems be most beneficial for the power flow as the site is located in the end of the distribution grid, reducing the need for power transmission along the distance Rørvik-Strand-Salbotn-Årsandøy-Kolsvik. The location of HH1 did also reduce the transmission losses, whereas expanding the site to HH2 did not contribute significantly in reducing the transmission losses per kWh.

10 Conclusion

The results show that Vikna reduces the energy grid losses significantly. There was a gain of 10% *transmission loss reductions* per kWh of wind energy produced. For Hundhammer stage I, the loss reductions were 6.6% relative to its energy production. For the bigger sites Hundhammer stage II and Austra, the change in transmission loss reductions were not significant.

Wind power's influence on energy losses in electricity grids are hereby quantified. Distance and fluctuations are of importance, as can be seen from the expression of transmission loss (1). The fact that wind power production correlates with the demand curve as well as the spot price over a year increase the value of wind power. The quantification of transmission loss reductions indicates that wind power can improve the power flow, which benefits the economy of wind power. The transmission loss reduction as a parameter is therefore significant for future wind power projects and should therefore be taken into consideration in future wind power projects, in terms of economy and placement.

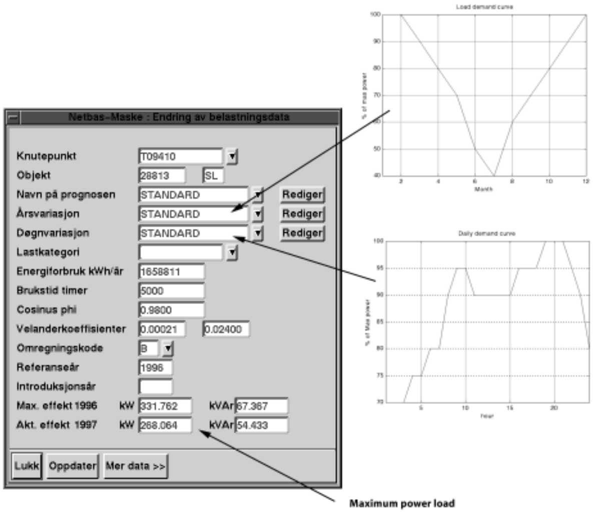
11 Appendix

Netbas

Netbas is a modern network information system for documentation, operation, maintenance and planning of electricity distribution systems. It is used by larger utility companies in Scandinavia. Netbas can perform simulations over several years with an hourly resolution. Netbas Archive is the database in which all necessary data and information about the grid is stored. The calculation method is based on well known methods for power grid simulations using Newton/Raphson and IEC standards. The load data are time-dependent, represented by daily demand curves and yearly demand curves for different categories of consumers, i.e households, public buildings etc. [6] The technical data for each object is stored in the database of Netbas (Netbas Archive), and the grid model comprise an interconnected grid of objects that determine the set of differential equations. The load object will be described more in detail, while the other objects are just mentioned briefly.

No. of units	NTE's regional grid	Rørvik local grid
Generators	42	1
Load objects	72	181
Capacitor s	16	none
Transformers	106	180
Lines/cables	162	340

Table 6 An overview of the components that represent NTE's regional grid and Rørvik distribution grid. Each components contains technical data, for instance, each cable object contain technical data used for the computations, such as length, impedance etc.



Netbas-Maske : Endring av belastningsdata

Knutepunkt	T09410	
Objekt	28813	SL
Navn på prognosen	STANDARD	
Årsvariasjon	STANDARD	
Døgnvariasjon	STANDARD	
Lastkategori		
Energiforbruk kWh/år	1658811	
Brukstid timer	5000	
Cosinus phi	0.9800	
Velanderkoeffisienter	0.00021	0.02400
Omregningskode	B	
Referanseår	1996	
Introduksjonsår		
Max. effekt 1996	kW 331.762	kVAr 67.367
Akt. effekt 1997	kW 268.064	kVAr 54.433

Figure 9 The load object in Netbas

Load objects

The load objects define the power demand for one consumer in the grid at each (hourly) time step. The load demand for time step i is [7] :

$$\begin{aligned} P_i &= P_{max} k_{1i} k_{2i} k_{3i} \\ Q_i &= Q_{max} k_{1i} k_{2i} k_{3i} \end{aligned} \qquad (6)$$

where P_{max} and Q_{max} is maximum active and reactive power value and the coefficients k_{1i}, k_{2i}, k_{3i} correspond to *prognosis, yearly variation* and *daily variation* respectively. *Prognosis* is the correction coefficient of the power demand relative to the reference year. For example, if $k_1 = 1.02$ for 1998, given 1997 as a reference year, it means that the power demand is expected to increase by 2% in 1998. *Yearly variation* is the variation of the power demand over a year expresssed as a percentage of P_{max} that particular year. The resolution here is one month. The third coefficient, k_{3i} describes the variation in consumer load within a day. Typically, noon is the peak hour for a public institution, while the daily demand curve for a household typically reaches its peak during the evening (see figure 9). k_{3i} is measured in percent of the peak value of the day. Alltogether, the expression defines the demand curve for the actual load object over a year with a resolution of one hour.

Other objects such as lines and cables contain technical data such as length, impedance etc. These technical data is stored in the database of Netbas. During simulation the power demand is estimated and Netbas will select which unit to operate, given the constraints defined in the generating unit object data (i.e. maximum power production). The generating units are ranged after their operating costs[4]. The prioritation of which unit to operate may differ from the real management as the power production is managed by the control centre of NTE. Operation of their units are based on long time experience in addition to cost estimates of the different generating units.

Calculations

In the simulation, the function *"Detailed simulation over a year"* was used, which creates a table of monthly max/min power -and energy consumption for the total grid, along with transmission losses in the electricity grid. The yearly energy consumption of a load object is then calculated by [7]

$$E_{SL} = P_{max} k_1 \sum_{i=1}^{12} 30 k_{2i} \sum_{j=1}^{24} k_{3j} \; [MWh] \qquad (7)$$

where j is hour No. j within the month i. The number 30 corresponds to the number of days in a month (a simplification made in Netbas). The transmission loss in the electricity grid was stated in section "Theory and program tools" on page 3. The transmission loss model in Netbas is likely to be a linearized model of (1) on page 4.

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[4] Actually, the decision of which generating unit to operate, is controlled manually, from the control centre of NTE. The production is planned and regulated on an hourly basis. According to NTE, energy losses in the transmission system is not taken into consideration when selecting genertaing units to operate.

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