TR A6337

Impact of integrating wind power in the Norwegian power system

John Olav Tande

www.energy.sintef.no

SINTEF Energy Research

April 2006

SINTEF

SINTEF

SINTEF Energy Research

Address: NO-7465 Trondheim, NORWAY
Reception: Sem Sælands vei 11
Telephone: +47 73 59 72 00
Telefax: +47 73 59 72 50

www.energy.sintef.no

Enterprise No.: NO 939 350 675 MVA

TECHNICAL REPORT

SUBJECT/TASK (title)

Impact of integrating wind power in the Norwegian power system

CONTRIBUTOR(S)

John Olav Tande

CLIENTS(S)

EBL Kompetanse AS

TR NO.	DATE	CLIENT'S REF.	PROJECT NO.	
TR A6337	2006-04-18	Hans Magne Ådland	12X423.01	
ELECTRONIC FILE CODE		RESPONSIBLE (NAME, SIGN.)	CLASSIFICATION	
051219RHA91928		Kjetil Uhlen	Unrestricted	
ISBN NO.	REPORT TYPE	RESEARCH DIRECTOR (NAME, SIGN)	COPIES	PAGES
82-594-3176-9		Petter Støa	14	47
DIVISION		LOCATION	LOCAL FAX	
Energy Systems		Sem Sælands vei 11	+47 73 59 72 50	

RESULT (summary)

Wind power may in the future constitute a significant part of the Norwegian electricity supply. 20 TWh annual wind generation is a realistic goal for 2020 assuming wind farms on-land and offshore.

The development of grid codes for wind farms is sound. It is recognising that large wind farms are basically power plants and may participate in securing efficient and stable power system operation. Modern wind farms may control the reactive power or voltage as any other power plant, and may also control active power or frequency as long as wind conditions permits. Grid code requirements must however be carefully assessed and possibly adjusted over time aiming for overall least cost solutions.

Development of wind farms are today to some degree hindered by conservative assumptions being made on operation of wind farms in areas with limited power transfer capacity. By accepting temporary grid congestions, however, a large increase in installed wind power is viable. For grid congestion that appears a few hours per year only, the cost of lost generation will be modest and may be economic over the alternatives of limiting wind farm capacities or increasing the grid transfer capacity.

Wind generation impact on power system operation and adequacy will be overall positive. Combining wind and hydro provides for a more stable annual energy supply than hydro alone, and wind generation will generally be higher in the winter period than in the summer. Wind will replace the generation with the highest operating cost, and reduce the average Nord Pool spot market price. 20 TWh wind will reduce price with about 3 øre/kWh and CO_2 emissions by 12-14 million tons for the case of replacing coal, and about 6 million tons for replacing natural gas. Wind impact on need for balancing power is small, i.e. the extra balancing cost is about 0,8 øre per kWh wind, and about half if investment in new reserve capacity is not needed.

In summary this report demonstrates options for large scale integration of wind power in Norway. Local control enables operation of a large wind farm on a fairly weak regional grid, and marked based balancing tackles large magnitudes of wind power. A future with high penetration of wind power seems thus viable, though the operational challenges with respect to operating reserves, frequency control and transmission capacity are expected to become increasingly important. The hourly wind power variations may be significant within local areas, but uncorrelated between distant sites. Hence, sufficient transmission capacity may be a key for efficient operation of a future Norwegian and indeed a European power system with a large share of wind power.

The findings of this report are largely based on literature survey. Specific Norwegian studies are generally lacking on wind impact on system operation, balancing and adequacy. It may thus be relevant to carry out such studies, and then possible both for Norway as a whole and for Norwegian regions.

KEYWORDS

SELECTED BY AUTHOR(S)	Wind power	Power system operation
	Grid integration	Power system adequacy

TABLE OF CONTENTS

Page

PREFACE

The scope of this report is to summarize the facts about the impact of integrating wind power in the Norwegian power system, but also pinpoint items that should be further investigated. The target audience is employees in energy companies, interest groups, industry organizations and public administration.

1 INTRODUCTION

1.1 The Norwegian power system

The Norwegian power system is operated as part of the Nordic electricity market being a joint market between Norway, Sweden, Denmark and Finland. Nord Pool organizes the trade of supply and demand, whereas the national Transmission System Operators (TSOs) secure reliability and balance of supply. Nordel facilitates cooperation between the TSOs aiming for an efficient and harmonised Nordic electricity market.

The Nordic power supply is dominated by hydro (48 %), conventional thermal (18 %) and nuclear generation (25 %). The Norwegian generation is almost entirely based on hydro (99 %), whereas for Sweden the hydro share of national supply is 40 % and for Finland 18 %. Wind generation is significant in Denmark (17 % of the generation in Denmark in 2004 was by wind), but constitutes presently only 2 % of the total Nordic supply. More detailed system data for 2004 is shown in Table 1.

Table 1: Generation, cross-border transmission and load for Nordic countries in 2004, [1].

	Denmark	Finland	Norway	Sweden	SUM
Installed capacity (MW)	**12710**	**16488**	**28327**	**33551**	**91076**
Hydro (MW)	11	2 986	27 925	16 137	47 059
Thermal (MW)	8 888	8 423	121	5 803	23 235
Nuclear (MW)	0	2 671	0	9 471	12 142
Wind (MW)	3 122	79	158	442	3 801
Bio (MW)	418	2 198	96	1 545	4 257
Waste (MW)	271	131	27	153	582
Generation (GWh)	**38 377**	**81 920**	**110 545**	**148 484**	**379 326**
Hydro (GWh)	26	14 726	109 280	59 529	183 561
Thermal (GWh)	29 050	34 173	582	5 284	69 089
Nuclear (GWh)	0	21 779	0	75 039	96 818
Wind (GWh)	6 583	120	260	850	7 813
Bio (GWh)	1 365	10 146	296	6 971	18 778
Waste (GWh)	1 353	976	127	811	3 267
Import (GWh)	**8 768**	**12 218**	**15 335**	**15 586**	**51 907**
Export (GWh)	**11 643**	**7 221**	**3 840**	**17 624**	**40 328**
Total consumption (GWh)	**35 502**	**86 917**	**122 040**	**146 446**	**390 905**
Max load (MWh/h)	**6 445**	**14 040**	**19 984**	**26 400**	**66 869**

As hydropower dominates the supply and the annual hydro generation capability may vary significantly from year to year, cross-border transmission capacity for electricity import and export is a key for reliable and efficient power system operation. In a year with average hydro inflow the sum hydropower generation in the Nordic countries is 204 TWh, but can vary about +/- 40 TWh depending on yearly precipitation. For Norway the same figures are 119 TWh +/- 30 TWh. The main cross-border transmission capacities are shown in Figure 1.

Figure 1: Main cross-border transmission capacities given as aggregate figures. Dotted lines are planned. Source: Statnett.

Data from system operation shows a fairly tight supply situation, in particular for Norway, see Figure 2, and Statnett (Norwegian TSO) sees a significant need for both new generation and transmission capacity, [2].

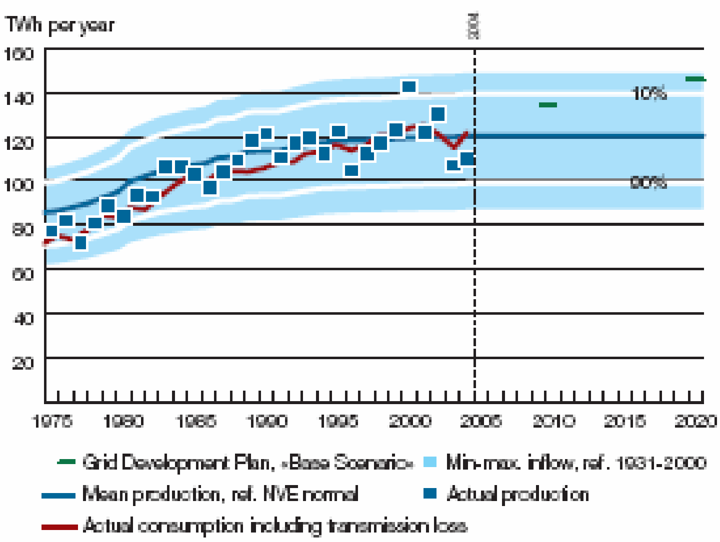


Figure 2: Annual Norwegian consumption, generation and hydro inflow. Copy from [2].

1.2 Plans and potential for wind power in Norway

There is currently a significant interest in developing wind farms in Norway. At present (April 2006) the installed wind power capacity is 281 MW producing annually about 0,8 TWh, whereas recent forecast from NVE (Norwegian Water Resources and Energy Directorate) states 3 TWh in 2010, 5-7 TWh in 2015 and 7-10 TWh in 2020 [5]. Indeed, the available wind resource in Norway is for any practical purpose unlimited[1], thus development is basically a question about economic feasibility and willingness to prioritize. Given the great wind potential in Norway, both for generation and for industrial development, [1] argues that 20 TWh is a realistic goal for 2020 assuming wind farms on-land and offshore. 20 TWh annually wind production will require about 6-7000 MW of installed wind power capacity that can be realized within areas totalling some few hundred square km, e.g. 10x70 km (the Norwegian land area 307 860 km^2). Figure 3 shows current project plans.

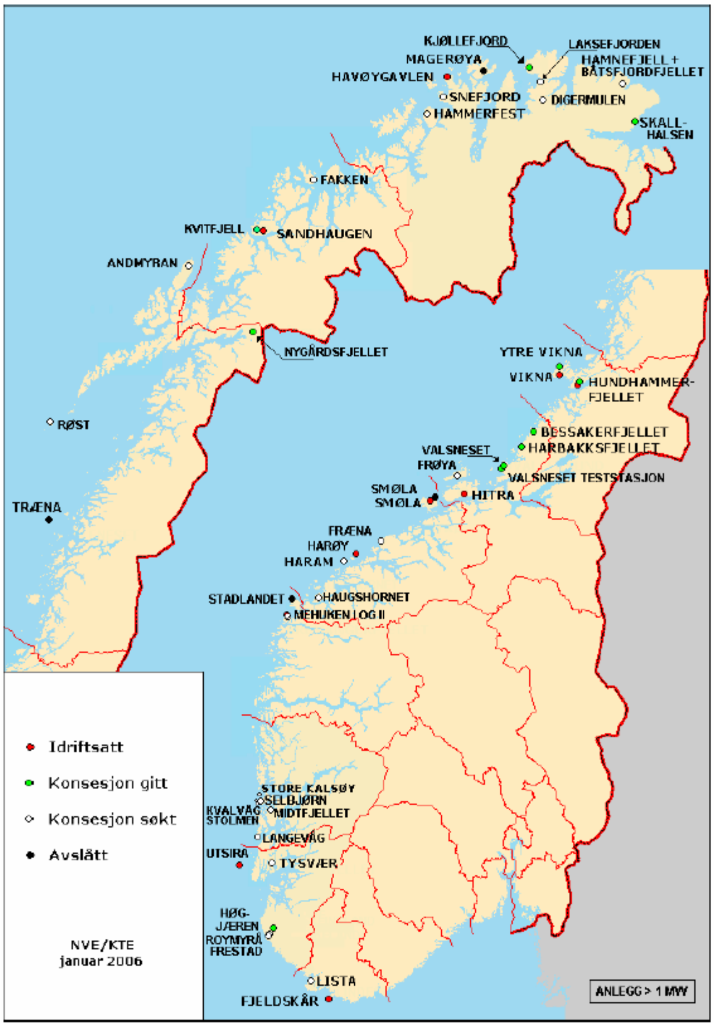


Figure 3: Wind power projects in Norway. Wind farms in operation total 281 MW (red dots). Concession is granted for an additional 838 MW (green dots), and another 2275 MW has applied for concession (white dots). Total including projects in earlier planning stage (not shown on the map) amounts to an annual wind generation of +20 TWh. Source: NVE.

---

[1] The Norwegian Wind Atlas [4] states that wind farms in Norway (on-land coastal areas) theoretically can supply +1000 TWh and an additional 800 TWh from shallow water Norwegian offshore sites (< 50 m water depth).

The wind farms will mainly be fairly large and located in areas with relatively weak grids. This has put focus on grid issues. Considering the potential and scale of plans for wind power in Norway, in the future, wind power may constitute a significant part of the supply system, and the implications of this have become an issue of debate. Indeed, this is not only a Norwegian issue. The globally installed wind capacity has developed very rapidly, see Figure 4, and forecasts predicts this to continue as a means to reduce greenhouse gas emissions, cut-back on fuel dependency and improve power system reliability, see also note[2]. The significant amounts of wind power installed in Europe, in particular in Germany (18 424 MW), Spain (10 027 MW) and Denmark (3 122 MW) demonstrate that wind can constitute large scale generation, but for efficient and reliable power system operation grid issues must be carefully assessed.

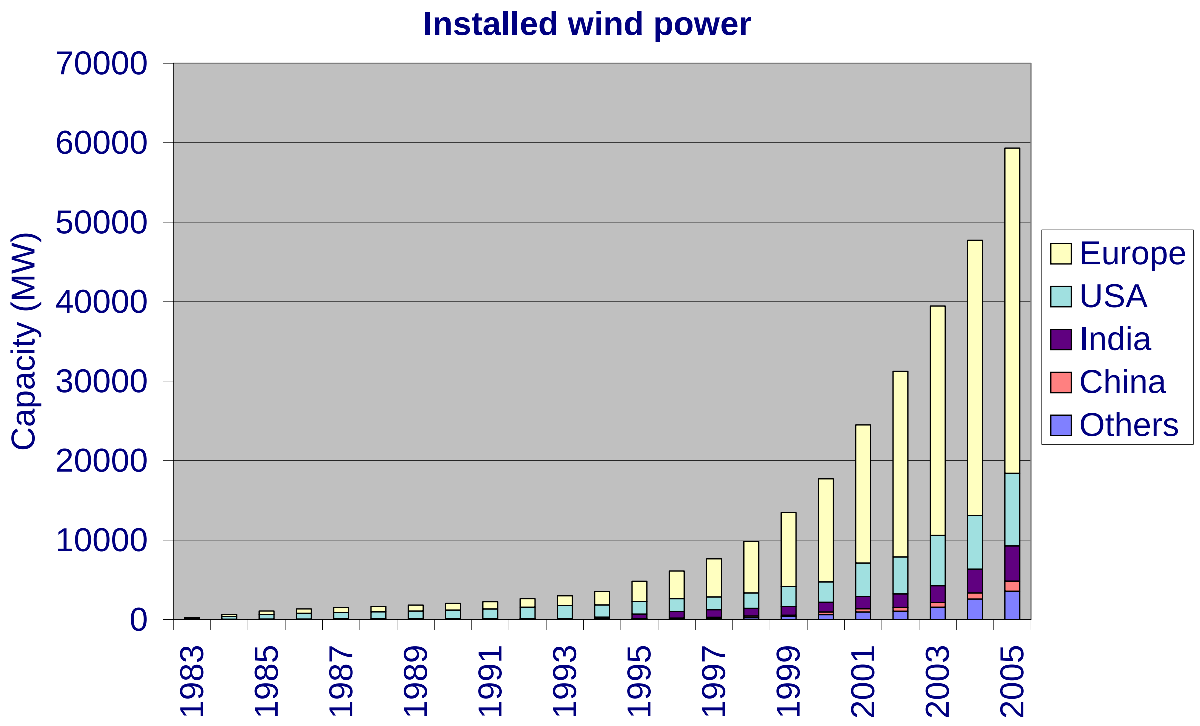


Figure 4: Installed wind power capacity.

Norway is in many ways an ideal country for large scale wind generation. Large areas on land and offshore exposed to high wind speeds provide for a great wind potential. At on-land sites being considered by developers in Norway the annual utilization time (full load hours) is typically + 3000 hours and cost of generation 25-35 øre/kWh (see also note[3] and Figure 5, offshore wind may be more expensive). Considering that volume of market and technology development will continue bringing down cost of new wind generation, it is likely that at good Norwegian sites wind will be the cheapest option for new non-polluting generation. In comparison, in most other countries less wind utilization time is expected and thus higher cost of generation, e.g. in

[2] The European Parliament has voted September 2005 to strongly support renewable energy by adopting a report [6] calling for an increase of the share of energy from renewable sources from 6 % in 2001 to 20 % by 2020 (equivalent to 33 % of electricity from renewable energy sources, and a large portion of this will be wind).
[3] The cost of wind generation is 30 øre/kWh for assuming an annual utilization time of 3000 hours, an investment cost of NOK 8 million per MW, operation and maintenance at 5 øre/kWh, 20 years lifetime and 7 % p.a. discount rate. The investment cost includes NOK 5 million per MW for wind turbine price ex factory and NOK 3 million per MW for freight, site works and installation. 1 NOK = 100 øre. 8 NOK ~ 1 euro.

Germany the utilization time of wind farms is typically 1500 - 2000 hours. Further, the hydro-based Norwegian power system offers very good regulation capabilities that can perfectly match wind generation, and a much better partner for wind than the thermal-based power systems of most other countries. Still, aiming that large scale generation of wind shall contribute to efficient and reliable power system operation, it is highly relevant to carefully address wind implications on grid and power system operation. This is relevant not only for considering wind generation in Norway, but also as the Norwegian hydro-based system can be utilized for balancing wind in other countries.

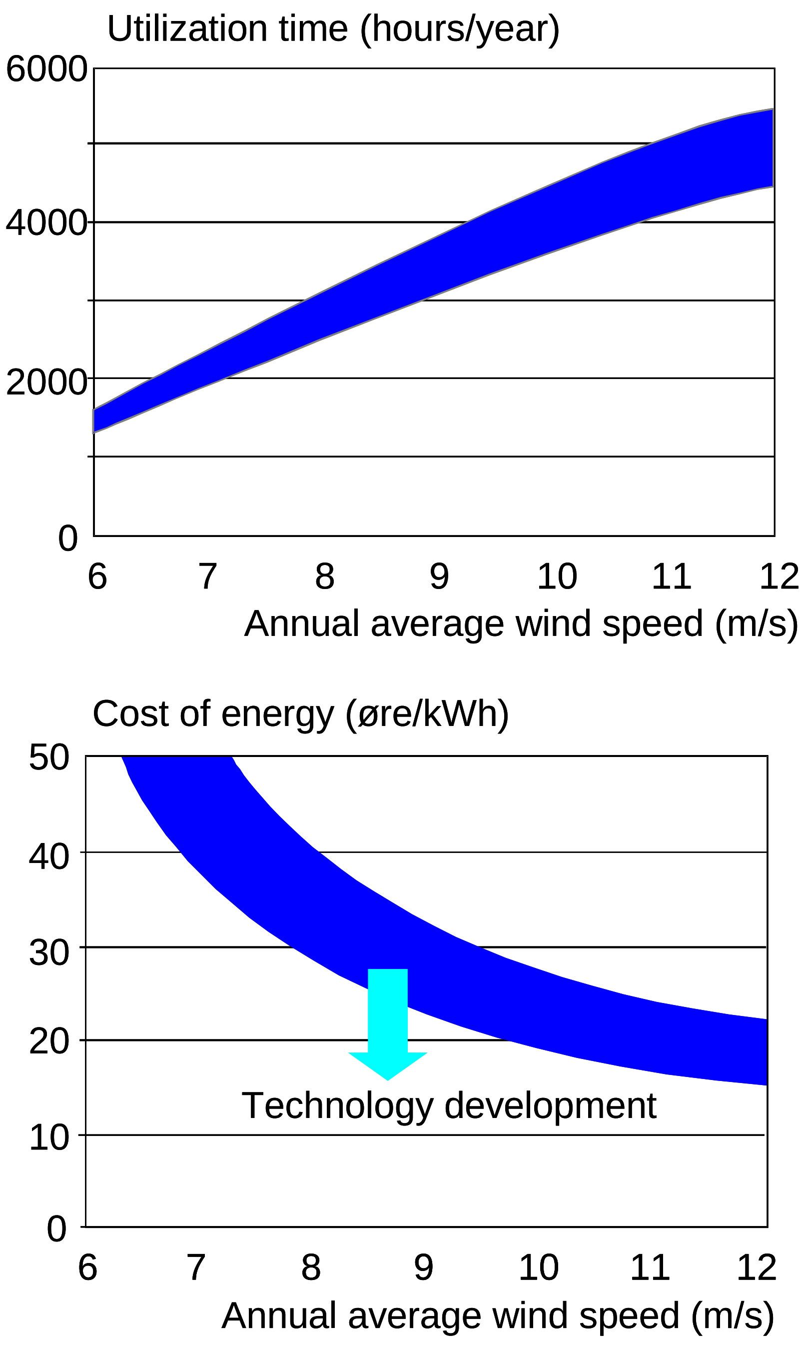


Figure 5: Utilization time (upper graph) and cost of on-land wind generation (lower graph) as a function of annual average wind speed.

2 WIND POWER TECHNOLOGY

Wind energy technology has made major progression since the industry started in the early 1980s, and is now available for large scale generation from large energy companies. Total turnover in 2005 was about NOK 100 billion. Vestas (DK), Enercon (DE), Gamesa (ES), GE (USA) and Siemens (DE) are the top five in market share. Norwegian industries are mainly sub-suppliers (export in 2004 was about NOK 400 million), whereas ScanWind design and manufacture large wind turbines (+ 3 MW).

Modern wind turbines are designed for autonomous operation, i.e. they can be connected to a grid and left to operate without any manual interference than for maintenance service or repair. The technical availability is typically about 97 %, EWEA [7].

The wind generation will vary with the wind speed, see Figure 6. Normally wind turbines start producing at 4-5 m/s (cut-in wind speed) and then increasing until rated power is reached at 12-15 m/s (rated wind speed). At higher wind speeds the generation is limited to rated power, whereas wind turbines are normally stopped for wind speeds exceeding 25 m/s (cut-out wind speed). It is technically possible to design wind turbines for operation at higher wind speed, though this may cost extra for reinforcing the construction and must be balanced against the benefit of extra generation.

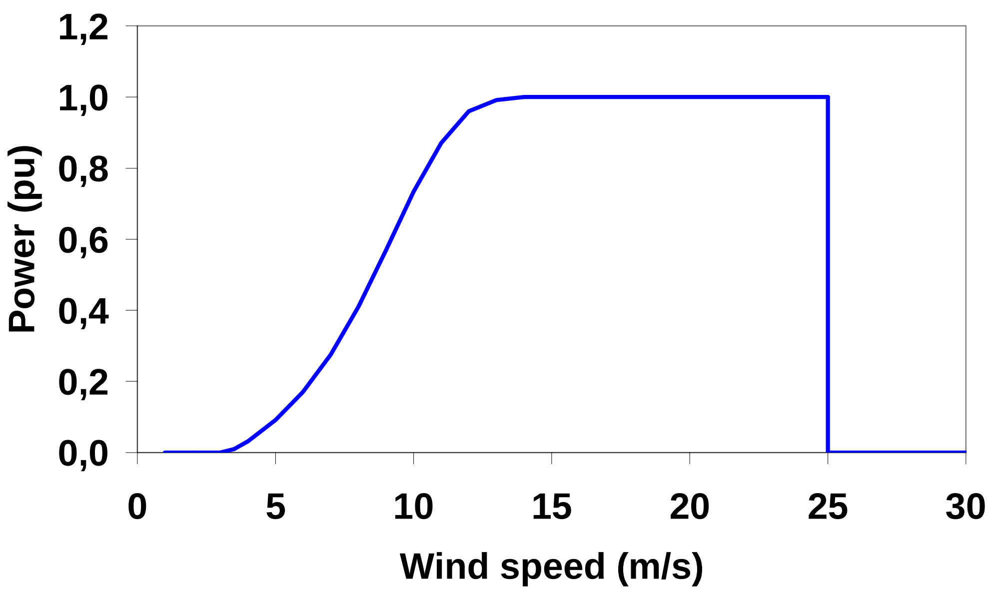
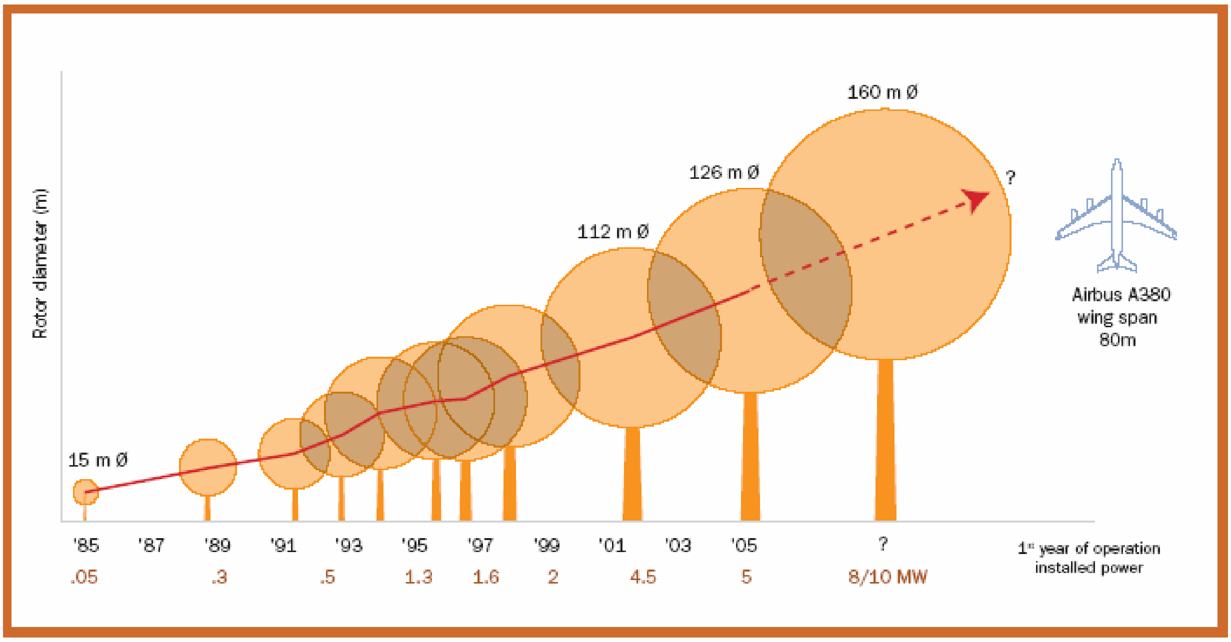


Figure 6: Power curve of wind turbine (for illustration). The power curve gives the steady state relation between wind speed upfront of the turbine and the output power of the wind turbine.

Typical rated power for wind turbines are today 2-5 MW, see Figure 7. The trend is towards bigger turbines and installation in clusters constituting large wind farms. The generator voltage is normally 0.69 – 1 kV, but is connected with a transformer to give medium voltage (e.g. 20 kV). In wind farms medium voltage level is used for the internal grid with a transformer station (if required) for connection to the utility grid (medium or high voltage).



Source: Jos Beurskens, ECN

Figure 7: Development of wind turbine size.

Sizes of wind farms are ranging from a few MW up to several hundred MW. The wind farm characteristic depends on the applied wind turbine technology (fixed speed or variable speed), but also on the wind farm control system and ancillary equipment.

A modern wind farm may facilitate power plant characteristics that may participate in frequency and voltage control, see Figure 8, and also contribute to system stability and fault recovery.

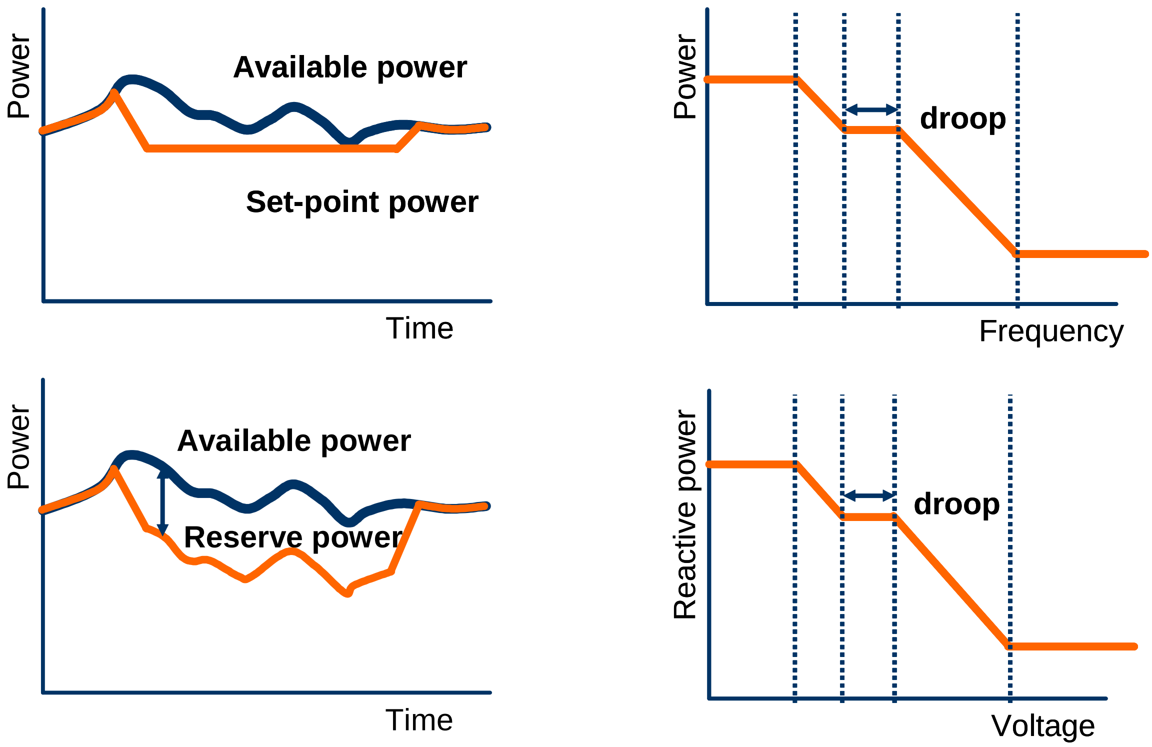
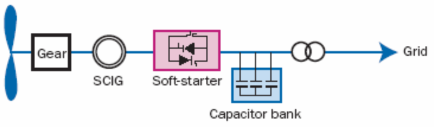
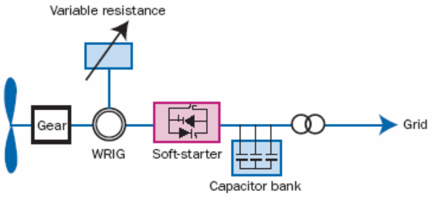
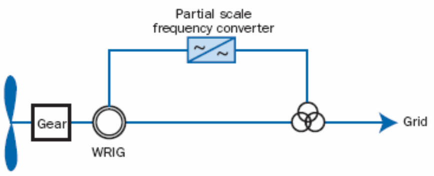
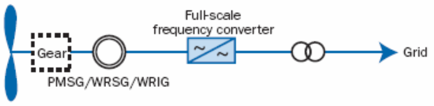


Figure 8: Modern wind farm control options.

Table 2 gives an overview of the main wind turbine technologies.

Table 2: Overview of wind turbine concepts, copy from [7].

Type of system	Description
A Fixed speed (one or two speeds)  **European market share (cum):** 30%.	Introduced and widely used in the 80s, the concept is based on a 'squirrel cage' asynchronous generator (SCIG), its rotor is driven by the turbine and its stator is directly connected to the grid. Its rotation speed can only vary slightly (between 1% and 2%), which is almost "fixed speed" in comparison with the other wind turbine concepts. The concept exists both in single speed and double speed versions. The double speed operation gives an improved performance and lower noise production at low wind speeds. Aerodynamic control combined with type A concept is mostly passive stall, and as a consequence there are few active control options, besides connecting and disconnecting, especially if there is no blade pitch change mechanism. The concept has been continuously further developed, for example in the so-called active stall designs, where the blade pitch angle can be changed towards stall by the control system. **Manufacturer:** Suzlon, Nordex, Siemens Bonus, Ecotècnia **Power plant capabilities:** Voltage control, Reactive power control
B Limited variable speed  **European market share (cum):** 10%	Type B wind turbines used by Vestas in the 80s and 90s are equipped with a 'wound rotor' induction generator (WRIG). Power electronics are applied to control the rotor electrical resistance, which allows both the rotor and the generator to vary their speed up and down to ± 10% during wind gusts, maximising power quality and reducing the mechanical loading of the turbine components, (however at the expense of some minor energy losses). The wind turbines of type B are equipped with an active blade pitch control system. **Manufacturer:** Vestas (V27, V34, V47) **Power plant capabilities:** Voltage control (power quality)
C Improved variable speed with DFIG  **European market share (cum):** 45%	Type C concept is presently the most popular system, combining advantages of previous systems with advances in power electronics. The induction generator has a wound rotor, which is connected to the grid through a back-to-back voltage source converter that controls the excitation system in order to decouple the mechanical and electrical rotor frequency and to match the grid and rotor frequency. The application of power electronics provides control of active and reactive power, enabling active voltage control. In this type of systems, approximately up to 40% of the power output is going through the inverter to the grid, the other part is directly going to the grid, and the window of speed variations is approximately 40% up and down from synchronous speed. **Manufacturer:** GE (1.5 series and 3.6), Repower, Vestas, Nordex, Gamesa, Ecotècnia, Ingetur, Suzlon **Power plant capabilities:** Reactive power, Voltage control, Fault ride through
D Variable speed with full-scale frequency converter  **European market share (cum):** 15%	Type D wind turbines are offered with the classical drive-train (geared), in the direct-drive concept (with slow running generator) and even in a hybrid version (low step-up gearbox, and medium speed generator). Various types of generators are being used: synchronous generators with wound rotors, permanent magnet generators and squirrel cage induction generators. In type D wind turbines the stator is connected to the grid via a full-power electronic converter. The rotor has excitation windings or permanent magnets. Being completely decoupled from the grid, it can provide an even more wide range of operating speeds than type C, and has a broader range of reactive power and voltage control capacities. **Manufacturer:** Enercon, MEG (Multibrid M5000), GE (2.x series), Zephyros, Winwind, Siemens (2.3 MW), Made, Leitner, Mtorres, Jeumont **Power plant capabilities:** Reactive power, Voltage control, Fault ride through

3 WIND POWER CHARACTERISTICS

As introduced in section 2, wind farms are basically power plants. The distinction is that wind farms may produce a variable output depending on wind variations. Wind turbines are therefore not commonly designed for isolated operation, but rely on the connected power system to balance production and load. This is demonstrated to work well at the current level of wind power capacity installed, though the concern is that of a future situation when wind power is developed to constitute a more significant part of the supply.

3.1 Annual and seasonal wind power variations

The expected annual and seasonal variations in production from wind farms in Norway have been studied in [8]. The study shows that:

- the annual wind generation will vary less than the annual hydro generation, see Figure 9,
- the standard deviation of the annual wind generation is 10,49 %,
- the standard deviation of the annual hydro generation is 13,78 %,
- the correlation between the annual wind and hydro generation is weak (the correlation coefficient between the annual wind generation and the annual hydro inflow is 0,47),
- the seasonal wind power variations will on average fit well the consumption, see Figure 10, and is opposite to the average seasonal hydro inflow.

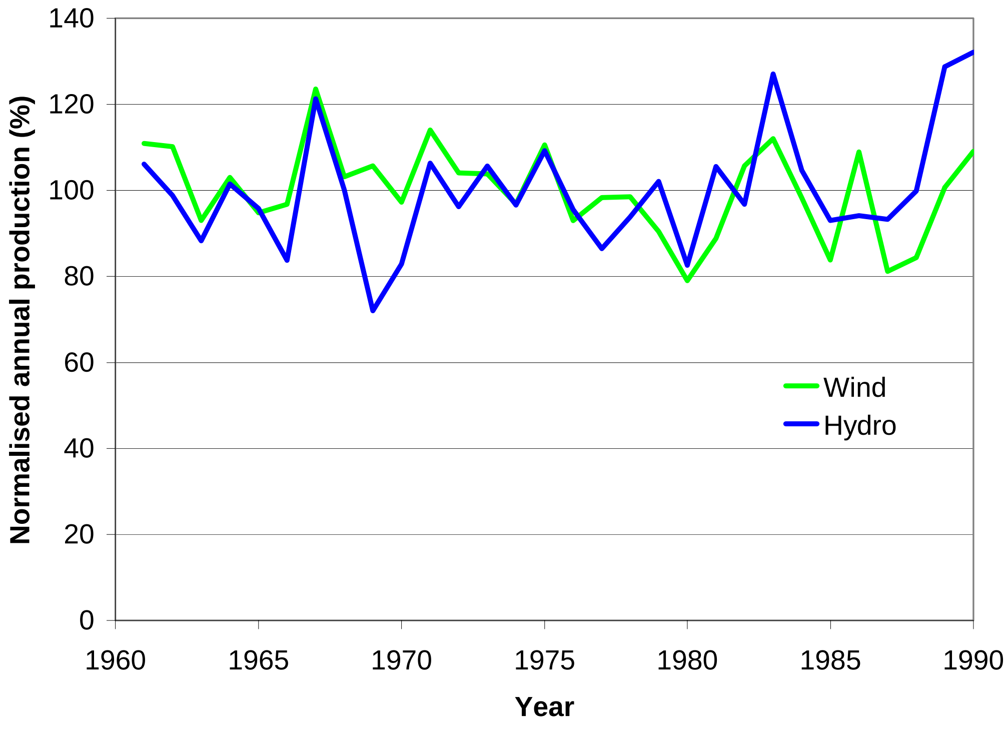


Figure 9: Normalised annual variations of hydro and wind power, [8].

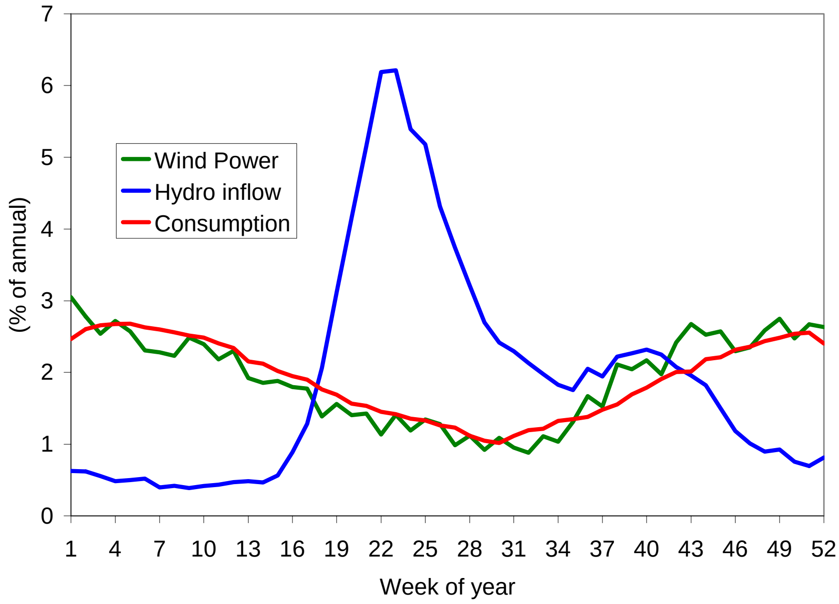


Figure 10: Expected week by week variation in wind power production, compared with consumption and hydro inflow, [8].

3.2 Hourly wind power variations

Figure 11 shows results of a German study [9] that has assessed wind power variations on shorter time scales. The graph basically tells that variations in wind power production will be uncorrelated between sites as long as these are sufficient far apart, e.g. hourly variations will be uncorrelated for distances about 80 km and above, 2 hourly variations will be uncorrelated for distances above 200 km and so on. The relevance of this is that data from a single wind turbine or wind farm should not simply be scaled to indicate expected variations of wind power from a region of some size, but rather such estimates must be based on data from more sites that reflects the geographical distribution of the wind power installations.

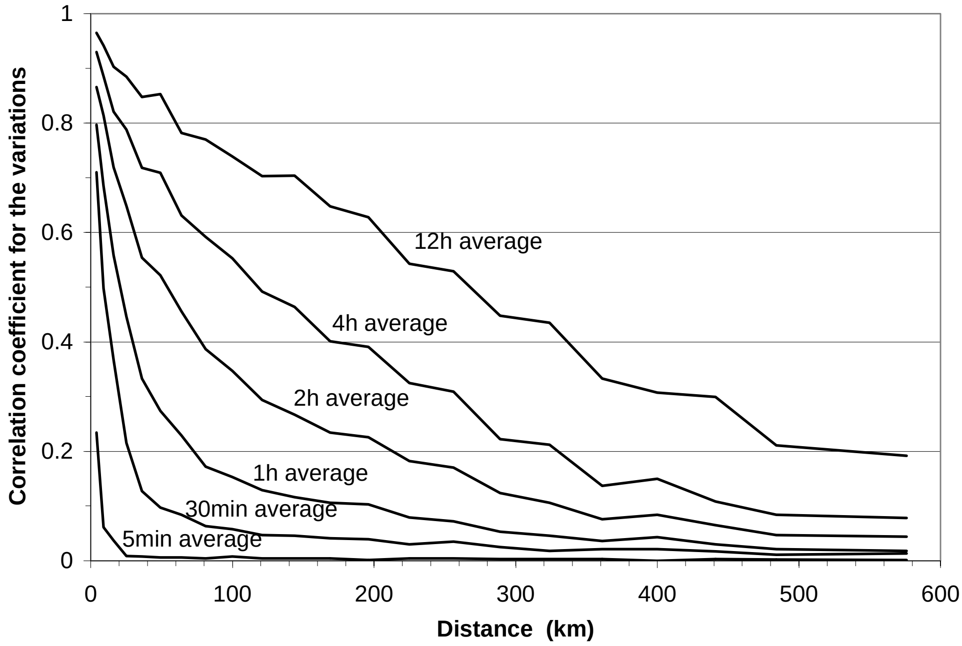


Figure 11: Correlation coefficient between wind power variations from various sites depending on distance between sites and of the applied averaging period, [9].

Records of measured wind speed from five sites have been applied to assess expected hourly wind power variations in Norway, see Figure 12. The graph indicates that the hourly wind variations between the sites are uncorrelated (as expected since these are +100 km apart), and that the sum wind production will be fairly stable. Assuming that the wind production is distributed on 20 sites (i.e. a rough estimate for the number of wind farm sites along the Norwegian coastline that can be considered uncorrelated with each other with regards to hourly variations), the standard deviation of sum hourly production is estimated to 4 % of the installed wind capacity. In a similar way, taking Finnmark as an example, a conservative estimate would suggest that wind power production within the region can be distributed on three sites more than 100 km apart, hence the sum hourly variations of wind power production would yield a standard deviation of about 11 %.

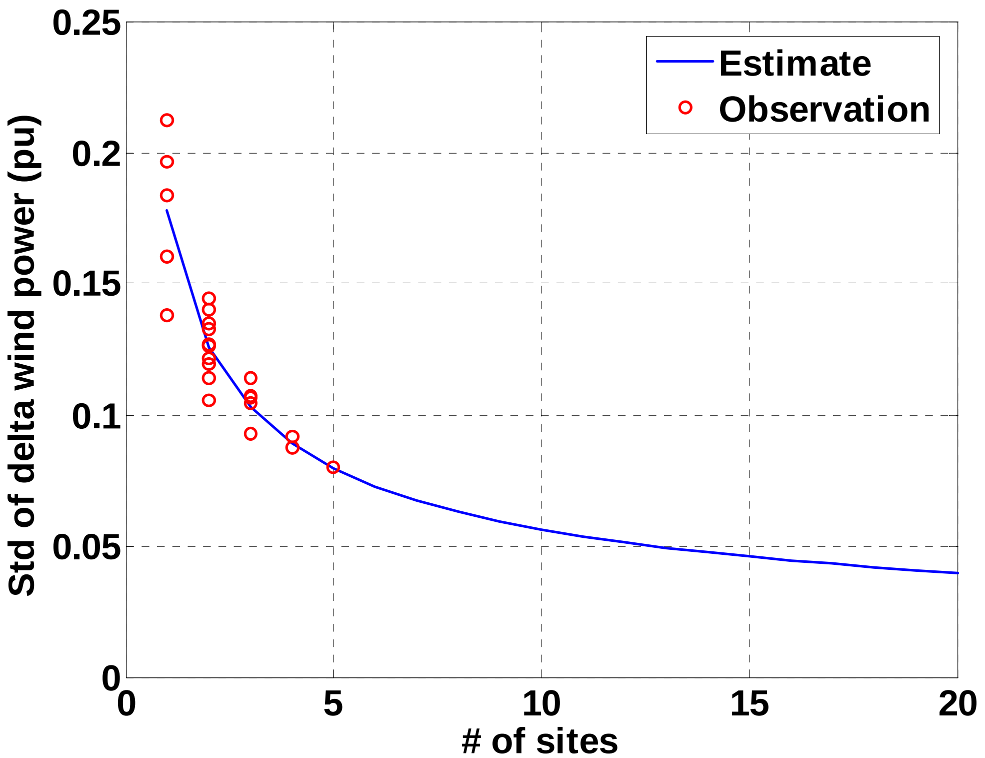


Figure 12: Standard deviation of sum wind power variation from one hour to the next as a function of the number of wind farm sites included in the sum. The observations are from five Norwegian sites and the estimate is prepared assuming no correlation in hourly wind power variations between the sites, [10].

Figure 13 shows results of analyzing measured hour by hour wind data from three sites at north in Norway, and transferring these to simulated hour by hour wind farm output power. The graph illustrates that the sum production from three wind farms will be significantly more stable than from one single wind farm. It is observed that the probability of zero power output is 20 % for a single wind farm, while the corresponding value for the sum power output from three wind farms is less than 5 %. The smoothing effect is also evident for the periods with high wind speed; the three wind farms generates at full power almost never at the same time, compared to about 5 % of the year for a single wind farm.

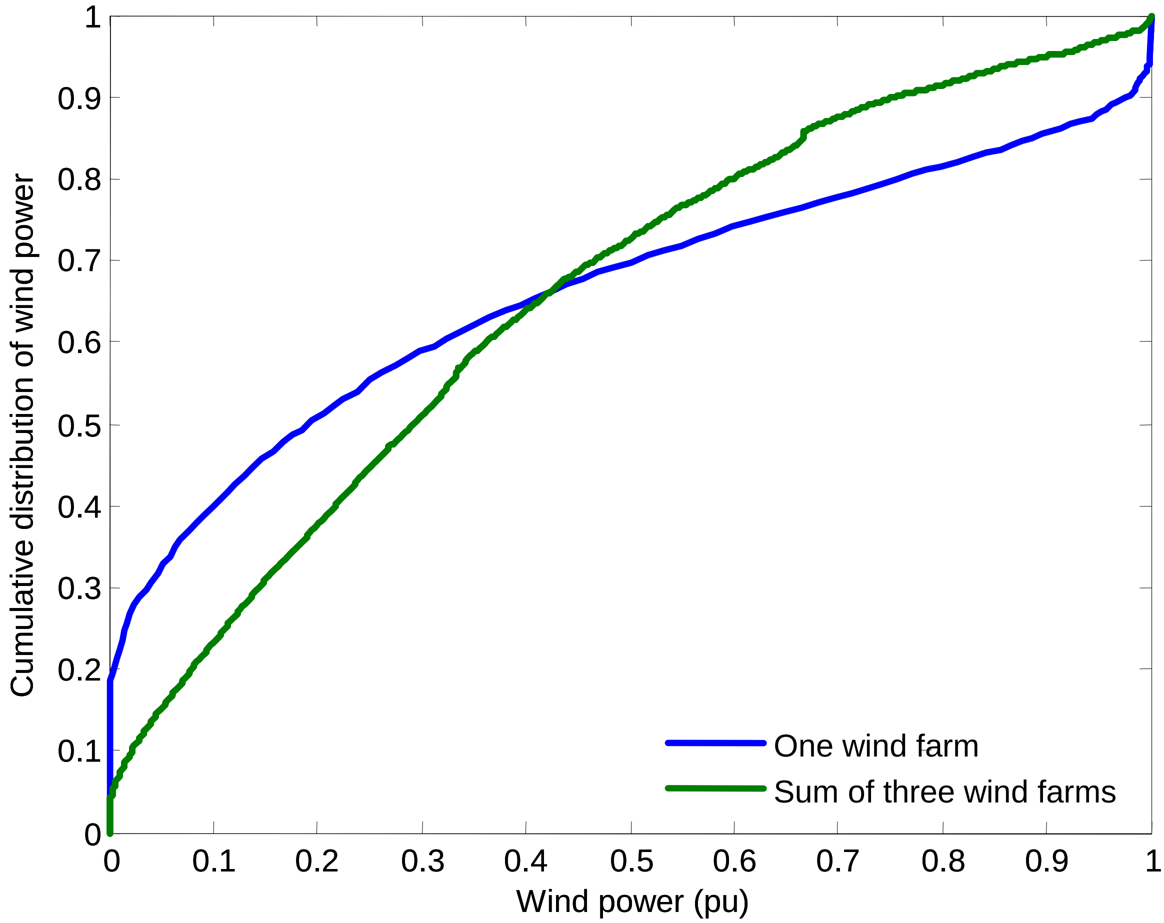


Figure 13: Cumulative distribution of hour by hour wind power production. The sum production of the three wind farm sites will be more stable than from one single wind farm. Cumulative distribution of wind power = probability of wind power being less or equal to the values on the x-axis.

Ref [11] gives a detailed assessment on the impact of large scale wind power on the Nordic electricity system. The study includes an assessment of hourly wind power variations expected in sum from the Nordic countries (Finland, Sweden, Denmark and Norway), see Figure 14 and Figure 15.

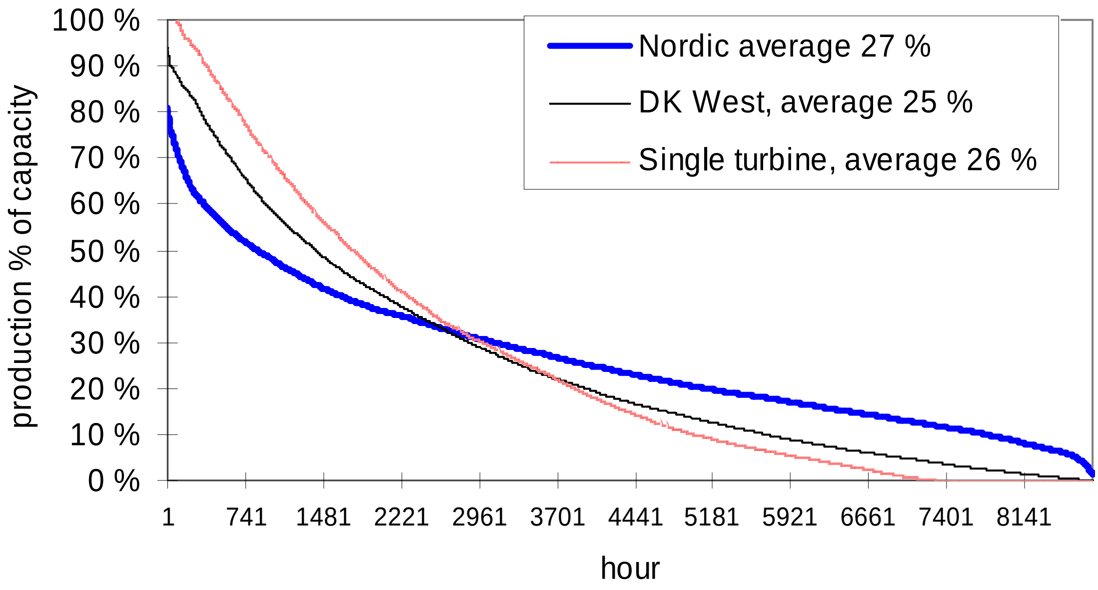


Figure 14: Duration curve of hour by hour wind power production. The sum production of the Nordic wind farm sites will be more stable than of one single wind farm, or a smaller region (DK West) [11].

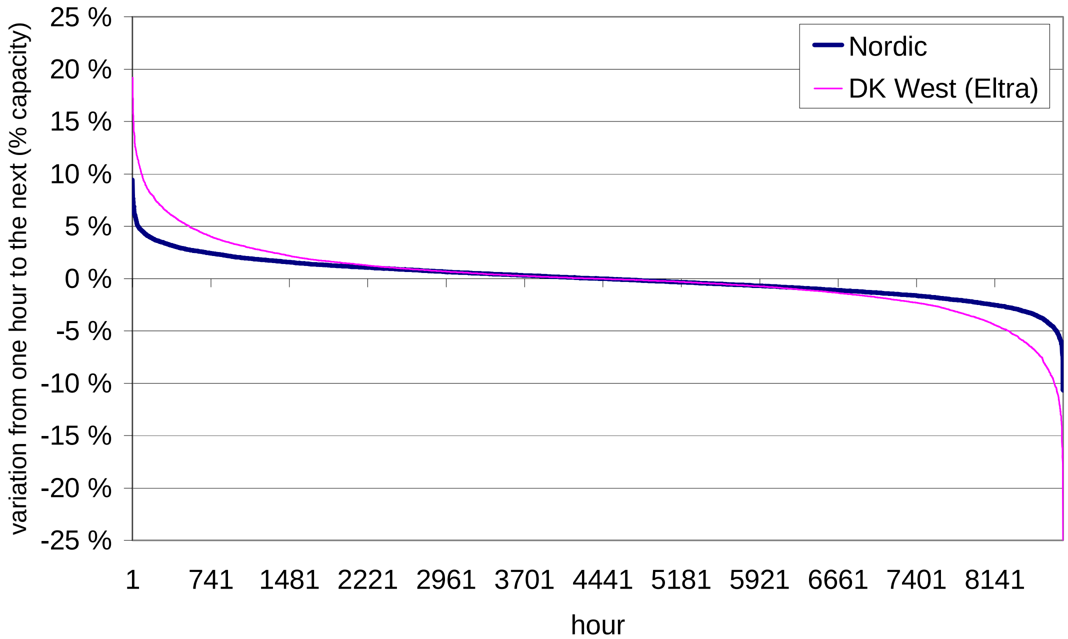


Figure 15: Variation in wind power production from one hour to the next, [11].

3.3 Wind power forecasting

Wind power forecasting tools facilitate a means to predict the wind power production some hours or days in advance. The accuracy depends on the tool, but also on the forecasting period and wind farm area. Generally, accuracy is better for short time periods ahead and aggregated production from a large area than for long periods and for one particular wind farm site only.

A general forecasting tool may consist of the following parts:
- Numerical Weather Prediction (NWP) data for area (weather forecast)
- "Physical" model to estimate wind speed on wind farm site (numerical model using landscape data to transport NWP data to local scale); may be combined with "statistical" model
- "Statistical" model to estimate wind speed on wind farm site (numerical model using relation between historical NWP data and measurements of wind speed at site); may be combined with "physical" model
- Power curve model giving relation between wind speed and wind farm power output

An overview of operational wind power forecasting tools is given in Table 3.

Table 3: Overview of operational short-term wind power forecast models (copy from [7])

PREDICTION MODEL	MODEL DEVELOPER	METHOD	OPERATIONAL STATUS, REGION	OPERATIONAL SINCE
Prediktor	Risø National Laboratory* (DK)	Physical	Spain, Denmark, Ireland, Germany, (USA)	1994
WPPT	IMM, Technical University of Denmark*	Statistical	≈2.5 GW, Denmark (East and West)	1994
Previento	University of Oldenburg and Energy & Meteo Systems (DE)	Physical	≈ 12 GW, Germany	2002
AWPPS (More-Care)	Armines/Ecole des Mines de Paris (F)	Statistical, Fuzzy-ANN	Ireland, Crete, Madeira	1998, 2002
RAL (More-Care)	RAL (UK)	Statistical	Ireland	-
Sipreólico	University Carlos III, Madrid Red Eléctrica de España	Statistical	≈ 4 GW, Spain	2002
LocalPred-RegioPred	CENER (ES)	Physical	Spain	2001
Casandra	Gamesa (ES)	Physical	Spain, Portugal and USA	2003
GH Forecaster	Garrad Hassan (UK)	Physical and Statistical	Spain, Ireland, UK, USA, Australia	2004
eWind	TrueWind (USA)	Physical and Statistical	Spain (represented through Meteosim) and USA	1998
HIRPOM	University College Cork, Ireland Danish Meteorological Institute	Physical	Under development	-
AWPT	ISET (DE)	Statistical, ANN	≈ 15 GW, Germany	2001
AleaWind	Aleasoft (ES)	Statistical	Spain	2004
Scirocco	Aeolis (NL)	Physical	Netherlands, Spain	2004
Meteologica	MBB	Physical	Spain	2004
Meteotemp	No specific model name	Physical	Spain	2004

* Risø and IMM form the Zephyr collaboration.

A Norwegian effort on wind power forecasting is reported in [25]. Here, a system is developed that forecast wind production 6 to 48 hours ahead. The system uses input from the NWP model

HIRLAM10 (see note4) combined with a statistical model for providing wind farm production forecasts. Example results of predicting output from a single wind turbine using the system are shown in Figure 16.

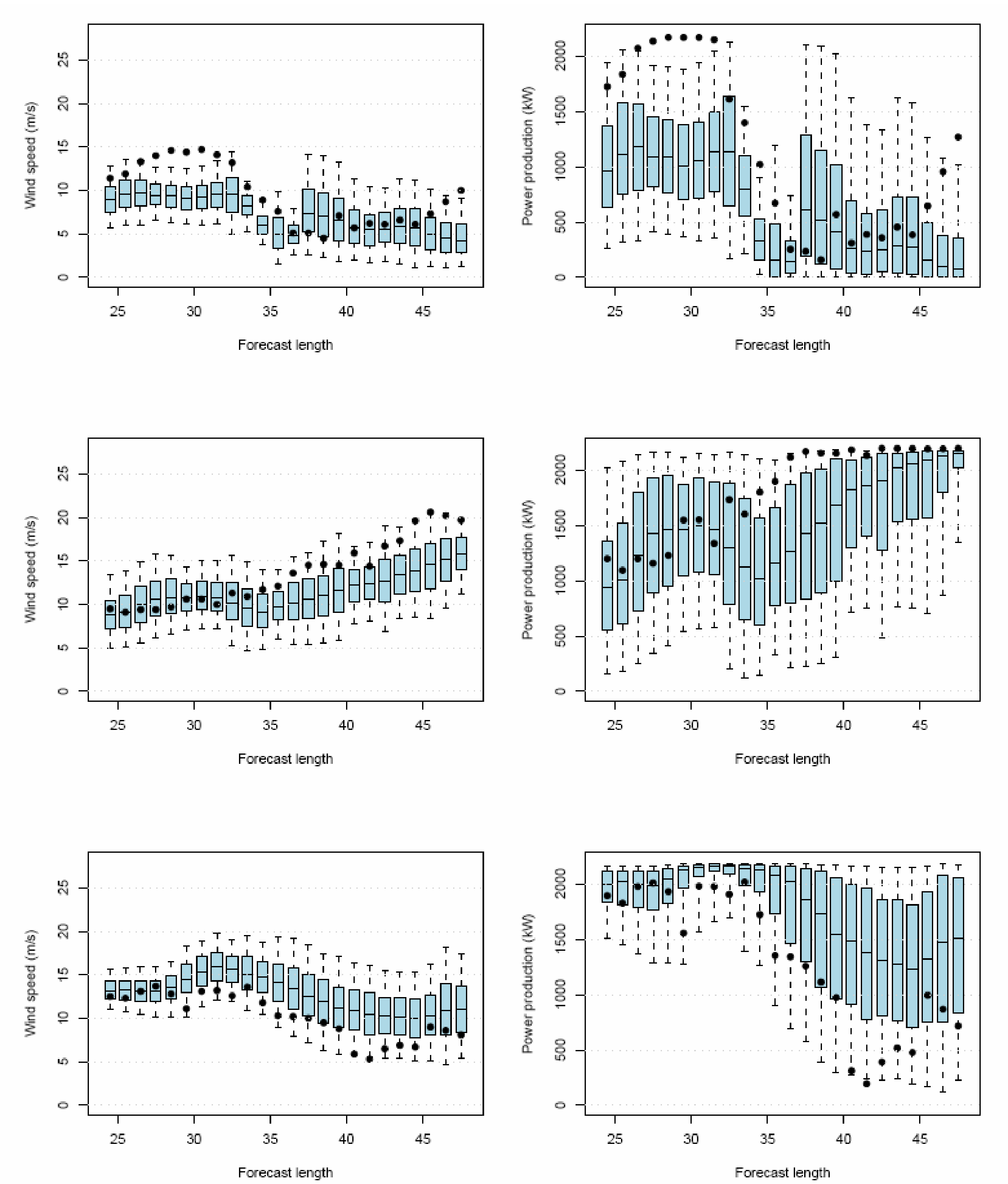


Figure 16: Examples of hourly forecasts in terms of the 5, 25, 50, 75, and 95 percentiles for wind speed (left) and power production (right). Observations are indicated by filled circles. Copy from [25].

[4] HIRLAM10 has 10 km horizontal resolution. HIRLAM10 is operated on routine basis by the Norwegian Meteorological Institute (met.no).

Further efforts reported in [25] conclude that using a NWP model with better resolution can significantly improve accuracy, i.e. especially for sites in complex terrain and for longer forecasting periods.

Forecasting accuracy will be better for aggregated wind production within a large area. Data gathered from the web pages of the Germany energy company EnBW (www.enbw.com) illustrate this. EnBW operates within the region of Baden Wüttemberg[5] and uses day-ahead forecasts for wind generation in their power system planning. More than 100 MW wind power is installed in this region and the forecast system is called PREVIENTO (www.energymeteo.de).

In Figure 17 the total hourly wind generation in the area has been plotted for several days, together with the wind generation prognosis for the same hours. Two characteristic features can be observed from the figures: a) the wind generation does not vary much over the day, and b) the forecast accuracy is very good, even for forecasts 24 hours ahead.

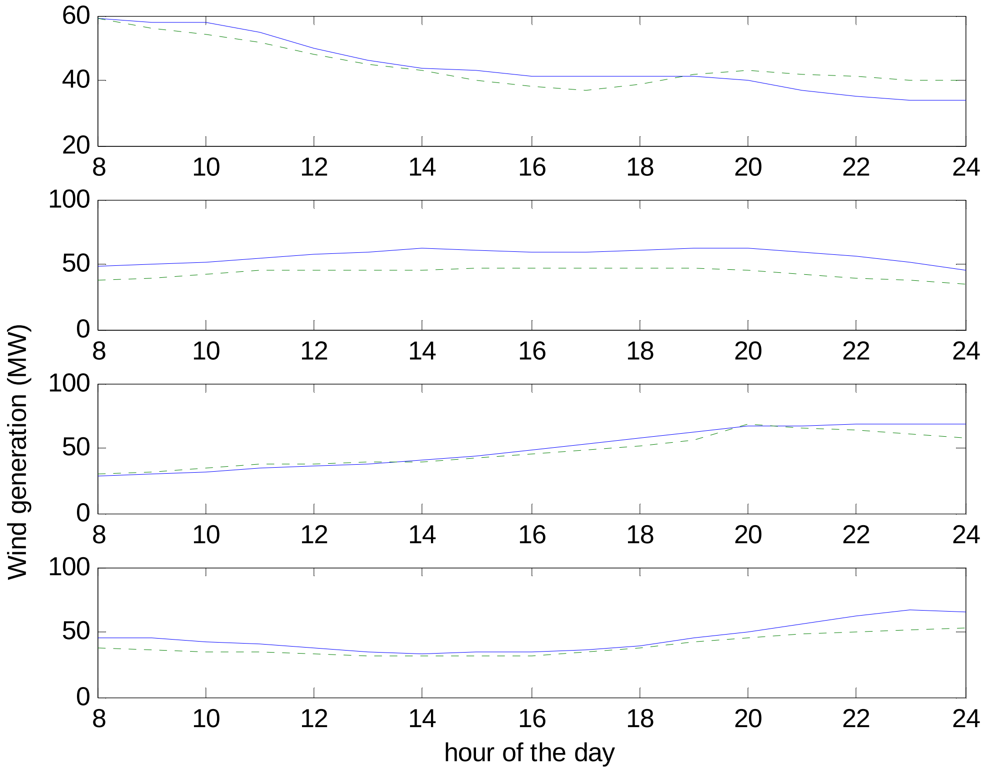


Figure 17: Actual wind generation (solid blue line) and forecasted generation (dotted green line) for the EnBW region in the period 24 – 27 January 2006.

[5] The area of Baden Wüttemberg is 35,751 km^2 bordered by France on the west, Switzerland on the south, and by the Länder (states) of Bayern (Bavaria) on the east and Rheinland-Pfalz (Rhineland-Palatinate) and Hessen (Hesse) on the northwest and north.

3.4 Conclusion

The annual wind generation may vary from year to year. Based on 30 years of recorded wind speed data it is found that in Norway the annual wind generation may vary +/- 20 %. In comparison the annual hydro inflow may vary +/-30 %.

The correlation between the annual wind and hydro generation is weak, and in total the combination of wind and hydro will provide for a more stable annual energy supply than hydro alone.

The wind generation will generally be higher in the winter period than in the summer. This seasonal wind variation fits well with the electricity consumption in Norway, and is opposite to the hydro inflow.

A preliminary assessment of wind variations on shorter timescales has been prepared. Results indicate that the hour by hour sum wind generation within Norway will be fairly stable, i.e. the standard deviation of sum hourly production is estimated to 4 % of the installed wind capacity. Generally, wind variations on shorter timescales will smooth out the bigger the area.

Hour by hour wind generation may be predicted. Forecast tools are being developed within Norway and internationally. Forecast accuracy depends largely on NWP model performance, but also on area of concern and forecast period. Accuracy is greatly improved for short forecast periods and for considering aggregated wind power production within a large area.

4 GRID CONNECTION OF WIND FARMS

4.1 Grid codes

Grid codes basically contain the rules for connecting generators to the grid. They are typically developed by the Transmission System Operator (TSO) to facilitate rules fitted to system needs; hence they may vary in items covered, level of detail and requirements to generator technology. Detailed requirements to wind power technology is a fairly new addition to grid codes, reflecting that wind farms until the end of the nineties generally were fairly small and had little impact on the system operation. The large wind farms being built and operated today may however have a significant impact, thus it is rational to include requirements to these in grid codes.

Statnett (the Norwegian TSO) has recently included requirements to wind farms in their grid code [12]. The requirements are for wind farms > 10 MVA connected to the regional or main transmission grid. This code is strictly a guideline that gives recommendations, though Statnett has the right and obligation to assess new installations and based on this decide whether the installation can be permitted to operate or not. Statnett’s recommendations to wind farms include the following aspects:

- Operation at varying grid frequency (normal 49.0-50.5 Hz, limited 47.0-51 Hz)
- Operation at varying grid voltage (normal +/- 10 %, cosφ = +/- 0.91 ref wind farm point of grid connection)
- Active power control (remote control of maximum production, system for ramp-rate limitation and participation in frequency control)
- Reactive power control (system to operate at two modes: a) set-point cosφ, b) active voltage control with droop)
- Operation in case of grid faults or abnormal grid voltages (fault ride-through for voltages down to 0.15 pu at the grid connection point of the wind farm)
- Verification of characteristic properties (analyze impact on system using simulation model and make numerical wind farm model available for Statnett for simulation using PSS/E or similar)

Statnett highlights the importance of dialogue in the planning process of wind farms, and through this achieve at fitted technical requirements for new installations. It is also so that grid codes for wind farms are a rather new thing, hence it must be expected that these will be adjusted over time.

It is important to distinguish grid code requirements and system operation, e.g. although grid codes states that wind farms shall be *able* to operate at a limited power output, this is not the same as saying that the wind farm shall actually operate in this mode. Limitation of wind farm power output to facilitate an active power reserve will mean loss of energy, and probably active power reserves can be obtained at less cost from other generation. The ability of wind farms to limit their active power output according to a remote set-point value can still be useful, e.g. in case of temporary grid congestions.

Reactive power control of wind farms has traditionally been limited to keeping cosφ to unity, or to allowing a small reactive consumption, but was generally not used for active voltage control.

The addition of recommending active voltage control as an alternative mode of operation seems rational, i.e. wind farms can then assist in maintaining a stable grid voltage in the same manner as other conventional generation and allow for connecting more wind power to the grid.

Until a few years back the rule was that wind farms should disconnect in case of grid disturbances, e.g. voltage dips. The idea was to protect the wind turbines as low voltage could cause over-speed and mechanical failures, but also that tripping of some small generation would anyhow not have any significant impact on system stability. The development of large wind farms changed this as tripping of such can possibly lead to local deficit of generation, line overloading and system instability. It is worthwhile to notice that implicit in this new way of thinking is also a recognition of wind farms as a source of firm power, i.e. the system is operated relying on the wind power generation.

Low-voltage fault ride-through capabilities of wind farms can be achieved in a variety of ways. The challenge is basically that as the voltage drops the current output must increase or else the turbines will accelerate to over-speed. Blade pitching can be activated to limit the aerodynamic power, and by this current and acceleration, but not immediately. Hence, the lower the voltage the wind farm shall be able to ride-through, the bigger the challenge.

Numerical wind farm models suitable for use with power system simulation tools like PSS/E are essential for assessing the impact on system stability. Such tools are however currently not a standard feature of commercial available power system simulation tools, but are being developed by research institutes, universities and commercial entities. The modelling is not trivial and model accuracy is critical. International cooperation within IEA Wind R&D Annex 21 has aided the development, [14], but also highlighted the importance of validating models against measurements. To this, work is now ongoing to update IEC 61400-21 [15][6] to include specifications of a standardized test for measuring the wind turbine response on a voltage dip. Hence, in the future, wind turbine manufacturers may refer to standard test certificates for demonstrating performance under voltage dips, and also these same test certificates may be used for validating dynamic models of wind farms for power system studies.

Comparison of national grid codes shows that these may vary from country to country, e.g. [13], though it is not always easy to establish the rational for differences. Statnett’s recommendations seem generally a bit tougher, especially on reactive power capabilities (cosφ = +/- 0.91 ref wind farm point of grid connection) and low-voltage fault ride-through (voltage 0.15 pu). Modern wind farms can be adapted to such performance, though it comes at a cost, hence requirements should be based on careful assessment of need. It may therefore be relevant to revisit these issues of Statnett’s grid code.

[6] A first committee draft of IEC 61400-21, ed. 2, is circulated for comments March 2006.

4.2 Grid connection of wind farms

As with any large power plant, development of large wind farms may require reinforcement of the power transmission system. Such grid reinforcement may be economic in any case, i.e. paid back by reducing losses, but often it is suggested as a necessity to ensure system stability. System stability is commonly assessed by considering the implications of various faults and combinations of system load and generation. In such analyses, a conservative approach assumes that the wind farms are uncontrollable and consequently the grid must be reinforced to maintain stable operation, even under the most unfavourable combination of wind farm and system operation. This approach may lead to suggestions for quite dramatic grid reinforcements that may prevent otherwise economic wind farms or seriously limit the permitted wind farm size. Indeed, such a conservative approach may have been quite reasonable, since most wind farms installed to now have been not very large and have operated with little regard for system requirements. However, today wind farms are becoming a significant part of power systems, so a new approach is necessary to ensure cost effective grid integration of wind farms. This section[7] considers this challenge, demonstrating, through a case study, that modern wind turbine technology and application of suitable control schemes facilitate viable operation of large wind farms in weak grids.

4.2.1 Case study specification

The case study considers the connection in Norway of a large 200 MW wind farm to a typical regional distribution grid, see Figure 18. The study is based on an actual system, though slightly modified to serve the purpose of this presentation. The regional distribution grid is connected to the main transmission grid via a long 132 kV line with a thermal power capacity limit of about 200 MW. Considering that the hydropower plant is rated 150 MW and that the local load may be as small as 14 MW, a conservative approach would suggest that the wind farm capacity should not exceed 64 MW (i.e. 200 – 150 +14), or indeed 50 MW (i.e. 200-150) to ensure operation if the local load disconnects. However, contrary to such conservative planning, this case study will demonstrate that installation of a much larger wind farm is viable.

[7] The content of this section is based on a previous publication [16] and [17], though revised and edited to fit this report.

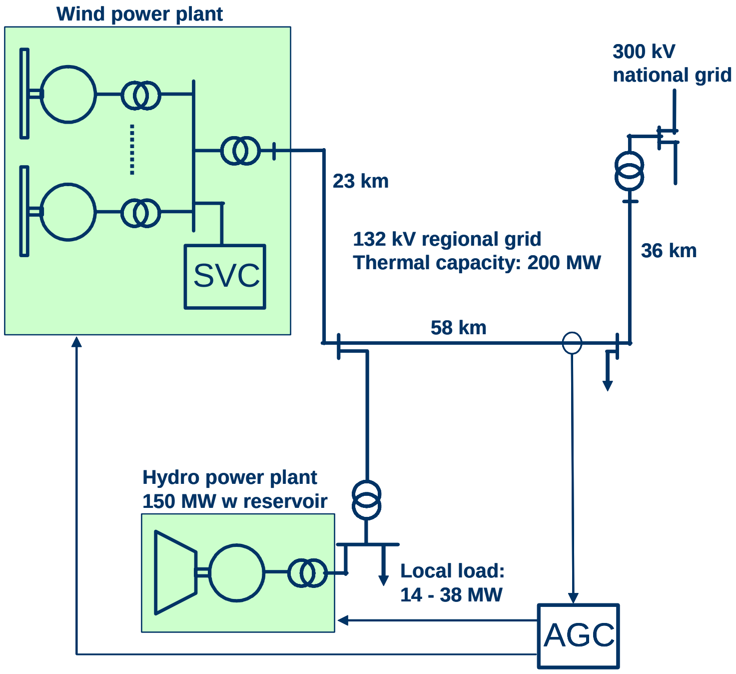


Figure 18: Outline of case study regional grid.

Due to environmental constraints, it is not an option in this instance to upgrade the 132 kV line for higher thermal power capacity. Hence, power electronics and control systems are applied to allow connection of the large wind farm.

Ref [18] shows that as long as the thermal capacity of the 132 kV line is respected, voltage control and stability is ensured by application of a Static Var Compensator (SVC) and/or utilization of the reactive control capabilities of modern wind turbines with frequency converters. As illustrated in Figure 19, sufficient reactive support enables a stable voltage for feed-in of 0 to 200 MW of wind power. Without that support, the wind farm size would have to be restricted to about 50 MW.

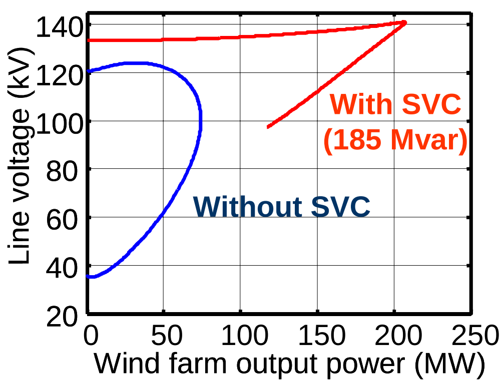


Figure 19: Result of dynamic simulations of power system with 0-200 MW of wind power [18].

Ref [19] demonstrates that Automatic Generation Control (AGC) of hydropower plant can be used to avoid overloading the 132 kV line. This is illustrated in Figure 20, showing a result of a dynamic simulation verifying the performance of the AGC.

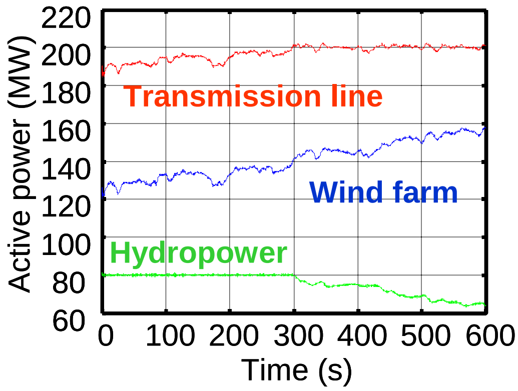


Figure 20: Result of dynamic simulation of power system with 200 MW wind farm and AGC control of hydropower plant [19].

A key question not answered in [18] or [19], but analyzed in this section, is to what degree the grid congestion may influence the annual output and energy sales from the hydro and wind power plants.

4.2.2 Simulation model

The regional power system operation during one year is simulated on an hour-by-hour basis. The model inputs include:

Time series with consumer load, market price of electricity, inflow to hydro reservoir and wind speed (specified in [16] and [17]).
Specification of the regional power system components, e.g. wind farm power curve, maximum storage capacity of reservoir (460 GWh), rated power of hydropower plant (150 MW) and thermal limit of 132 kV transmission line (200 MW).

The regional power system studied is assumed part of a much larger power system, so that the regional production will not significantly affect the assumed market price of electricity.

The hydropower plant is controlled to maximise the annual energy sales. With no grid congestion, an optimum hydropower production schedule is followed, where the annual output matches the annual inflow, and the hour-by-hour output follows the market price variations. Probably, this could not be achieved in practice, because a real-life schedule would have to rely on uncertain estimates of inflow and sales price. However, the optimum schedule is an acceptable basis to quantify the relative impact of grid congestion and the AGC operation.

The AGC operates to avoid line overloading. It may be set to control either (a) first the hydropower and secondly the wind power, or (b) the wind power only. With choice (a) “control hydro”, reduced hydropower output is followed by an increase of production as soon as possible, i.e. to obtain, as closely as possible, the non-congested annual energy sales. With only wind power control, (b) “control wind”, wind power is reduced intentionally to avoid line overloading and the hydro plant operates according to the optimum schedule.

Practical implementation of a scheme with wind power dissipation requires the wind farm(s) to be able to handle a 'maximum output power set-point' signal from the AGC controller. The maximum output power from wind farms with fixed speed, stall controlled wind turbines can be limited in steps by start/stop of individual wind turbines, whereas wind farms with pitch-controlled wind turbines (fixed or variable speed) may offer continuous limitation of the output power. This latter option is assumed in the model, whereas start/stop control may result in increased wind energy dissipation.

4.2.3 Simulation results - Operation with a 200 MW wind farm

In this case, the operation of the regional power system is simulated assuming 200 MW installed wind farm capacity. Two cases of AGC operation are assessed:

"control hydro", i.e. the hydropower plant is controlled first and the wind power second;
"control wind", i.e. only the wind power is controlled

The results of the simulations are shown in Table 4 and Figure 21 to Figure 24. The 'non-congested' column of Table 1 is included for reference showing results from assuming unlimited grid capacity.

Figure 21 shows the hydropower output. The hydropower output accords to the optimum schedule for the "control wind" case, whereas the "control hydro" case leads to a modified operation of the hydropower plant. Indeed, the operation of the hydropower plant may, in real life, be restricted by various factors, e.g. environmental concerns that are not considered in this simulation. Hence, the simulated operation in the "control hydro" scenario illustrates the concept, but should not be taken to suggest that the large hydropower fluctuations can be generally accepted.

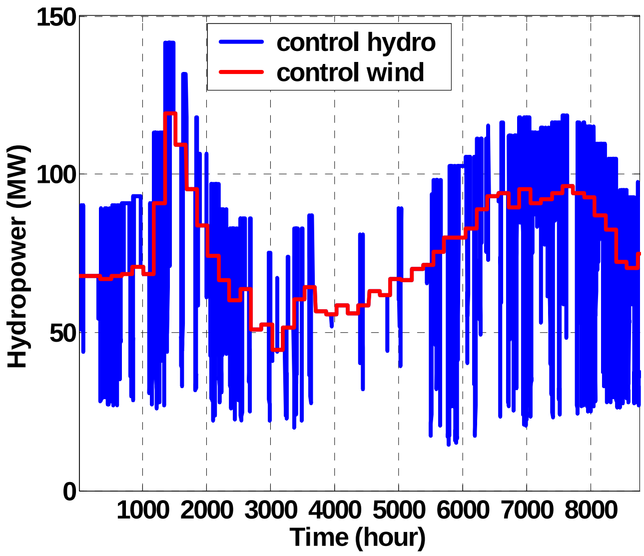


Figure 21: Simulated hydropower output assuming a 200 MW wind farm in the regional grid.

Figure 22 shows the reservoir content. In the "control hydro" case, the reservoir content is a little larger at the end of the year than at the start, i.e. as can be read from Table 4, the annual hydropower output has been limited to 98 % of its potential, due to the grid congestion. Implementation of a control algorithm that would allow a more rapid increase of the hydropower output after congestion could, in theory, provide for an annual hydropower output equal to that scheduled. However, actual operational restrictions on the hydropower plant may require less fluctuating production and so reduce the annual hydropower output to less than 98 %.

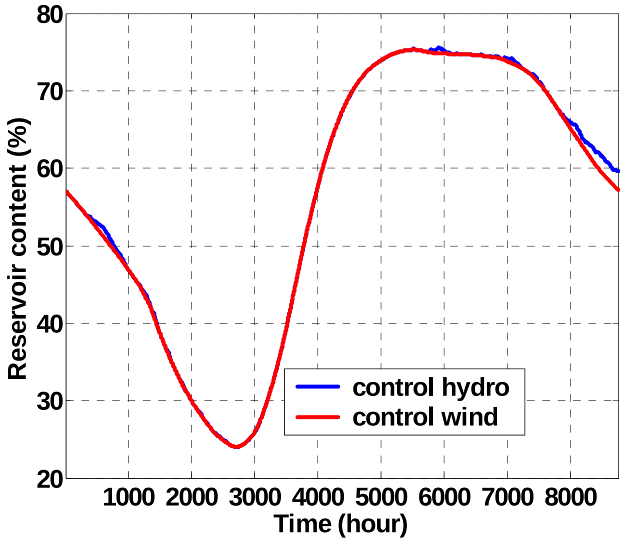


Figure 22: Simulated hydropower reservoir assuming a 200 MW wind farm in the regional grid.

Figure 23 shows the cumulative line load distribution. With no wind power, the line load is always, in practice, less than the 150 MW maximum capacity of the hydropower. With wind power, the line load, in both control strategies, is limited to 200 MW, i.e. the assumed thermal capacity limit of the line. The choice of control strategy changes the line load distribution, because the “control wind” option provides for slightly less annual energy transfer than the “control hydro” strategy, (see Table 4).

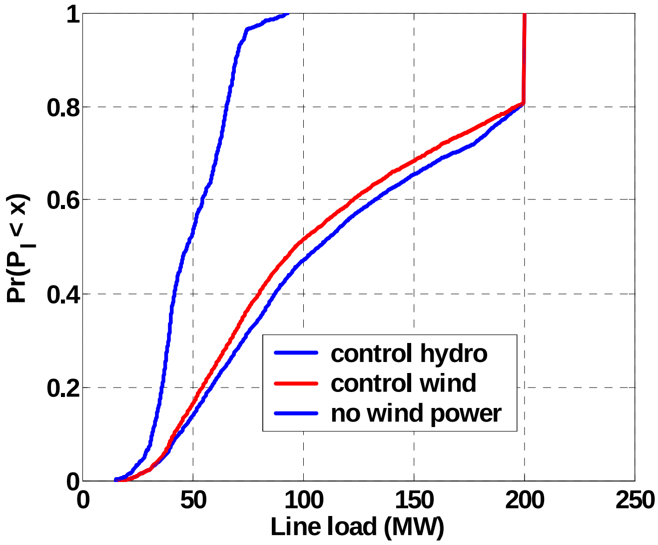


Figure 23: Cumulative line load distribution over the year with and without a 200 MW wind farm.

Figure 24 shows the cumulative wind power distribution. The "control wind" option limits the maximum output of the wind farm to 185 MW and the annual wind power output becomes 10 % less than the potential (see Table 4). In contrast, the "control hydro" option does not cause any reduction of the annual wind power output.

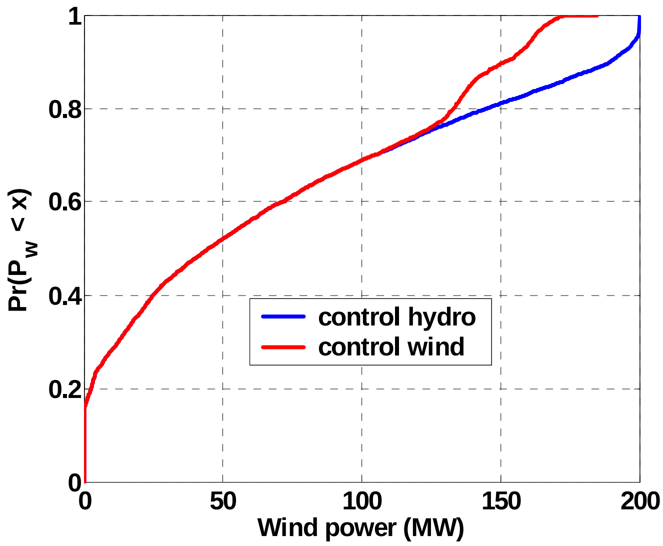


Figure 24: Cumulative output power distribution over the year of a 200 MW wind farm.

Table 4: Case study results with 200 MW wind farm. All numbers are in GWh/year.

	Control hydro	Control wind	Non-congested
Wind power	609	551	609
Hydropower	646	657	657
Local load	219	219	219
Line load	1036	989	1047

4.2.4 Simulation results - Operation with 0-400 MW wind farm

This sub-section summarise simulation results of assuming the wind farm capacity to vary from 0 to 400 MW.

Figure 25 shows the annual energy output and sales, in percent of the potential non-congested values. It is remarkable to notice that both AGC control schemes (control wind and control hydro) provide insignificant losses of potential energy output and sales income for wind farm sizes up to 150 MW. The reason for this is simply that hour by hour wind and hydro generation are basically uncorrelated, thus high wind production and high hydro production are seldom occurring at the same time.

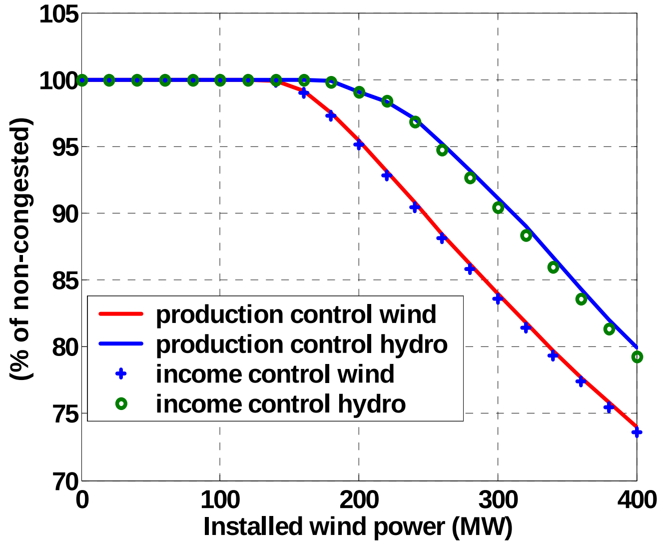


Figure 25: Annual energy output and sales in percent of the potential non-congested values; resulting from simulations assuming 0-400 MW wind power capacity.

4.3 Conclusion

The development of grid codes for wind farms as for other generation technologies is sound. It is recognising that large wind farms are basically power plants and may participate in securing effective and stable power system operation. The specific requirements must however be carefully assessed and possibly adjusted over time aiming for overall least cost solutions.

Connection of a wind farm to a regional power system with a weak link to the main grid has been assessed. Previous studies, [18] and [19], based on detailed power system dynamic simulations, conclude that a wind farm with rated capacity up to 200 MW may be connected with the following assumptions:

The wind farm must provide sufficient reactive control, i.e. by use of a SVC and/or the reactive control capabilities of modern wind turbines with frequency converters
AGC must be applied to avoid overloading of the weak link between the regional power system and the main transmission grid.

It has been studied to what degree AGC operation, to avoid line overload, may influence the annual output and energy sales from hydro and wind power plants. The study shows that control of both hydro and wind power generation are viable options. For wind farm sizes up to 150 MW both control schemes studied in the example give only insignificant losses in either energy output or sales. However, the results become sensitive to the control option for larger wind farms. Control of the hydropower plant gives only a very small loss of potential energy, whereas the alternative option of controlling the wind farm leads to more significant potential energy loss.

The simulations provide examples for strategic planning. More accurate analysis requires collection of further data for more than a single year of operation, see [20].

The main conclusion is that the maximum capacity of wind power that can be permitted on a grid depends on the particular circumstances and on the control strategies followed. It is therefore likely in the majority of situations that wind power capacity can be significantly greater than given by simplistic addition of maximum generating power and subtraction of minimum load. For the regional power system having a hydro component as assessed in this section, the maximum wind farm size ranges from 50 MW, by simplistic criteria, to 200 MW, by control criteria. Indeed, operation at grid congestion is not an ideal situation. Operation as illustrated by the case study may however be a fair solution for allowing increase of generation in areas with limited transmission capacity, i.e. instead of waiting for future grid upgrades.

5 WIND POWER IMPACT ON POWER SYSTEM OPERATION

The power system is generally operated to facilitate least cost reliable continuous supply of demand. Least cost operation implies that generation is allocated according to operating cost, and reliable supply is achieved by maintaining adequate generation reserves. To illustrate the ground rules, a small system a first considered:

- Assume a small power system with three 1 MW diesel generators. The load is varying between 0.9 and 1.7 MW, hence one of the generators is for back-up, whereas the other two can supply the load. Minimized operating costs can be achieved by running only one generator in hours with load less than 1 MW, but as the diesel operators do not have an accurate prediction of the load, and are aiming for reliable supply, the two generators are kept in continuous operation. The operating reserve in this system will thus vary between 0.3 and 1.1 MW.

- Assume now that a 0.5 MW wind turbine is connected to the system. This will reduce the load to be supplied by the diesel generators and hence save fuel. The actual fuel saving will depend on the wind generation, the diesel generator fuel characteristics and the operating strategy. A conservative approach would be to keep the two diesel generators running even in periods with high wind and low load. This would give fuel savings, and at the same time maintain or increase the operating reserve in the system, i.e. it will vary between 0.3 and 1.6 MW.

- Additional fuel savings can be achieved if stopping one of the diesel generators in hours with high wind and low load, though reliable operation will then depend on confident predictions of the wind power production. This way good forecast of wind generation enables more efficient use of reserves.

The above example demonstrates that adding wind power to the power system basically reduces the operating costs and potentially increases system reliability. The impact of adding wind power to a large power system is similar in principle, though a large system is generally more complex and impact of wind power maybe not so straight forward to understand.

5.1 Wind power in the Nordic electricity market

The Nordic electricity market is a joint market between Norway, Sweden, Denmark and Finland. Nord Pool organizes the trade of supply and demand, whereas the national Transmission System Operators (TSOs) secure reliability and balance of supply with Nordel as the common Nordic body facilitating cooperation.

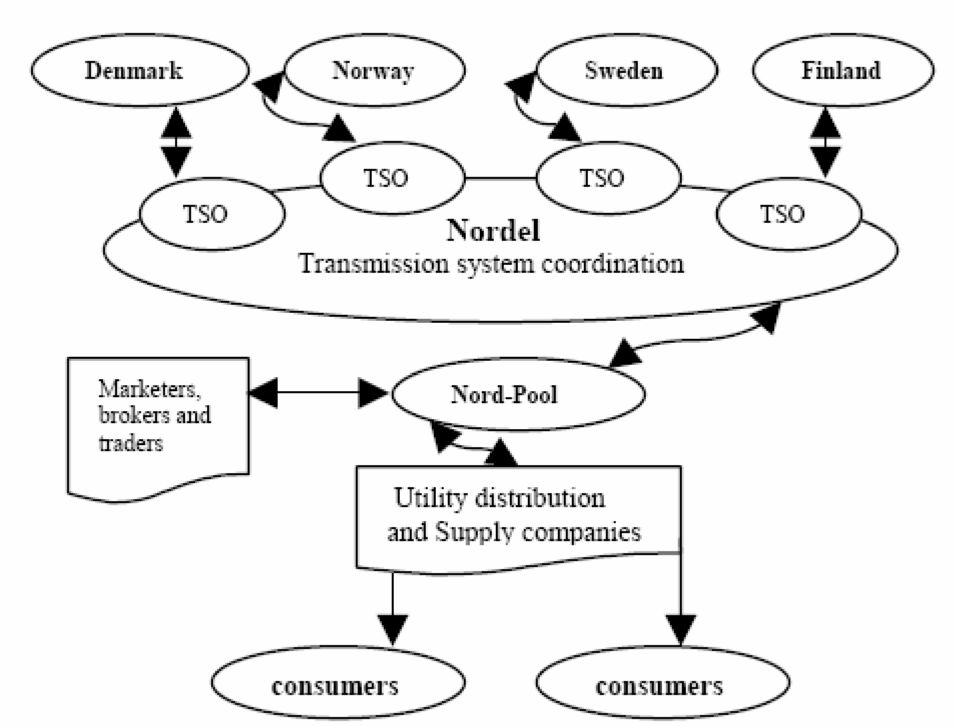


Figure 26: Nordic electricity market- major contractual relationships. Copy from [28].

Power contracts for day-ahead physical delivery are traded at the Nord Pool Elspot market. This is by auction with bids for purchase and sale for each hour of the next day. All bids have to be placed by noon, and after that Nord Pool sorts for each hour all sell and buy orders into one demand curve and one supply curve, see Figure 27. The intersection of the two curves gives the system price for the hour in question.

Generally orders for sale of generation reflect the marginal production cost, e.g. for wind close to zero and for gas governed by fuel cost. Introducing wind generation will thus generally reduce the system price (Nord Pool spot market price), whereas gas may end up being operated only as long as the system price is higher than fuel costs. Based on results from [11], the average market price will be reduced with about 5 øre/kWh if supply of wind generation is increased to cover 10 % of the Nordic power system demand.

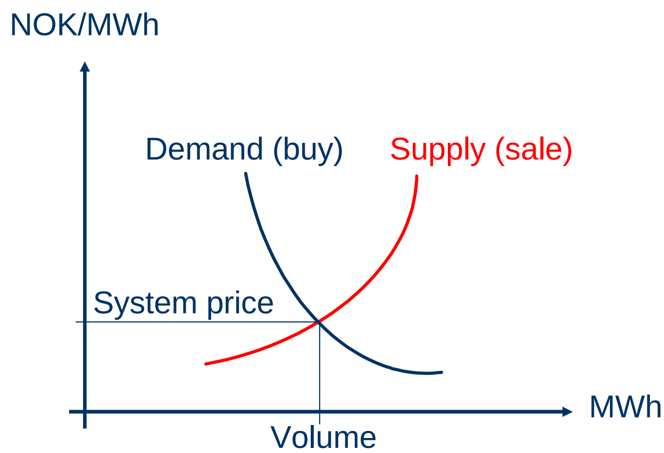


Figure 27: Spot market demand and supply curve.

The consumption and generation situation may obviously change after the clearing of the Elspot market and lead to real time imbalance. It may therefore be relevant to adjust consumption and generation plans close to real time. In Finland, Sweden and Eastern Denmark this can be done using the separate intra day market (Elbas) for trading hourly contracts until one hour before delivery, whereas for others adjustment of plans are depending on TSO acceptance.

As wind forecast accuracy is greatly improved for shorter time ahead, system operation will benefit from using the Elbas market or achieving general acceptance by the TSO to adjust generation plans close to the operating hour.

Real time imbalance may still occur, e.g. load or wind may be miss-predicted, or generation may fail. Generation frequency droop control will then automatically adjust generation (primary reserve), whereas the TSOs will restore nominal frequency by requesting adjustment of generation or controllable loads (secondary reserves). The price of the power regulation to counteract on the imbalance is given by the Balancing Market, i.e. a "staircase" of merit order regulating power bids received by the TSOs. Bids stating prices and volumes may be submitted until close to the operational time, either as bids for upward regulation (increased generation or reduced consumption) or as bids for downward regulation (decreased generation or increased consumption). TSOs use the priority-ordered lists for each hour to balance the power system, as needed. To resolve a power deficit, upward regulation is applied and the real-time market price within the hour is set at the highest price of the units called upon from the priority list. Similarly, in a grid power surplus situation, downward regulation is applied and the lowest price of the units called upon from the list sets the real-time price, [27].

Wind generators can in principle participate in the Balance Market, but probably not at a competitive price. Downward regulation of wind generation means dissipation of energy, and functionality to offer upward regulation can only be achieved if constantly operating below potential power, i.e. dissipating energy.

Wind impact on need for regulating power is treated in section 5.3.

The various markets and their timescales are shown in Figure 28.

Figure 28: The various markets and their timescales. Copy from [26].

5.2 CO_2 reductions due to wind energy

A comprehensive study on the impact of wind power on the operation of the Nordic power system is reported in [11]. The work comprises publication [22] that summarizes main findings with regards to CO_2 reductions due to wind energy:

- Quoting [22] (part of [11]): “Simulations with the power market model EMPS and the energy system model EFOM have been made to assess the effects of large-scale wind production on the CO_2 abatement in the Nordic countries. We are mostly focusing on the year 2010, comparing the results with substantial wind power amounts to a base case scenario. The results for the EMPS simulations with 16–46 TWh/a wind production in Nordic countries (4–12% of electricity consumption), show that wind power replaces mostly coal-fired power generation. As a result of all fuels replaced by wind production a CO_2 reduction is achieved, of 700–620 g CO_2/kWh. The results for the simulations of Finnish energy system show similarly that new wind power capacity replaces mainly coal-fired generation. In another scenario it has been assumed that the use of coal-fired generation is prohibited in order to meet the Finnish Kyoto target. In this case new wind power capacity would replace mainly natural gas combined-cycle capacity in separate electricity production and the average CO_2 reduction would be about 300 g CO_2/kWh. This case reflects the situation in the future, when there is possibly no more coal to be replaced.”

The findings on CO_2 reductions due to wind energy confirm what can be intuitively understood. Adding any new supply of energy to the power market will generally replace generation from plants with the highest operational costs. This holds for wind as for any other source of energy, and which generation replaced that is being replaced is simply a matter of which that has the highest operational costs. This was coal at the time the analysis in [22] was prepared and assumed to be so also in 2010. Now, the price of gas has increased significantly, and has in spite of CO_2 tax become more expensive than coal. Considering that European policy is to reduce CO_2 emissions, new incentives may however be put in place as again making polluting coal fired power plants the most expensive option.

5.3 Wind power impact on reserve requirements

As part of [11] the increased reserve requirement due to integrating wind in the Nordic power system is determined by simulation based on a 3-year time series, combining the wind power variations with varying electricity consumption. It was found that wind power, combined with the varying load, is not imposing major extra variations on the system until a substantial penetration is reached. The increased reserve requirement is seen on a 15 minutes to one hour time scale. The work comprises publication [22] that summarizes main findings with regards to wind power impact on reserve requirements:

- Quoting [23] (part of [11]): “The variations of wind power production will increase the flexibility needed in the system when significant amounts of load are covered by wind power. When studying the incremental effects that varying wind power production imposes on the power system, it is important to study the system as a whole: only the net imbalances have to be balanced by the system. Large geographical spreading of wind power will reduce variability, increase predictability and decrease the occasions with near zero or peak output. The goal of this work was to estimate the increase in hourly load-following reserve requirements based on real wind power production and synchronous hourly load data in the four Nordic countries. The result is an increasing effect on reserve requirements with increasing wind power penetration. At a 10% penetration level (wind power production of gross demand) this is estimated as 1.5%-4% of installed wind capacity, taking into account that load variations are more predictable than wind power variations."

A first thing to note is that the study considers the effect of large scale integration of wind power, i.e. to cover 10 % of the gross demand. The next is that the impact on load-following reserve requirement is still very small, i.e. 1.5-4 % of installed wind power capacity or more specifically, for Denmark the 2000 MW of wind power would increase the load following requirement by 30–40 MW, for Finland the 4000 MW by 120–160 MW and for the Nordic countries as a whole, the 19,000 MW of wind power would increase the load following requirement by 240–320 MW.

The term "load-following reserve" is here understood as part of the Fast Contingency Reserve (FCR) of Nordel. A brief account of the active power reserve requirements within Nordel is given below and summarized in Table 5; [21] gives more elaborate coverage:

- Frequency Activated Operating Reserve (FAOR) and Frequency Activated Contingency Reserve (FACR) are primary reserve that are automatically activated in case of frequency deviations, i.e. commonly achieved by droop control of generators operated the requested reserve below rated power. Basically, FAOR=600 MW is for matching the continuous load variations within each hour and FACR=1000 MW is for the case of contingencies. The FAOR shall be fully activated in case the frequency drops to 49.9 Hz, and the FACR in case the frequency drops to 49.5 Hz (all within 30 s).
- The Fast Contingency Reserve (FCR) is a secondary reserve that is for restoring FAOR and FACR after a contingency. The FCR shall be available within 15 minutes, and the basic idea is that the FCR shall be available within the country responsible for the imbalance.
- The Slow Contingency Reserve (SCR), or tertiary reserve, comprises capacity available after 15 minutes. If necessary, these are activated to re-establish fast reserves that are "spent" after a contingency.

Table 5 Summary of current active power reserve requirements in Nordel [21].

	Consumption 2003 (TWh)	FAOR (MW)	FACR (MW)	FCR (approx.) (MW)	SCR (MW)
East Denmark	14	24	90	600	No specific MW requirement given
West Denmark	-	-	75	620	
Finland	85	141	205	1 000	
Norway	115	192	313	1 600	
Sweden	145	243	303	1 200	
TOTAL	**358**	**600**	**1 000**	**5 020**	

In [11] the effect of wind power on additional Frequency Activated Operating Reserve (FAOR) and Frequency Activated Contingency Reserve (FACR) is also considered. The conclusion is that the impact will basically be insignificant. Fast fluctuations (second/minute) from geographically dispersed wind turbines / wind farms will be uncorrelated with each other, hence smoothing the sum power and not imposing any significant requirement for additional FAOR. The FACR requirement is given by the dimensioning fault (~1200 MW, e.g. a nuclear power plant in Sweden or the largest hydro power plant in Norway) minus self-regulation of load (200 MW), hence as long as the largest amount of wind power that can disconnect at one instance is less than about 1000 MW, wind power will have no impact on FACR requirement.

Indeed, the study ([23], [11]) does not conclude that new investments must be made to facilitate the calculated extra FCR requirement. There are significant possibilities to reduce reserve requirements and reserve costs in the Nordel system. This is studied in [21] that concludes (amongst others) that “The total amount of Fast Contingency Reserve (FCR) can be reduced by removing any requirement of national balance and operating the Nordel system by frequency and congestion handling alone.” and that “Loads can in many cases provide much more cost-effective services than generating units. Through a combination of new technology, market design and incentives consumption can contribute to nearly all reserve requirements.” If however it is still assumed that new reserve capacity must be bought, [23] estimates that the increased reserve cost is of the order of 0,8 øre/kWh wind at a 10% penetration level and 1,6 øre/kWh wind at 20% penetration of wind power. If investment is not required, it is estimated in [23] that the cost of added regulation will be about half of the aforementioned figures.

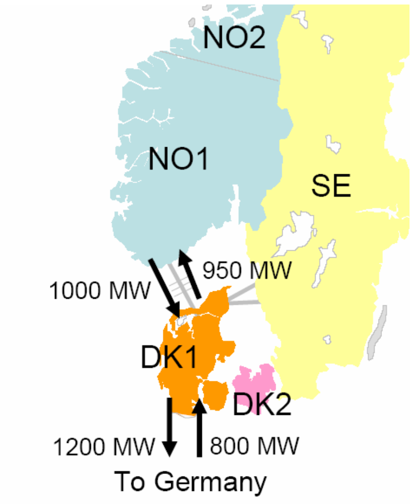
The calculated additional “load-following reserve” (part of FCR) due to wind power in [11] includes accounts for Finland, Denmark and Nordel as whole, but no separate figures for Sweden or Norway. A study on this has however recently been prepared for Sweden, [24], and it would be relevant to do the same also for Norway, and then possibly also taking account for transmission bottlenecks that may influence reserve requirements.

5.4 Real life case of balance handling

This case considers actual operational data from the Nordic power system (see Table 6). At 8 January 2005 the hurricane "Gudrun" crossed over southern Scandinavia initially causing high wind power production in Western Denmark. At a certain time however the wind turbines started to cut-out due to excessive wind speeds and the wind power production was reduced from 2200 MW to 100 MW during the afternoon hours. The loss of wind power production amounted to more than half of the consumer loads in Western Denmark.

Table 6: Data for western Denmark and map with indication of normal interconnection capacities.

Data for DK1, west Denmark 2003	MW
Central power plants	3,516
Decentralised CHP units	1,567
Decentralised wind turbines	2,374
Offshore wind farm Horns Rev A	160
Maximum load	3,780
Minimum load	1,246



It is interesting to note that even if this storm was an extreme event, it did not cause all the wind power production to cut-out at the same instant (see Figure 29). It actually took ten hours to go from maximum wind production (2200 MW) to minimum production (100 MW), whereas the steepest drop was about 600 MW in one hour (corresponding to 24 % of the installed wind power capacity). The reason for this fairly smooth reduction is the geographical distribution of the wind turbines so that changes in the weather conditions will not affect all of them simultaneously.

Figure 29 also shows how this situation was handled in operation. The loss of generation was compensated through the balancing power market (mostly activated in Southern Norway) and by regulating the HVDC link between Norway and Denmark from full export to full import. The example illustrate clearly that the Nordic power system can handle large amounts of wind power through the existing marked based mechanisms.

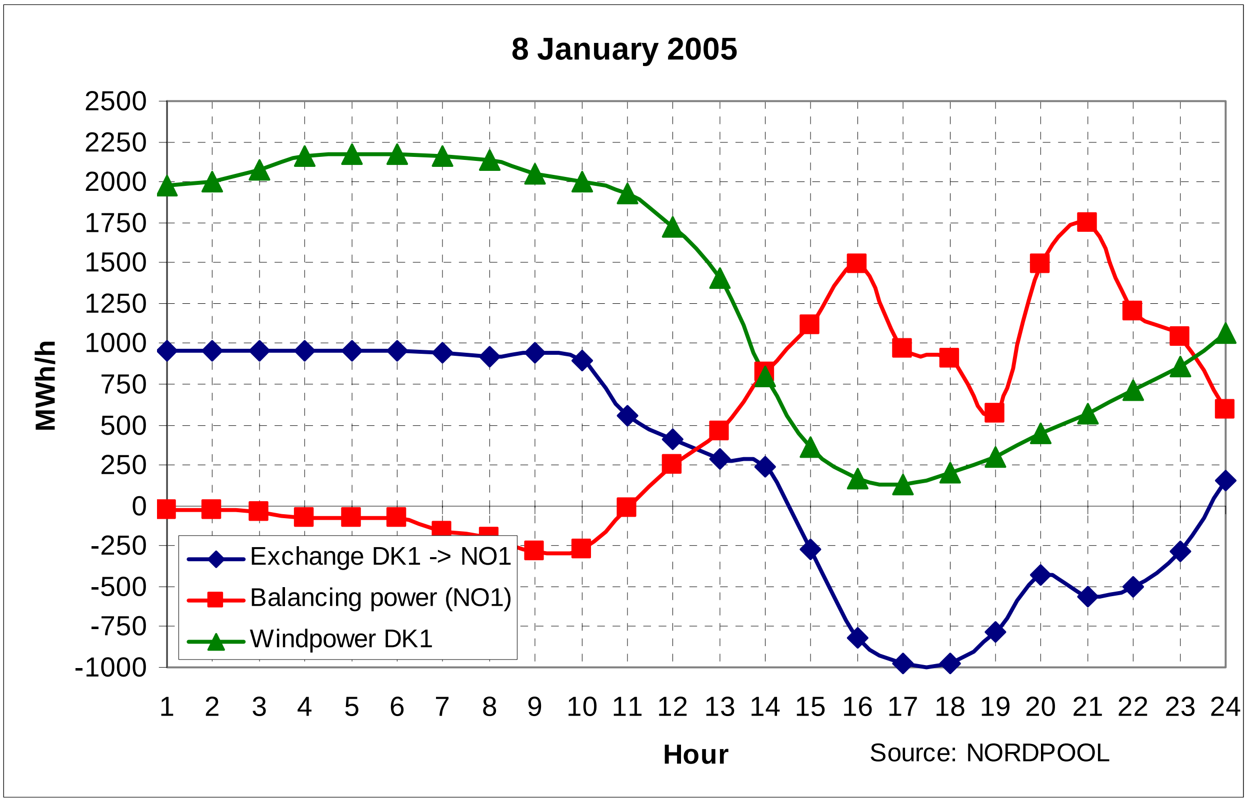


Figure 29: Wind and system operation during the hurricane "Gudrun" passing over Denmark 8 January 2005. Actual hour-by-hour data of wind power in Western Denmark (DK1), balancing power in Southern Norway (NO1) and power exchange over the HVDC line between Southern Norway and Western Denmark.

The percentage drop in wind generation would be less if a larger area than western Denmark had been considered[8], i.e. due to spatial correlation effects. It is also so that a storm takes time to develop and therefore it is fairly easy to predict if wind generation is likely to cut-out due to high wind speed (exceeding cut-out wind), and modern wind farms may even facilitate smooth down regulation of power instead of going directly to stop as the case is for the (older) wind generation installed in western Denmark.

5.5 Conclusion

Wind generation in the Nordic electricity market will generally reduce system price and CO_2 emissions. The reduction in system price will depend on the amount of wind in the system, i.e. the higher the wind generation the lower the system price. Reduction in CO_2 emissions due to wind will be 700–620 g CO_2 per kWh wind generation for the case of replacing coal, and about 300 g CO_2 per kWh wind for replacing natural gas. The case of coal or natural gas generation being replaced by wind is simply a matter of which that has the highest operational costs. With current fuel prices and CO_2 tax this is gas, but considering that European policy is to reduce CO_2 emissions, new incentives may facilitate polluting coal generation to become more expensive.

[8] Denmark total land area is 42 394 km^2, western Denmark is about ¾ of this. Norway total land area is 307 860 km^2, Finnmark alone is 48 000 km^2.

As day-ahead generation plans for wind generation may be inaccurate, system operation will benefit from receiving adjusted plans closer to the operating hour. The Elbas market of Finland, Sweden and Eastern Denmark facilitates this. Norwegian participation in this market should be investigated, possibly also development of Elspot and Elbas into one combined market allowing updated plans close to the operating hour. This is recommended not only for the case of integrating wind, but for generally improving system operation and reducing the need for acquiring balancing power.

Wind generators can in principle participate in the Balance Market, but probably not at a competitive price. Downward regulation of wind generation means dissipation of energy, and functionality to offer upward regulation can only be achieved if constantly operating below potential power, i.e. dissipating energy.

Wind generation impact on need for balancing power has in [11] and [23] been studied in detail for the Nordic system. It is concluded that the required extra balancing is very small, i.e. even for a future situation with wind supplying 10 % of demand the extra balancing amount to only 1.5-4 % of the installed wind power capacity. More specifically, extra balancing is 240–320 MW for assuming 19 000 MW of installed wind capacity in the Nordic countries. Assuming that this requires investment in new reserve capacity, the extra balancing cost 0,8 øre per kWh wind, and about half if investment in new reserve capacity is not needed. In [11] and [23] no account is made specifically for wind in Norway, thus it may be relevant to study this and then possibly also taking account for transmission bottlenecks that may influence reserve requirements.

Recordings of operational data indicate that the Nordic power system can well handle large amounts of wind power even during extreme weather conditions. The event of the hurricane “Gudrun” 8 January 2005 caused first all wind generation in western Denmark to operate close to rated, but then started to cut-out due to excessive wind speed. It took ten hours to go from maximum wind production (2200 MW) to minimum production (100 MW), whereas the steepest drop was about 600 MW in one hour (corresponding to 24 % of the installed wind power capacity). The drop in wind generation was however excellently compensated through the balancing power market (mostly activated in Southern Norway) and by regulating the HVDC link between Norway and Denmark from full export to full import. The example illustrate clearly that the Nordic power system can handle large amounts of wind power through the existing marked based mechanisms.

6 WIND POWER IMPACT ON SYSTEM ADEQUACY

System adequacy relates to the ability of the power system to meet the load demand. In this section wind power impact on system adequacy is addressed considering a) the system's ability to supply the annual load and b) the system's ability to meet the peak demand.

6.1 Annual energy supply

Historical data of the Norwegian hydro supply system show that the annual generation capability may vary +/- 30 %, i.e. in a normal year the annual hydro inflow is about 120 TWh, whereas a dry year may facilitate about 84 TWh and a wet year about 156 TWh. Thus, considering that the annual load is about 120 TWh, the system adequacy with regards to annual energy supply is presently depending on cross-border transmission capacity for energy import and export. Adding wind will help on the situation just as adding any other source of generation, i.e. by virtue of supply diversity. Indeed, wind generation may also vary from year to year, but less than hydro and generally not in phase with hydro inflow, see section 3.1, Figure 9 and Figure 10. Hence, combining wind and hydro provides for a more stable annual energy supply than hydro alone.

6.2 Peak power demand

The system ability to meet the peak demand is basically a matter of available generation and transmission capacity. A rational measure on this is the loss of load probability (LOLP), i.e. the probability of the system meeting the peak demand. This can be calculated taking account for the installed generation and transmission capacity and the probability of these being in operation or having failed. Wind generation can be included in such calculations taking account for wind variations. International studies taking this approach show that wind generation contribute to reducing the LOLP level. Intuitively this can be understood as no generation or transmission is 100 % reliable – all have some probability of failing. Hence, even if wind generation may not be available at all times, this is also the case with all other system assets, and as such wind contributes to reducing the LOLP level in principle just as other generation.

The "capacity credit" is a useful measure for comparing the impact of adding wind with adding other types of generation, say gas or hydro. The capacity credit can be defined for any type of generation as the amount of 100 % reliable generation required for replacing the generation without changing the loss of load probability. Applying this definition, the capacity credit of a 1000 MW thermal power plant is about 950 MW, [24], and for wind, at low to moderate penetration levels, the capacity credit is equal to the average wind power produced during times of peak demand (typically 35% of installed wind power capacity, depending on the site conditions). At higher wind power penetration levels, wind's relative capacity credit becomes lower than the average wind power output in times of peak demand, [7].

6.3 Conclusion

Wind generation will have a positive effect on system adequacy, both in terms of annual energy supply and meeting peak demand. The impact have however not been studied in any detail for Norwegian conditions, but should be. It is relevant to study the impact both on national and regional level (e.g. mid-Norway).

SUMMARY AND CONCLUSION

The wind power technology has gone through a remarkable development. Some twenty years ago the common wind turbine was about 50 kW, whereas today multi-MW wind turbines are put up in big wind farms constituting power plant characteristics. Modern wind farms may control the reactive power or voltage as any other power plant, and may also control active power or frequency as long as wind conditions permits.

Total wind industry turnover in 2005 was about NOK 100 billion. Vestas (DK), Enercon (DE), Gamesa (ES), GE (USA) and Siemens (DE) are the top five in market share. Norwegian industries are mainly sub-suppliers (export in 2004 was about NOK 400 million), whereas ScanWind design and manufacture large wind turbines (+ 3 MW).

The available wind resource in Norway is for any practical purpose unlimited, thus development is basically a question about economic feasibility and willingness to prioritize. Given the great wind potential of Norway, both for generation and for industrial development, 20 TWh is a realistic goal for 2020 assuming wind farms on-land and offshore. This requires about 6500 MW of installed wind power capacity that can be realized within areas totalling some few hundred square km. Cost of generation is 25-35 øre/kWh for on-land sites, whereas offshore wind may be more expensive. Considering that volume of market and technology development will continue bringing down cost of new wind generation, it is likely that at good Norwegian sites wind will be the cheapest option for new non-polluting generation.

The annual wind generation may vary from year to year. Based on 30 years of recorded wind speed data it is found that in Norway the annual wind generation may vary +/- 20 %. In comparison the annual hydro inflow may vary +/-30 %, hence combining wind and hydro provides for a more stable annual energy supply than hydro alone. It is also so that the wind generation will generally be higher in the winter period than in the summer. This seasonal wind variation fits well with the electricity consumption in Norway, and is opposite to the hydro inflow, i.e. being beneficial for system operation.

Variations in wind generation on shorter timescales will generally smooth out the bigger the area. A preliminary analysis on this assuming large scale wind distributed along the Norwegian coast-line indicates very modest sum hourly variations, i.e. a standard deviation of 4 % of the installed wind capacity. Indeed, hour by hour wind generation may be predicted and forecast tools are being developed within Norway and internationally. The forecast accuracy depends largely on the performance of the applied Numerical Weather Predictor model, but also on the geographical area of concern and forecast period. Accuracy is greatly improved for short forecast periods and for considering sum wind power production within a large area.

In total wind generation will have a positive effect on system adequacy, both in terms of annual energy supply and meeting peak demand. The impact have however not been studied in any detail for Norwegian conditions, but should be. It is relevant to study the impact both on national and regional level (e.g. mid-Norway).

The development of grid codes for wind farms as for other generation technologies is sound. It is recognising that large wind farms are basically power plants and may participate in securing efficient and stable power system operation. The specific requirements must however be carefully assessed and possibly adjusted over time aiming for overall least cost solutions.

A large portion of the planned wind farms in Norway are located in areas with limited power transfer capacity, and conservative assumptions may lead to unnecessary strict limitations on the possible wind installation. By coordinated power system operation, however, a large increase in installed wind power is viable, e.g. for the example case in this report the maximum wind farm size ranges from 50 MW, by simplistic criteria, to 200 MW, by control criteria. In general, for planning grid connection of wind farms, it is essential to take account for the power system flexibility and the stochastic and dispersed nature of wind power. Indeed, operation at grid congestion is not an ideal situation. Operation as illustrated by the case study may however be a fair solution for allowing increase of generation in areas with limited transmission capacity, i.e. instead of waiting for future grid upgrades.

Adding wind generation will (just as adding any other generation with low operating cost) reduce the average Nord Pool spot market price. The actual reduction will depend on the amount of wind in the system, i.e. the higher the wind generation the lower the price. Indicatively, increasing the wind generation to cover 10 % of the Nordic power system demand will result in a market price reduction of about 5 øre/kWh.

Reduction in CO_2 emissions due to wind will be 700–620 g CO_2 per kWh wind generation for the case of replacing coal, and about 300 g CO_2 per kWh wind for replacing natural gas. The case of coal or natural gas generation being replaced by wind is simply a matter of which technology that has the highest operational costs. With current fuel prices and CO_2 tax this is natural gas, but considering that European policy is to reduce CO_2 emissions, new incentives may facilitate polluting coal generation to become more expensive.

As day-ahead generation plans for wind generation may be inaccurate, system operation will benefit from receiving adjusted plans closer to the operating hour. The Elbas market of Finland, Sweden and Eastern Denmark facilitates this. Norwegian participation in this market should be investigated, possibly also development of Elspot and Elbas into one combined market allowing updated plans close to the operating hour. This is recommended not only for the case of integrating wind, but for generally improving system operation and reducing the need for acquiring balancing power.

Wind generators can in principle participate in the Balance Market, but probably not at a competitive price. Downward regulation of wind generation means dissipation of energy, and functionality to offer upward regulation can only be achieved if constantly operating below potential power, i.e. dissipating energy.

Wind generation impact on need for balancing power is very small, i.e. even for a future situation with wind supplying 10 % of demand in the Nordic power system the extra balancing amount to only 1.5-4 % of the installed wind power capacity. Assuming that this requires investment in new reserve capacity, the extra balancing cost 0,8 øre per kWh wind, and about half if investment in new reserve capacity is not needed. No account is made specifically for wind in Norway, thus it may be relevant to study this and then possibly also taking account for transmission bottlenecks that may influence reserve requirements.

Recordings of operational data indicate that the Nordic power system can well handle large amounts of wind power even during extreme weather conditions. The event of the hurricane "Gudrun" 8 January 2005 caused first all wind generation in western Denmark to operate close to rated, but then started to cut-out due to excessive wind speed. It took ten hours to go from maximum wind production (2200 MW) to minimum production (100 MW), whereas the steepest drop was about 600 MW in one hour (corresponding to 24 % of the installed wind power capacity). The drop in wind generation was however excellently compensated through the balancing power market (mostly activated in Southern Norway) and by regulating the HVDC link between Norway and Denmark from full export to full import. The example illustrate clearly that the Nordic power system can handle large amounts of wind power through the existing marked based mechanisms.

In summary this report demonstrates options for large scale integration of wind power in Norway. Local control enables operation of a large wind farm on a fairly weak regional grid, and marked based balancing tackles large magnitudes of wind power. A future with high penetration of wind power seems thus viable, though the operational challenges with respect to operating reserves, frequency control and transmission capacity are expected to become increasingly important. The hourly wind power variations may be significant within local areas, but uncorrelated between distant sites. Hence, sufficient transmission capacity may be a key for efficient operation of a future Norwegian and indeed a European power system with a large share of wind power.

ACKNOWLEDGEMENTS

This report has been prepared with funds from EBL and the Norwegian Research Council.

REFERENCES

[1] Nordel Annual statistics 2004 (Årsstatistik 2004), available at www.nordel.org
[2] Grid Development Plan, 2005-2020, Statnett, June 2005, www.statnett.no
[3] John Olav Tande, Petter Støa (2004) *Norway as a leading wind power nation* (in Norwegian) HORISONT nr. 1/2004, available at www.nho.no/files/horisont_nr_1_2004.pdf
[4] Norwegian wind atlas (2003), available at http://www.nve.no/vindatlas/
[5] NVE (2005) *Electric Power Balance in Norway by 2020 – update June 2005* (in Norwegian), available at www.nve.no
[6] Report on the share of renewable energy in the EU and proposals for concrete actions (2004/2153 (INI)), http://www.europarl.eu.int/oeil/file.jsp?id=5199472
[7] EWEA (2005) *Large scale integration of wind energy in the European power supply: analysis, issues and re and recommendations*, available at www.ewea.org
[8] Tande J.O., K.O. Vogstad (1999) *Operational implications of wind power in a hydro based power system*. EWEC'99.
[9] Ernst B. (1999) *Analysis of wind power ancillary services characteristics with German 250 MW wind data*. NREL report TP-500-26969.
[10] Tande JO, K Uhlen, T Gjengedal (2005) *Options for Large Scale Integration of Wind Power*, IEEE PowerTech, St.Petersburg, Russia, June 27-30, 2005
[11] Holttinen, H. *The impact of large scale wind power on the Nordic electricity system*. VTT Publications 554, 2004 (PhD Thesis) http://www.vtt.fi/inf/pdf/publications/2004/p554.pdf
[12] Statnett, 2005, Veiledende systemkrav til anlegg tilknyttet regional- og sentralnettet i Norge (Guideline system requirements to installations connected to the Norwegian regional and main transmission grid) http://www.statnett.no/
[13] David Milborrow (2005) *Going mainstream at the grid face*. Wind power monthly, September 2005, pp 47-50.
[14] Tande JO, E Muljadi, O Carlson, J Pierik, A Estanqueiro, P Sørensen, M O'Malley, A Mullane, O Anaya-Lara, B Lemstrom (2004) *Dynamic models of wind farms for power system studies – status by IEA Wind R&D Annex 21*, European Wind Energy Conference (EWEC), 22-25 November, London, UK.
[15] IEC 61400-21: *Wind turbine generator systems - Part 21: Measurement and assessment of power quality characteristics of grid connected wind turbines*, Ed. 1.0, International Standard, 2001.
[16] Tande J.O., K Uhlen (2004) *Cost analysis case study of grid integration of larger wind farms*, Wind engineering, volume 28, No3, 2004, pp 265-273.
[17] John Olav Giæver Tande, Kjetil Uhlen, *Cost efficient grid integration of large wind farms*, EWEC'2003, 16-19 June 2003, Madrid, Spain.
[18] M.T.Palsson, T.Toftevaag, K.Uhlen, J.O.G.Tande, *Large-scale Wind Power Integration and Voltage Stability Limits in Regional Networks*, 2002 IEEE-PES Summer Meeting.

[19] M.T.Palsson, T.Toftevaag, K.Uhlen, J.O.G.Tande, *Control Concepts to Enable Increased Wind Power Penetration*, 2003 IEEE-PES Summer Meeting, 13-18 July 2003, Toronto, Canada.
[20] Magnus Korpås, John Olav Tande, Kjetil Uhlen, Terje Gjengedal (2006) *Planning and operation of large wind farms in areas with limited transfer capacity*. EWEC'06
[21] Bakken, B.H, Petterteig, A (2005) *Alternatives to reduce reserve requirements and reserve costs in the Nordel system*, SINTEF TR A6034
[22] Hannele Holttinen, Sami Tuhkanen, *The effect of wind power on CO2 abatement in the Nordic Countries*, Energy Policy 32 (2004) 1639–1652
[23] Hannele Holttinen, *Impact of hourly wind power variations on the system operation in the Nordic countries*, Wind Energy, Volume 8, Issue 2, Date: April/June 2005, Pages: 197-218
[24] *4000 MW wind power in Sweden. Impact on regulation and reserve requirements*. Elforsk rapport 05:19
[25] Erik Berge, Finn Nyhammer, Lars Tallhaug, Fredrik Villanger, John Bjørnar Bremnes, Morten Ø. Køltzow, John Smits, Andreas Knauer (2003) *Forecasting wind and wind energy production in Norwegian wind farms*, Kjeller Vindteknikk, KVT/EB/2003/005.
[26] I. Glende, T. Tellefsen & B. Walther (2005) *Norwegian System Operation facing a Tight Capacity Balance and Severe Supply Conditions in Dry Years*, HYDROPOWER'05, Stavanger, Norway 23 – 25 May 2005
[27] *The Nordic Power Market Electricity Power Exchange across National Borders*, Nord Pool, 1 April, 2004
[28] Prabodh Bajpai and S. N. Singh (2004) *Electricity Trading In Competitive Power Market: An Overview And Key Issues*, International Conference On Power Systems, ICPS2004, Kathmandu, Nepal
[29] *Reliability Standards and System Operating Practices in Nordel* (2002) Report from Nordel ad hoc group, September 19, 2002

SINTEF Energiforskning AS
Adresse: 7465 Trondheim
Telefon: 73 59 72 00

SINTEF Energy Research
Address: NO 7465 Trondheim
Phone: + 47 73 59 72 00