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Power Management and Forecasting in Areas with High Wind-Energy Penetration Levels

Where the Wind Blows

THE POWER SYSTEMS IN DENMARK, SPAIN, IRELAND, AND NEW ZEALAND HAVE some of the highest wind penetrations in the world (see Table 1).

The management of the different power systems to date, with increasing amounts of wind energy, has been successful. There have been no incidents in which the wind has directly or indirectly been a major factor causing operational problems for the system. However, there are a number of parameters that are being monitored that indicate the need for active management in the near future (and in some cases already today). In this article, we briefly describe the situations in these four countries, giving special emphasis to the market integration of wind power, the use of wind forecasting, and curtailment experience. The final section provides an overview of the main wind forecasting methodologies and challenges.

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Digital Object Identifier 10.1109/MPE.2009.934658

 1540-7977/09/$26.00©2009 IEEE

table 1. Overview of wind-penetration levels.

	Denmark (west + east)	Spain	Ireland	New Zealand
Peak Demand (GW)	3.7 + 2.6 = 6.3	45.4	4.5	7
Minimum Demand (GW)	1.2 + 0.9 = 2.1	18.5	1.65	1.5*
Wind Power Capacity 2008 (GW)	2.4 + 0.7 = 3.1	16.74	1.0	0.3
Maximum Penetration (wind power capacity/minimum demand)	W: 200% E: 77%	90.5%	60.6%	15%

*This is the minimum demand in the North Island of New Zealand, where nearly all wind generation is located.

Denmark: Design of the Nordic Power Market

One of the main tools for integrating a large amount of wind power into the Danish power system is a well-functioning Nordic electricity market common to Norway, Sweden, Finland, and Denmark. The Nordic power market consists of two main markets: the Nordic Power Exchange (NPX), which itself is divided into three marketplaces, and the TSOs' real-time electricity markets.

The Nordic electricity spot market, Elspot, facilitates the main part of the physical day-ahead electricity trade in the Nordic countries. If a market player cannot fulfill the obligations assumed in the Elspot market, it is possible to trade at the intraday Elbas marketplace up to one hour prior to the hour of operation. The third market place is not for physical contracts, like the first two, but for financial contracts.

The TSOs run two additional marketplaces: a regulating power market for trading balancing power and a system power market for trading ancillary services.

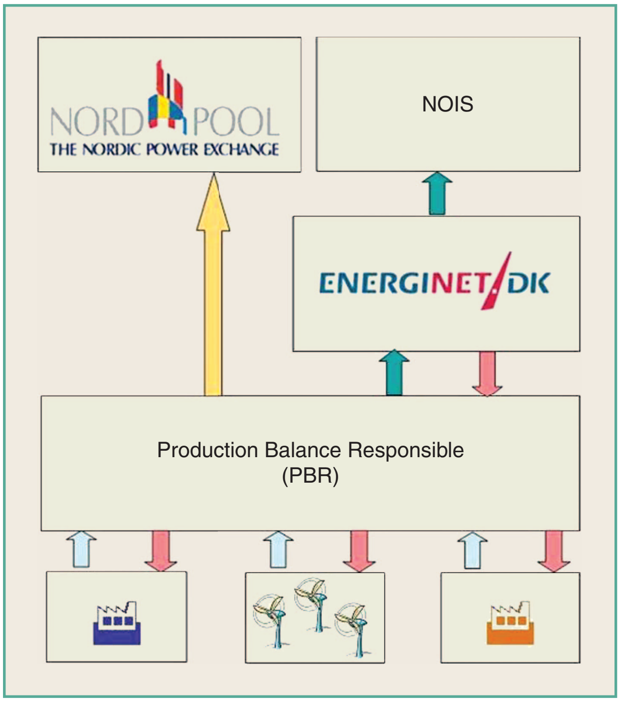

figure 1. Nordic electricity market overview.

The Danish producers sell their energy to a production-balance-responsible market player (PBR), which either sells it directly to the Nord Pool spot market at the NPX or announces the capacity to Energinet.dk, the system operator (see Figure 1). Energinet.dk transfers the regulation power bids to the Nordic TSO's Operational Information System (NOIS) visualizing the regulating and system power market.

Demand can participate in both markets: the day-ahead spot market and the intraday market.

Regulating Power

Regulating power is divided into three categories: primary, secondary, and tertiary reserves. Primary reserves are automatically activated as soon as a frequency deviation is measured in the system. Secondary reserves are automatically activated in the event of a deviation between scheduled and measured generation or consumption.

Tertiary reserves are manually activated in the common Nordic regulating power market up to about one hour prior to operation. In order to ensure a sufficient volume in the regulating power market prior to the day of operation, it is possible for a TSO to purchase regulating options, i.e., a guarantee that a given player will submit bids in the regulating market at a given hour that add up to a predetermined amount of energy.

Balancing Power

If a player does not generate or consume the amount of electricity that was agreed on in the spot market, the player automatically trades the deviation with the TSO. This energy is called balancing power: it reestablishes the balance between generation and consumption for each player. The price of balancing power is the least favorable price between the regulating price and the spot price. In this way, the regulating power expenses paid by the TSO are transferred to the players responsible for the imbalance. This is done in the regulating power market.

Applying the Nordic Power Market for Optimal System Design

Importance of Interconnectors

For the Danish TSO, the interconnections to neighboring systems are of vital interest. In the two Danish systems

> Many energy traders already use day-ahead wind-power forecasts on an aggregated level, as the amount of wind power has a strong impact on spot prices.

(east and west, each belonging to a different European synchronous zone), there is interconnection capacity to export 40% of the generated capacity and import 70% of the maximum consumption.

The availability of hydropower in Norway and Sweden via DC interconnectors is ideal and is often used e.g., to balance wind power in western Denmark using market mechanisms, whereas the AC connection to the German thermal system in the south mainly contributes to a stable frequency.

Danish Phenomenon: Combined Heat and Power Production on Market Terms

Today, more than 50% of the Danish heat demand is produced as combined heat and power (CHP) production connected to the district heating system. Thus inversely, the thermal electricity generation is nearly completely organized in CHP units with even the smallest units having to be scheduled according to the spot market. Currently, one-third of the local scale CHP plants are not only operating on market terms but also active in the regulating power market, thus contributing to the market for ancillary services. In addition, due to a change to the tax system on using electricity for heating purposes, electric boilers have been installed with connections to some CHP plants. These units are constructed for bidding on the down-regulating power market (i.e., increased consumption) and/or the reserve power market.

Negative Spot Prices

Today the Nord Pool spot price is set to zero during hours of excess generation due to wind. Improved performance could be obtained by implementing negative spot prices, giving stronger incentives for suppliers to reduce their supply bids in hours with very strong wind forecasts and for consumers to use electricity in hours with negative prices. Presently, Nord Pool Spot is planning to implement negative spot prices as an option in the market-clearing process in 2009.

Applying the Nordic Power Market for Optimal System Operation

Wind Power Forecasts

The Danish TSO aims to use the best available wind power forecasts. Since meteorological forecasts inherently have a high degree of uncertainty, several different forecasts by different providers are used in parallel. At present, the overall annual mean absolute error (MAE) on day-ahead forecasts amounts to 5% relative to the installed wind power capacity.

Energinet.dk uses wind power forecasts aiming at several targets:

- ✔ operation planning some days before the day of operation
- ✔ trading on Nord Pool's spot market
- ✔ trading on the intraday regulating power market.

Operation Planning

The probability of an excess or deficit of generation is estimated some days before the day of operation. With a large share of wind power capacity in the grid, it is important to know whether wind power capacity is available or out of operation due to too much or too little wind.

Spot Market Trading

The Danish TSO is the production-balance-responsible player (PBR) for about one-third of the installed Danish wind power capacity. This provides a financial incentive to use optimized wind power forecasts when trading on the spot market at noon for the next day of operation. As shown in Figure 2, wind power forecast errors are not the only source of regulation activity.

Real-Time Trading

Up to 15 minutes before the hour of operation, the Danish TSO trades itself into balance on the regulating power market. It is essential to have an idea about wind-power generation some hours ahead. This estimate is made by correcting the wind-power forecasts, by comparing them with actual generation.

Future Challenges

The construction of 20 GW of offshore wind power connected to the German power system (in the direct vicinity of the Danish grid) will affect the ability of the Nordic countries to balance wind-power generation between themselves and Germany. The correlation between wind conditions in Denmark and Germany makes it harder for these neighbors to rely on each other to balance their own wind-power generation. It is necessary to find a common solution to the related challenges.

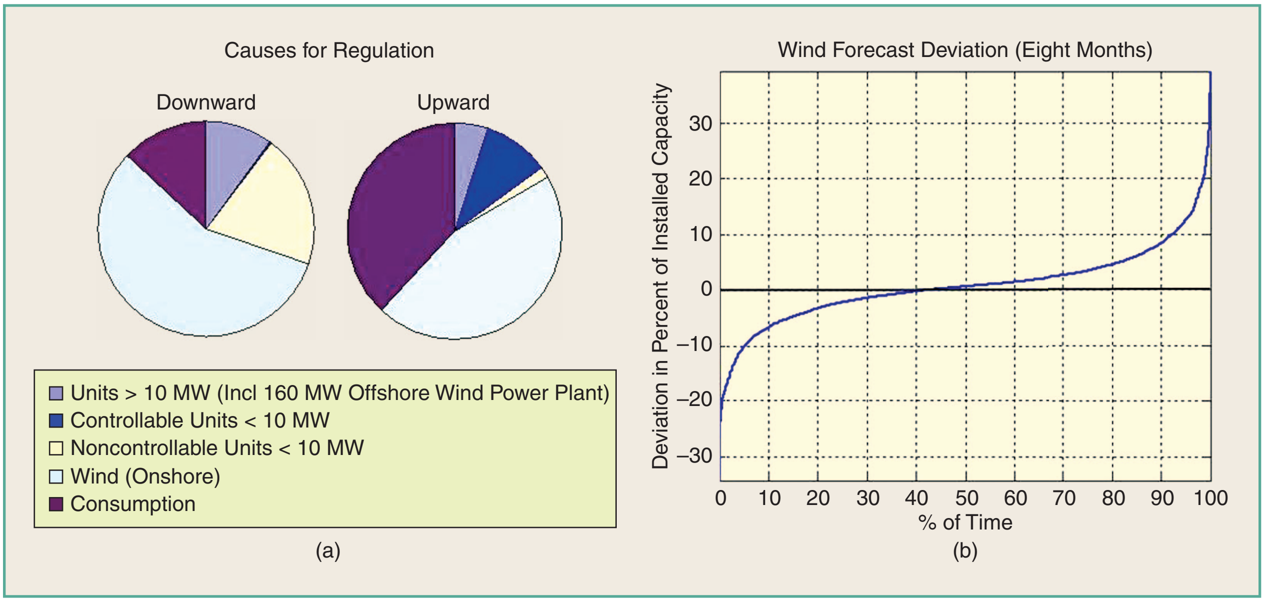

figure 2. (a) Sources for imbalances during a typical month for Denmark's western zone. (b) Wind-production forecast errors for the Danish onshore wind production for a typical eight-month-period (late summer to spring).

Spain

In the last few years, wind energy has become one of the main generation technologies in the Spanish peninsular system, with an installed wind capacity in January 2009 of 16,740 MW. Wind power was the fastest-growing generation technology in 2008, with 1,609 MW of new installed capacity, accounting for 11.5% of the electricity produced.

Wind variability and forecast uncertainties are one of the main challenges for wind-energy integration in isolated or weakly interconnected systems such as the Spanish one. Imbalances must not be greater than 1,300 MW and must be corrected within ten minutes. Otherwise, the interconnection with France may overload or even trip, isolating the peninsular system from the rest of Europe. The biggest influence of wind energy has proven to be on spinning reserves. Spinning reserves include tertiary reserves. They can be deployed from within 15 minutes to approximately two hours and consist of the running reserves of connected thermal units, runoff river hydro plants, and pumped hydro storage plants. Spinning reserves are evaluated continuously from the time when the daily market results are received in day D–1, before 11 a.m.

The goal is to guarantee appropriate amounts of reserves, both upward and downward, to restore system balancing quickly and efficiently but also to minimize the ecological footprint and operational costs. If reserves are found not to be sufficient to overcome the expected uncertainties, thermal groups are switched on or off via a market-based mechanism called "technical constraints management."

In day D–1, spinning reserves are sized taking the TSO's internal probabilistic wind prediction for every hour of the next day into consideration. In particular, the prediction tool provides an hourly value of wind generation with an 85% confidence interval. This method saves reserves and costs in those days with stable climatic conditions, and the method itself increases the amount of reserves for possible wind-forecast errors in those days when the weather (and hence wind generation) is less predictable. On average, 630 MW of additional reserves must be procured to compensate for wind-forecast errors in day D–1 (see Figure 3).

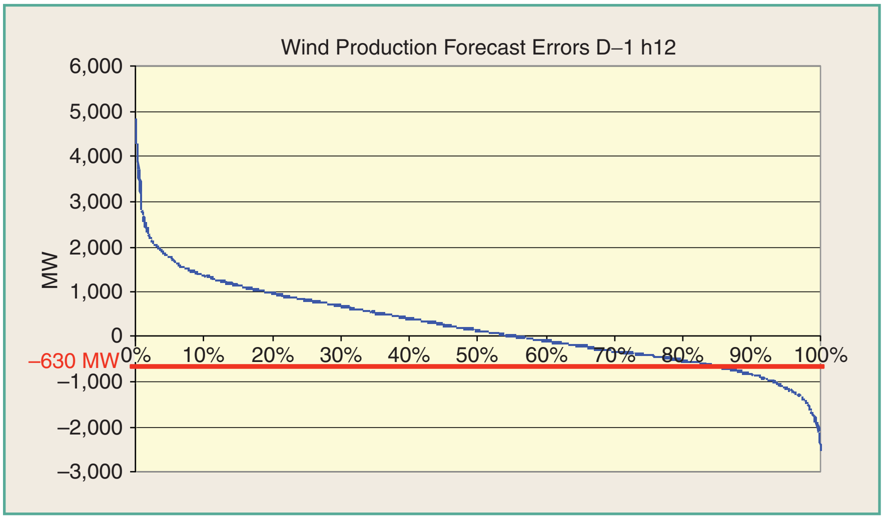

figure 3. Hourly wind-forecast errors 24 hours in advance in Spain in 2008.

> The key issue in wind-power forecasting is to transform the given numerical weather data into the power output of a wind turbine.

The approach of preallocating spinning reserves in day D–1, taking into account the influence of wind power on the overall system, keeps an adequate amount of reserves available at a reasonable cost. The units providing these reserves are also informed well in advance if they are supposed to be running on the following day. However, approximately 15% of the time the added reserves are too small to cope with the actual wind-energy prediction errors, and rescheduling the connection of more thermal groups during peak hours or the disconnection of units in off-peak hours is necessary in real time as a consequence of wind-forecast errors. It should be noted that thermal groups have a minimum time of notice before they can deliver their full capacity. These times range from about two to three hours to switch on a second gas turbine in a 2 × 1 combined-cycle power plant to 16 to 20 hours for a coal-fired power plant.

Wind-prediction errors start to influence spinning reserves if they are not corrected within certain times. From day-ahead technical congestion management to about six hours in advance, wind producers can correct wind-program errors by means of intraday markets in order to avoid imbalance penalty payments. Just like any other market player, wind producers in Spain are financially responsible for their deviations and are penalized for imbalances if their deviation is contrary to the system's needs in that hour. If the spinning reserves have not been restored by market-driven mechanisms, the TSO must then use its internal wind forecast to decide whether connection of thermal units is needed in the real-time operation. If internal wind-prediction errors are not corrected six hours ahead of real time based on updated forecasts, thermal groups may not be able to be connected quickly enough to restore appropriate reserves. If the remaining wind-forecast errors persist and consume the available reserves, the TSO will then need to issue consumption-reduction orders to interruptible loads.

Similar situations can arise during off-peak hours, when available downward reserves are usually lower. Real-time dispatching and shutdown of combined-cycle units may be necessary. If wind-forecast errors persist up to one to two hours beforehand, however, the situation cannot be corrected by shutting down thermal generation because of the time needed to decrease production and disconnect in a stable and secure way. Such a situation occurred, for example, on Sunday morning, 2 November 2008, when wind production increased unexpectedly at a rate of 1,500 MWh (see Figure 4), building up a prediction error of more than 2,500 MW two hours beforehand, which consumed all available downward reserves. Several combined-cycle units were ordered to switch off in real-time operation, but the wind deviation was nevertheless so large that tertiary and secondary reserves ran out and the system went out of balance. As a last resort, wind power was sent a reduction instruction from 7:22 a.m. to 9:30 a.m. to restore system balance.

Ireland

Wind power is now a significant factor in Ireland's overall energy mix. In 2008, wind and hydroelectric generation contributed 11.4%, or around 1,000 MW, of the overall power generation in Ireland. In particular time intervals, wind has represented more than 37% of total system generation. It has even been as high as 26% of total energy production on a given day. Of the 1,077 MW of installed wind power in Ireland, more than 532 MW have a form of direct control from the National Control Centre (NCC) to dispatch its output down. Total wind-power generation

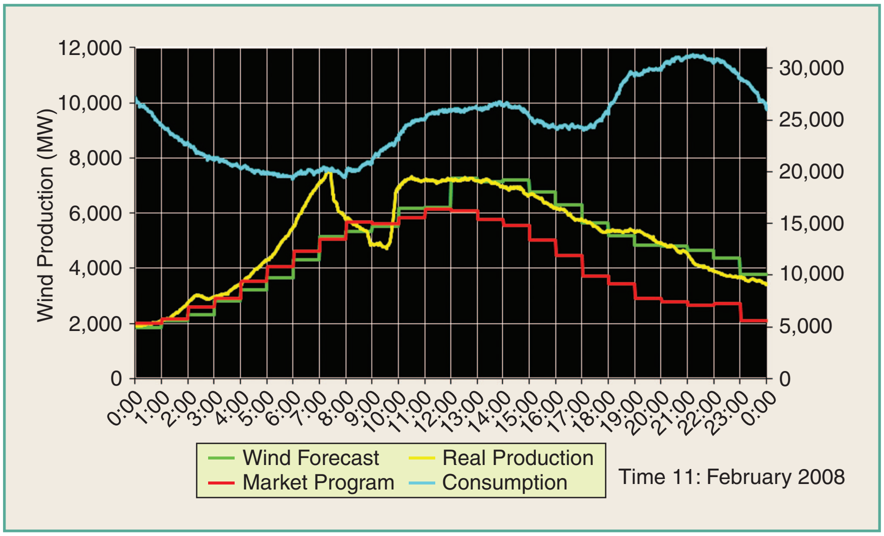

figure 4. Wind forecast, real wind production, wind-market program, and load demand on 2 November 2008.

is connected almost equally between the transmission and distribution systems.

The Irish power system has a minimal level of regional interconnection. At present, interconnection is routed through three interconnector tie lines between Ireland and Northern Ireland and a 500-MW HVDC line between Northern Ireland and Great Britain. There is currently no direct interconnection between the Republic of Ireland and Great Britain. There are advanced plans to construct two HVDC links between the two jurisdictions by the end of 2012.

Experience to Date

To date, there have been no incidents in which wind-power generation has directly or indirectly caused operational problems for the Irish system. The electrical stiffness of the system is being reduced, however, due to the significant amounts of wind power being integrated into the system. Following a two-year analysis of frequency events, there is a correlation between high-wind scenarios and a light system. This has particular relevance in a relatively small power system with little interconnection, such as the Irish one. To help manage this issue, an investment is being made in an online wind-power generation secure level assessment tool (WSAT) to support operational decisions in real time. This tool will be able to assess the highest instant secure amount of wind generation on the power system based on voltage and transient stability analyses of transfers between wind and conventional power generation in the base case and all trip and credible contingency scenarios.

In 2008, wind-power stations were dispatched down three times for security reasons. It is interesting to note that this was the first year Ireland made a dispatch decision for wind plants based on security reasons. While the impact of these decisions was minimal given the relatively small amounts of power (approximately 40 MW) involved, they have raised a number of regulatory issues surrounding payment to wind plants. The design of the all-island single electricity market (SEM) rewards a wind plant that is dispatched down for what it could have generated, not for what is asked. In essence, it is a benign regime for wind-power stations. Where wind power stations make up a small proportion of overall power generation, the economics of such situations are not a problem. But given a scenario within which wind penetration is expected to increase considerably, it will probably become necessary to review this payment mechanism.

Future Challenges and Next Steps

The most recent EU directive on renewable energy aims to increase the share of renewable energy across the entire European Union from 8.5% to 20% of overall energy consumption by 2020. Under this directive, Ireland's renewable energy target is set at 16% of total energy consumption by 2020. In order to meet this target across the heating, transport, and electricity sectors, the Irish government has set challenging targets of 40% of electricity to come from renewable energy and 10% of transport from electric-powered vehicles by 2020. The electricity target is to be substantially met by wind (approximately 5,500 MW, or 37% of electricity generation). It is anticipated that the integration of this level of wind power into the Irish system will create several key technical issues under the broad headings of infrastructure, operations, and portfolio performance that will need to be managed.

Infrastructure

To meet the anticipated increase in demand and to enable the Irish power system to absorb large amounts of wind power and manage the associated variability issues, the Irish transmission network will need to be upgraded. In 2008, the transmission system operator (TSO) published a long-term strategic review of all necessary works to be undertaken to facilitate government targets. The document, called *Grid25*, estimates that the overall investment required will be approximately €4 billion. This national strategic review reaffirms the need for an upgraded grid network and is useful to support all necessary planning applications. In addition, the TSO, with the energy regulator, is running a connection offer (Gate 3) process to allow an additional 3,900 MW of renewable plant, on top of the 2,500 MW of renewable plant already issued in the previous Gate 1 and 2 processes, to connect to the system by 2020.

Operations

As more wind farms connect to the system, it is expected that the operation of the power system, at least in the near term, will become more complicated. The management of this complexity will require understanding the characteristics of the power system better (e.g., the wind stability tool) and stretching the existing infrastructure (for example, via dynamic line rating). In the longer term, however, there are three significant areas of operational concern. The first has to do with the nature of a power system with more than 40% of renewable energy integrated into the system. The second concern relates to the movement of controls at the transmission network to the distribution network, and the third concern is associated with the changing nature of demand behavior.

Regarding the technical problems that may emerge from having 40% of renewables on the system, the TSO is commissioning a series of studies, known as the Facilitation of Renewable (FoR), to examine the dynamic and transient stability, reactive power control, short-circuit, and frequency behavior of the system. The results of these studies are expected by the end of 2009 and will lay the basis for developing operational policy on the island as well as influencing the development of market incentives.

Portfolio Performance

For the power system to work securely, efficiently, and safely with 40% renewable penetration, it is necessary to develop the "right" portfolio of generation and demand

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controls to manage intermittency and operate to acceptable standards. This is very important in a synchronized system like the island of Ireland that cannot rely on significant power flows from neighboring systems. The FoR studies outlined above should indicate what the requirements of the "right" portfolio mix might look like. In order to turn these requirements into a workable portfolio, the following steps are considered necessary:

- ✔ A systematic objective performance report should be introduced providing detailed information on all users of the power system. This system report will help quantify the performance of the current system, identify noncompliance with standards, and help evaluate the performance gap between what is needed and what is being provided.
- ✔ The grid and distribution codes must be developed so that the standards reflect the technology of the time as well as the long-term needs of the power system. This needs to be matched by appropriate commissioning processes to check for compliance before any unit, conventional or renewable, is deemed operational.
- ✔ A reexamination of the incentives for investment based on the requirements of a power system with a high penetration of renewables is necessary. It should include an assessment of current performance capabilities. This is something the regulatory authorities are now considering. However, based on the relative size of monies in the energy, capacity, and ancillary services markets (in SEM, €4 billion, €600 million, and €60 million respectively), it is likely that a significant change in the level of ancillary service payments will be required.

New Zealand

The New Zealand power system consists of two separate 50-Hz AC power systems (one each for the North Island and the South Island) connected by an interisland HVDC link with a 700-MW capacity. New Zealand is not connected to any other power system. Generation sources are typically located far from major load centers. Generation is predominantly hydroelectric (60%), with geothermal (7%) and thermal in the mix as well.

Most of New Zealand's experience of wind integration is gained from experience with the wind generation located in the lower North Island. The outputs of these wind-generation stations are highly correlated. The correlation is especially evident at times of rapid changes in wind-generation output.

Analysis of sudden large changes in regional wind-generation output (of 33% or greater of installed wind capacity in the region) indicates large changes occur around 20 times per year. Large sudden changes of wind generation output in the lower North Island have been observed to occur frequently (e.g., a change equal to 66% of installed capacity over five minutes). Such large changes in output over a short period have the potential to cause noticeable power system frequency excursions in a small power system like that of New Zealand.

Figure 5 shows the effect of a sudden large change in lower North Island wind-generation output that occurred on 15 November 2004.

The present lack of diversity in the location of wind-generation capacity in New Zealand results in significant times when there is no or very little total wind-generation output. This frequently occurs on windless cold winter nights, at times of peak demand.

Investigations indicate existing wind-generation forecast methods have inherent errors that will dominate load forecast error in the market-scheduling and dispatch processes for relatively low levels of installed wind-generation capacity (around 1,000–2,000 MW). These errors are expected to be reduced by improved forecasting processes, but wind-generation forecast error is likely to be significant for large-scale wind generation.

The variability of wind-generation output during dispatch is not a major issue. The extent of the predicted variability of significant installed wind-generation capacity during dispatch was similar to the variability of demand. The effects of the variability of wind-generation output on scheduling and dispatch are mitigated by the inherent flexibility of the predominance of hydro-based generation in the New Zealand power system.

The effects of wind-generation reactive capability were not found to have material effects on management of steady-state voltages or static voltage stability. In cases where wind-generation technology with limited ability to support frequency during frequency excursions displaced other generation that provided support, additional instantaneous reserves were required to keep the frequency excursion within the required targets. Wind-generating plant is not unique in this regard, as some other generation on the New Zealand system does not contribute to frequency management during excursions either and requires the procurement of additional reserves to support frequency.

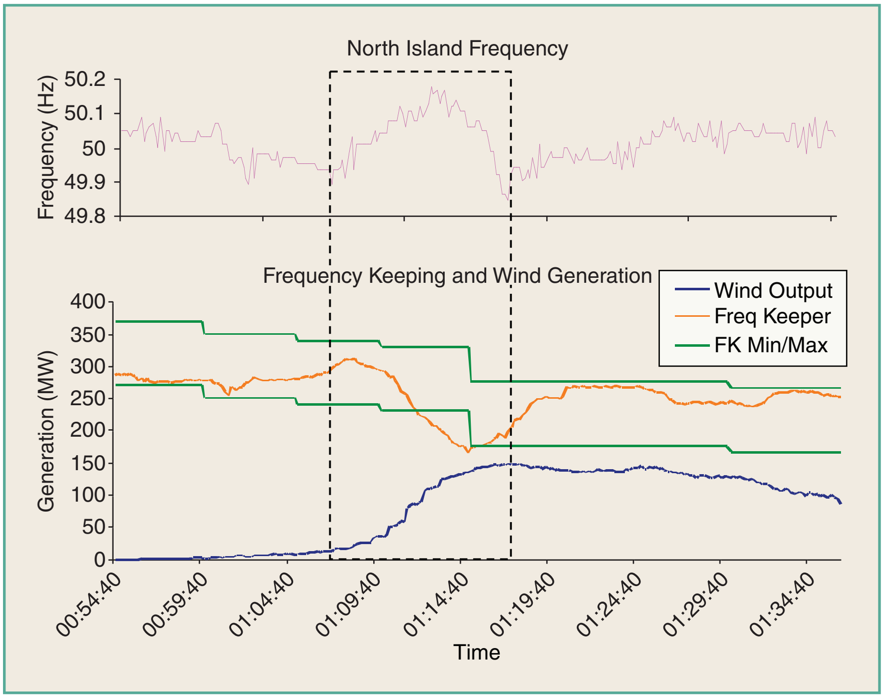

figure 5. Wind generation output increased from 20 MW (12% of installed capacity) at 01:06 to 150 MW (95% of installed capacity) at 01:16. The effect of the change on North Island frequency was to cause a rise from 49.9 Hz to 50.1 Hz, followed by a drop to below 49.9 Hz as other generation was redispatched to compensate. The size of the wind-generation change was greater than the dispatched range (+/−50 MW) of the frequency-keeping station.

Wind generators are required to be price takers in the wholesale market and are limited to pricing their dispatch bids at either zero price or NZ$0.01 per MWh. Generators are paid the market clearing price at the location where the wind generation injects into the grid. This nodal clearing price is determined as the cost of the marginal generator adjusted for losses and congestion costs at each injection node.

Future Challenges and Next Steps

The ability to forecast wind generation accurately will be critical to the way in which the technical standards and market and operational arrangements will need to change to accommodate large-scale wind generation in New Zealand. The system operator is preparing a position paper on the operational needs and uses of wind-generation forecasts in different time frames ranging from close to real time to grid-planning horizons. The Electricity Commission of New Zealand has commenced a wind-integration project to develop optimal arrangements for wind-generation forecasting in the market.

Existing wind generation in New Zealand has been built in those areas of high wind speed that are close to existing transmission or distribution lines. There are a number of areas in New Zealand with high wind-generation potential that are sufficiently distant from transmission capacity that the cost of the necessary transmission circuit to connect to the grid would make the wind generation uneconomic.

A new process allowing new transmission investment to connect new renewable generation to be approved, with investment costs to be recovered from existing transmission customers, is being implemented.

Role of Wind Forecasting

Wind generators are required to provide updated forecasts of output for the trading periods two hours ahead of dispatch to one day ahead. These forecasts are used in the scheduling and dispatch of generation. Forecasts provided by wind generators have demonstrated limited accuracy. One study has indicated that 10% of wind generation forecasts at two hours ahead of dispatch were in error by up to 33% of installed wind-generation capacity.

Integration into the Market

New Zealand has a compulsory-dispatch pool model. All generation for dispatch (including wind generation) must be offered to the pool. Connection of generation plant to the New Zealand power system does not guarantee right of dispatch or rights to transmission capacity. Wind generation (along with any other generation) may experience times when its output is constrained or even dispatched off in accordance with market outcomes or transmission congestion.

Generators can revise their offers up until market "gate closure," which is two hours prior to dispatch. Offers can only be revised for specified reasons after this time. Wind generators provide updated forecasts of future output for the period from day ahead until dispatch. For the period between gate closure and dispatch, a persistence-forecast methodology is mandated.

Overview of Wind-Forecasting Issues

As described in the previous sections, wind-power forecasts are used for a number of different purposes. Grid operators need forecasts for time frames ranging from minutes to days for balancing, to predict local grid congestion, and for overall planning procedures such as the day-ahead congestion forecast required by the European Network of Transmission System Operators for Electricity (ENTSO-E). With increasing accuracy, grid operators integrate these forecasts deeper into their decision making, for example by embedding highly localized wind-power predictions for specific grid nodes into load flow calculations.

Many energy traders already use day-ahead wind-power forecasts on an aggregated level, as the amount of wind power has a strong impact on spot prices. If a lot of wind power is available, the price decreases as wind power displaces expensive fossil fuel units.

The portfolio of wind-power forecasting products includes time scales from the shortest-term predictions (minutes to a few hours ahead) to short-term (intraday and day-ahead forecasts) and medium-range forecasts (several days). Besides ongoing R&D activities to further improve the accuracy of the forecasts, users require a high service level regarding the availability and timeliness of the forecasts.

Basic Approaches

Modern wind-power prediction systems use numerical weather predictions (NWPs) and provide forecasts for a time horizon of up to ten days in advance.

The key issue in wind-power forecasting is to transform the given numerical weather data into the power output of a wind turbine. For this purpose, different approaches, including statistical approaches, physical approaches, and approaches that are hybrids of the two, have been developed and applied successfully in recent years.

A Physical Prediction System

Previento is an example of a physical prediction system that is based on the physical description of the lower atmosphere (see Figure 6). To calculate the wind speed at hub height, the thermal stratification of the atmosphere is modeled in detail. The wind speed is transferred to power output by the power curve; either the certified curve or a site-specific curve that has been determined at the location can be used. The forecasting system also calculates the forecast uncertainty as a confidence interval for each forecast time depending on the prevailing weather situation.

Multiple Meteorological Input Data

The accuracy of the weather data used has a major impact on the accuracy of the power prediction. The reason for this is quite clear: if, for example, the NWP predicts a storm front with a time delay of two hours, the wind-power prediction system cannot compensate for this delay and generates a phase error. Therefore, many state-of-the-art wind-power forecasting systems use several NWP models as input. These can either be provided by a so-called ensemble forecasting system where one NWP model is perturbed in a specific way in order to simulate uncertainties in weather development or by a number of deterministic NWP models.

For example, Previento uses an "optimal" combination of weather models in which the different models are weighted according to their capabilities in different weather situations as determined by an automatic weather-classification scheme.

The combined wind-power forecast significantly outperforms the best forecast based on a single weather model, as well as that obtained from a simple fixed combination. In dynamic weather situations in particular, the combined forecast reduces large and costly forecast errors. In other words, it can be shown that the combination forecast offers the greatest benefits in extreme situations (see Figure 7).

Future Techniques

Although forecasting techniques are being increasingly refined, more weather forecasts are being used in operational environments, and computer advancements provide the possibility of specifically targeted weather forecasts, it is unrealistic to expect that day-ahead forecasts will one day reach an accuracy level that is sufficient for the detailed day-ahead planning of wind as firm scheduled generation.

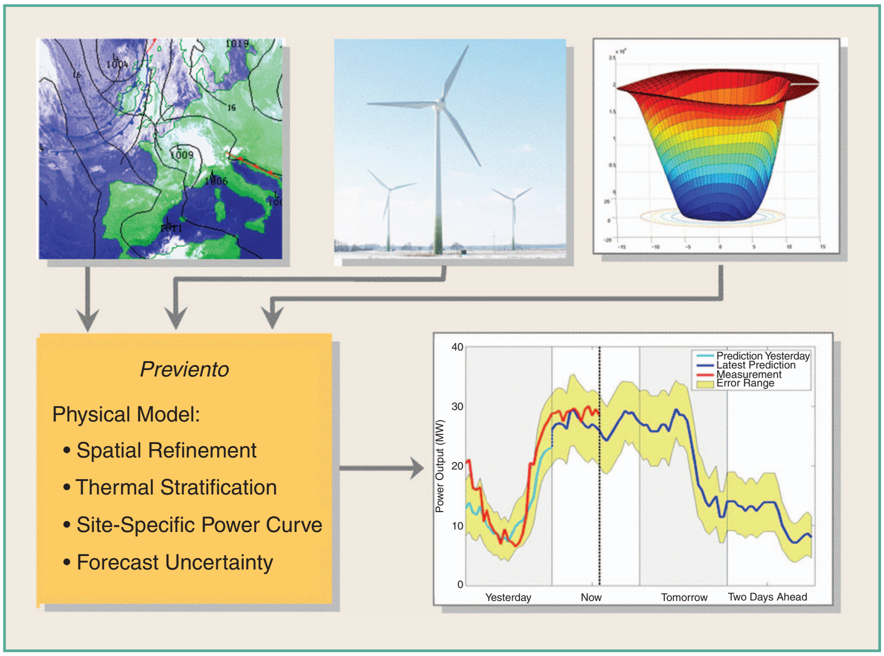

figure 6. Basic scheme of a physical prediction system that uses different weather models to calculate predictions for single wind farms or to make regionally aggregated predictions.

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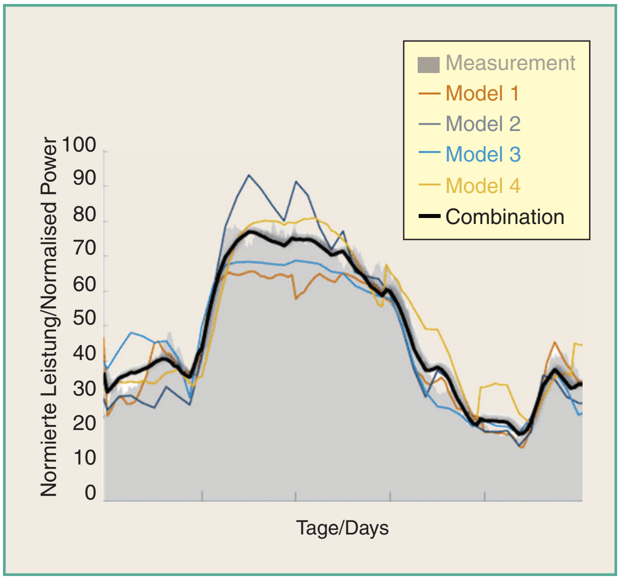

figure 7. By selecting the optimal combination of numerical weather models for individual weather situations (thick black line), the danger of large forecast errors in extreme events such as storm fronts is minimized.

As described in the previous sections, high wind-penetration levels will become a reality in many countries in the near future. Hence more-flexible generation resources will need to be operated in order to manage the increased variability. This also means that more-advanced methodologies of data handling and management will be required in the future, both at the system operator (control room) level for safe operation of the grid and with the power generators in order to enable the trading of various types of energy in an economical fashion.

Weather forecast uncertainty will then become the main source of imbalance between generation and demand. Therefore, using many forecasts (as the ensemble forecasting technique is doing) is expected to play a central role in future weather forecasting. Neither single, deterministic weather forecasts nor pure statistical prediction methodologies will meet the requirements of increased penetration of intermittent energy sources. Using physically based weather ensemble forecasts in tandem with a statistical methodology has the capability of combining various sources of information with an embedded check on physical consistency. The so-called ensemble Kalman filter approach (EnKF) is such a hybrid technique, with the potential to solve many of the aforementioned issues.

The MSEPS-EnKF system is an example of such an EnKF approach, where the ensemble weather input is obtained from a multischeme ensemble prediction system (MSEPS) targeted to simulate the uncertainties of the lower boundary layer processes that are especially important for wind predictions. The MSEPS-EnKF contains many more features than the ordinary EnKF; it is able to combine the relatively gently varying area-averaged MSEPS ensemble weather forecasts with responsive local meteorological and nonmeteorological measurements without losing accuracy or meteorological consistency.

The approach is designed to fully trust measurements, if they pass the quality check.

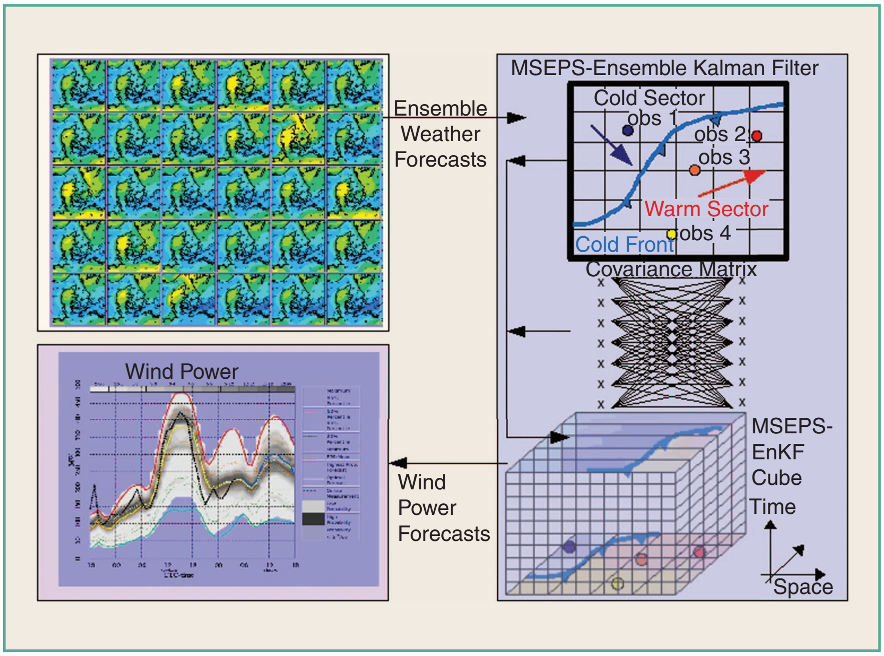

figure 8. Ensemble Kalman filter (EnKF) technique for data assimilation of wind-power and meteorological measurements and translation into online forecasts and short-term probabilistic forecasts.

This also applies to measurements under the influence of local terrain effects, even if they are unresolvable in the weather forecasts.

By filling the EnKF cube from the covariance matrices with ensemble forecasts, measurements, and time, this approach is capable of assimilating measurements in time and space into the overall system and generating reliable online estimates, as well as short-term forecasts (see Figure 8). A single forecast can be generated for any size power system within a few seconds. Thus, it will be such approaches that are required to meet the response requirements for interactive use in the control room, and allow the operator to, for example, add a fictitious measurement and verify the response of the grid within seconds.

Conclusions

Experience with the integration of high amounts of wind generation into power systems around the world has shown no incidents in which wind generation has directly or indirectly caused unmanageable operational problems. The key elements for the successful integration of high penetration levels of wind power are:

- ✔ There must be well-functioning markets over large geographic areas—combining a number of balancing areas—that enable an economical way of sharing balancing resources. This situation also enables aggregation of a more diverse portfolio of wind plants, which reduces the output variability. Well-functioning markets must also offer a range of scheduling periods (i.e., day-ahead, hour-ahead, and real-time) to accommodate the uncertainty in wind-plant forecasts. A fundamental requirement for such a well-functioning market over large geographic areas is an appropriately designed transmission system to interconnect the different network areas.
- ✔ Advanced wind-forecasting systems based on a variety of weather input and their active integration into power-system operation are needed.
- ✔ New simulation tools are necessary to evaluate the impact of wind power on the security of supply and load balancing in near real time. The corresponding right to curtail wind power, when necessary from a system security point of view, is also key.

In addition, grid codes that recognize the increasing capabilities of wind turbines and are applied in a consistent manner to all generation technologies are key elements for the successful integration of high penetration of wind power.

For Further Reading

Spanish Ministry of Industry, Commerce and Tourism. (2007). REAL DECRETO 661/2007, de 25 de mayo, por el que se regula la actividad de producción de energía eléctrica en régimen especial [Online]. Available: http://www.boe.es

Spanish Ministry of Industry, Commerce and Tourism. (2006). RESOLUCIÓN de 4 de Octubre de 2006, de la Secretaría General de Energía, por la que se aprueba el procedimiento de operación 3.7 Programación de la generación renovable no gestionable [Online]. Available: http://www.boe.es

G. Giebel, R. Brownsword, and G. Kariniotakis. (2003). State of the art on short-term wind power prediction. ANEMOS Rep. D1.1 [Online]. *Available*: http://anemos.cma.fr

M. Lange and U. Focken, *Physical Approach to Short-Term Wind Power Prediction*. Berlin: Springer-Verlag, 2005.

M. Lange, U. Focken, R. Meyer, M. Denhardt, B. Ernst, and F. Berster, "Optimal combination of different numerical weather models for improved wind power predictions," in *Proc. 6th Int. Workshop Large-Scale Integration of Wind Power and Transmission Networks for Offshore Wind Farms*, Delft, 2006, pp. 273–276.

P. L. Houtekamer and H. Mitchell, "Data assimilation using an ensemble Kalman filter technique," *Monthly Weather Rev.*, vol. 126, no. 3, pp. 796–811, 1998.

A. Orths and P. B. Eriksen, "European test field—VPP Denmark," in *Proc. IEEE PES GM 2009*, Calgary, Canada, to be published.

P. B. Eriksen and A. Orths, "The challenges and solutions of increasing from 20 to 50 percent of wind energy coverage in the Danish power system until 2025," in *Proc. 7th Int. Workshop Large Scale Integration of Wind Power and on Transmission Networks for Offshore Wind Farms*, Madrid, Spain, May 2008, pp. 27–33.

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