Wind Energy and the National Electricity Market with particular reference to South Australia

A report for the
Australian Greenhouse Office

Prepared by

Hugh Outhred

Version 8
March 2003

Contact details for Hugh Outhred
Tel: 0414 385 240; Fax: 02 9385 5993; Email: h.outhred@unsw.edu.au

Summary

Wind energy appears likely to be the first stochastic resource to be widely used for generating electricity. For that reason alone, wind energy brings new issues that should be addressed prior to its extensive deployment. However, the exploitation of wind energy also brings innovative use of generator technologies, including widespread use of induction generators and power electronic interfaces, which may have implications for electricity industry operation. The key issues that arise are:

- *Uncertainty in the future power output and energy production of wind turbines, wind farms and groups of wind farms*, arising from effects such as topographic features, short-term turbulence, diurnal, weather and seasonal patterns, and long-term phenomena such as climate change.
- *Voltage and frequency disturbances* due to starting transients, power fluctuations during operation and stopping transients initiated by high wind speeds or network disturbances.
- *Potential problems in fault detection and/or fault clearance* caused by either inadequate or excessive fault level in the vicinity of a wind farm.
- *Potential difficulties in managing frequency and/or voltage* in power systems with a high penetration of wind turbines due to low inertia and/or lack of voltage control capability.
- *Difficulties in capturing economies of scale in network connection for wind farms,* because the network rating that minimises per-unit network connection cost may exceed the effective network rating required by a single wind farm (which will usually be less than the nameplate rating of the wind farm due to diversity effects).

These issues have technical and commercial implications for both wind farm developers and other industry participants. However, wind turbines can be designed to ride-through network disturbances, reduce starting and stopping transients and contribute to voltage and frequency control. Also, there are useful diversity effects and short and long-term wind farm production forecasts can be produced. Finally, appropriate planning protocols could capture economies of scale in network connection costs. Therefore, the following recommendations are made:

- Wind power forecasting techniques should be further refined by systematically combining meteorological models with fine-scale boundary layer models and measurements of wind farm production. To investigate diversity effects, it would be desirable to collect synchronised 30-second data on the power outputs of all wind farms in Australia.
- These enhanced forecasting techniques should be used to forecast wind power and energy production for timescales and degrees of spatial aggregation that are appropriate for ancillary services, spot energy and derivative markets and the REC market.
- Advanced wind turbine designs and control strategies should be used and tests should be conducted of the ability of wind farms to ride-through plausible network disturbances.
- Planning protocols should be developed that facilitate the deployment of wind farms in a manner that minimises grid connection costs while maximising the benefits of diversity between wind farm power outputs, for example by encouraging joint ventures.
- The National Electricity Code should be reviewed with respect to the neutrality of implementation of ancillary services, spot and derivative markets and projections of system adequacy in the context of stochastic energy resources such as wind energy.

These recommendations would require governments to take a more active role in the wind energy industry than they have taken to date. The minerals industry provides a precedent, although there would be differences in the specific roles that government would play.

Table of Contents

Introduction

Wind farms are one of the most cost effective of the "new" renewable energy technologies and, when installed in appropriate locations, can produce electrical energy at a cost that is comparable with fossil-fuel power stations if externalities are taken into account. However, wind farms also introduce new generating technologies and new resource characteristics to the electricity industry, with implications that should be considered prior to the large-scale exploitation of wind energy. For example, the power output of a wind farm is characterised by its variability, relative unpredictability and limited controllability (BWEA, 1982; Hirst, 2002; Milligan et al, 2002; Leonhard and Muller, 2002).

The following issues are important in maximising the cost-effectiveness of wind farms:

- Wind resources must be adequate, with a hub-height annual average wind speed of 8 m/s to be commercially viable in the Australian context at a REC price of $35 (Wilkinson, 2002). Moreover, the commercial outcome is very sensitive to wind speed, thus siting is important (PriceWaterhouseCoopers, 2002). It is also sensitive to the REC price, and REC forward price behaviour is important. In the absence of RECs, an emission-trading regime would need a significant emission reduction target to give an equivalent result.
- Grid-connection costs must be sufficiently low to allow an adequate rate of return. This may require the capture of all available network economies of scale because good wind resources are often found in locations with high connection costs because they are remote from both major load centres and existing power stations.
- Wind turbine starting and stopping transients and power fluctuations during operation must not lead to unacceptable voltage or frequency fluctuations, excessive load-following costs or excessive wear and tear on turbine components.
- Wind farm designers and network service providers must avoid unsatisfactory network voltage profiles and protection problems due to either excessive or insufficient fault level.
- Predictions of wind farm production must be sufficiently accurate to avoid unnecessary network investment or generation reserve requirements and to satisfy wind farm investment risk management criteria.

This paper discusses the above issues in the Australian context with particular attention to South Australia. Arnott (2002) and Western Power (2002) address a similar range of issues.

Characteristics of the power density of the wind

Wind power density (PD) is defined by the relationship:

PD = $[0.5DV^3]$ W/m^2, where:
D = air density (kg/m^3), around 1.22 kg/m^3 at sea level, and
V = wind speed (m/s)

Thus wind power density has a cube law relationship with wind speed, for example, wind power density increases by a factor of eight for a doubling of wind speed. The cube law relationship means that site selection has a critical influence on wind farm energy production. It also means that it is more important to forecast wind farm energy production than wind speed, however this must take account of the fact that wind turbines have a power conversion characteristic that is a non-linear function of wind speed.

Wind power density reflects the dynamic behaviour of the atmosphere, which in turn depends on the combination of solar energy flux from the sun, the structure of the atmosphere including the effects of moisture, the earth's surface characteristics and the effects of the earth's rotation. Wind regimes vary with latitude, being particularly strong in the "roaring forties" and thus in the vicinity of the southern coastline of the mainland and Tasmania, where the annual average wind power density may significantly exceed 500 W/m^2 at 50 m height above ground level. A modern wind turbine with characteristics matched to the wind regime can capture approximately 30% of this energy.

Wind velocity at a particular location varies in speed and direction. Most of the variation occurs in the time scale of weather and seasonal phenomena, with maximum variability in a timescale of a few days. There can also be diurnal effects due to differential heating and cooling of land and water as well as slower, climatic variations, which may cause the standard deviation of the annual energy yield of wind farms to exceed 10% (Danish Wind Industry Association, 2002).

The wind regime can be quite turbulent in the earth's boundary layer where wind turbines operate. Turbulence mainly arises because local topography and surface roughness effects transfer some of the wind energy density in the weather timescale to the higher-frequency turbulence timescale of less than one hour. As a result, the wind velocity at a particular point can fluctuate rapidly in both speed and direction. The nature of turbulence can vary significantly from one location to another.

Figure 1 shows a spectral analysis of 17 years of wind data collected at 7m above the ground at a site in Denmark. The weather and local turbulence phenomena are clearly visible, as is the "spectral gap" between them. For this data set, the peak of the turbulence variance spectrum is at a periodicity of approximately 30 seconds.

It is important to know what fraction of the wind energy density at a prospective wind farm site appears in the turbulence spectrum because this may have lower commercial value in a restructured electricity industry than wind energy density in the weather spectrum because of the additional ancillary service costs incurred to regulate frequency.

Some power system operators also believe that there may be additional costs associated with hourly and daily fluctuations in wind energy. For example, Ilex Energy Consulting (2002) concludes that there would be additional costs associated with 20% penetration of wind farms in a recent UK study. As will be discussed later, a study by Western Power (2002) of the South West Interconnected System reaches similar conclusions and proposes a charge for all energy produced by wind farms to pay for these additional costs, and to initially limit wind farm penetration to 10%.

However neither of these studies adequately account for appropriate wind farm control strategies or advanced forecasting techniques, or of diversity between wind farm sites. Thus they are likely to be "worst case" estimates.

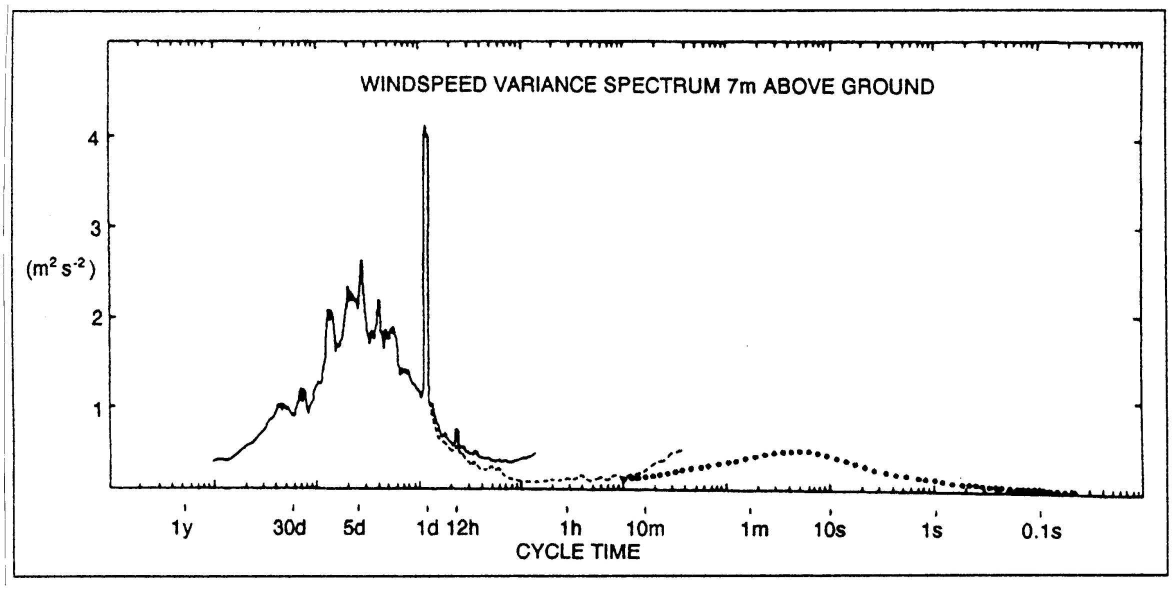

Figure 1. Spectral analysis of 17 years of wind data collected at a site in Denmark (Sorensen, 2000, Fig 2.110, p 194)

Design features of wind turbines and wind farms

Modern wind turbines used for electricity production have the following key features as illustrated in Figure 2:

- A propeller-type rotor usually consisting of three controllable pitch blades connected to hub and low-speed shaft that turns in bearings mounted on a steerable nacelle on a tubular steel tower. Blade diameter and hub height may exceed 100 metres.
- The shaft connects the rotor to an electrical generator either directly or via a step-up gearbox with a ratio of up to 100:1.
- Direct drive wind turbines use a purpose-built low-speed electrical generator because of the low speed of rotation (typically 10-20 rpm). The direct drive wind turbine shown in Figure 3 uses a radial-flux synchronous generator with a high pole-number DC winding on the rotor. The synchronous generator is connected to the electricity network via a variable frequency DC link inverter, allowing the rotor speed and the power factor to be varied. Varying the speed and thus rotor kinetic energy can smooth the power output and varying the power factor can contribute to voltage control. An optional load bank could provide greater control in high wind-speed conditions or following loss of supply.
- Wind turbines with a gearbox as shown in Figure 4 typically use a wound-rotor induction generator with a four, six or eight pole winding and a variable speed of rotation of 1000-2000 rpm (older designs use a squirrel cage rotor and in some cases a pole-switched (two-speed) stator winding). The induction generator stator winding is connected directly to the network and the wound rotor may be connected either to a variable resistor bank or to the network via a variable frequency inverter. Both configurations permit variable speed operation but an inverter can provide a wider speed range, greater conversion efficiency and, with appropriate inverter design, the ability to contribute to network voltage control.
- Wind turbine gearboxes must be protected from shock loadings arising from both fluctuations in wind power due to wind turbulence and fluctuations in electrical power due

to voltage (or frequency) disturbances. Rapid blade pitch and rotor speed control can assist with the former and an inverter or Static VAr Compensator can assist with the latter.

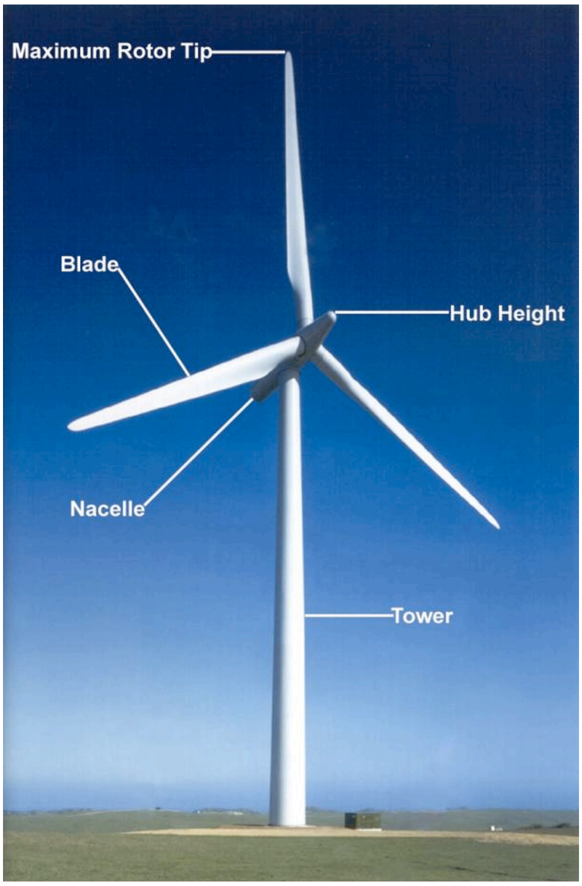

Figure 2. A modern 1.3 MW turbine of the kind used in Codrington wind farm, Victoria (www.bonus.dk)

Figure 3. Wind turbine using direct drive variable speed synchronous generator, of the kind used in the Albany wind farm (www.enercon.de)

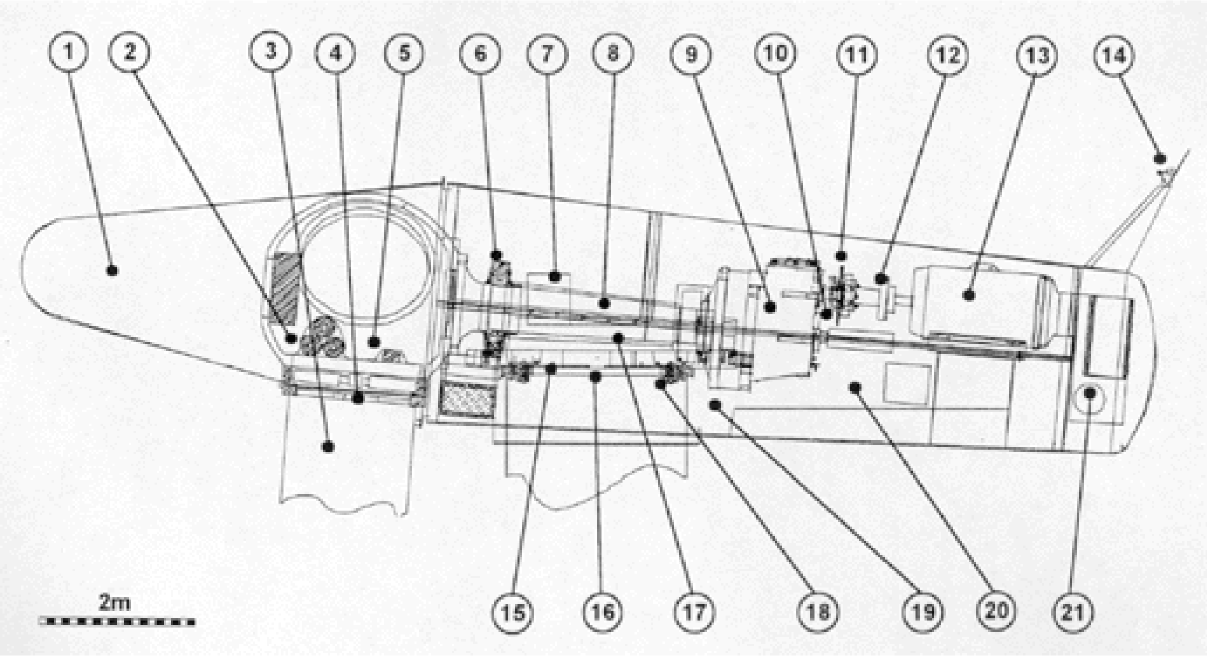

Figure 4. Wind turbine design using gearbox and induction generator, of the kind used in Codrington wind farm (www.bonus.dk)

Figure 5 shows very effective smoothing of wind power fluctuations achieved for a 3.6 MW turbine by combined blade pitch and rotor speed control. It seems unlikely that this degree of smoothing could be achieved under all circumstances.

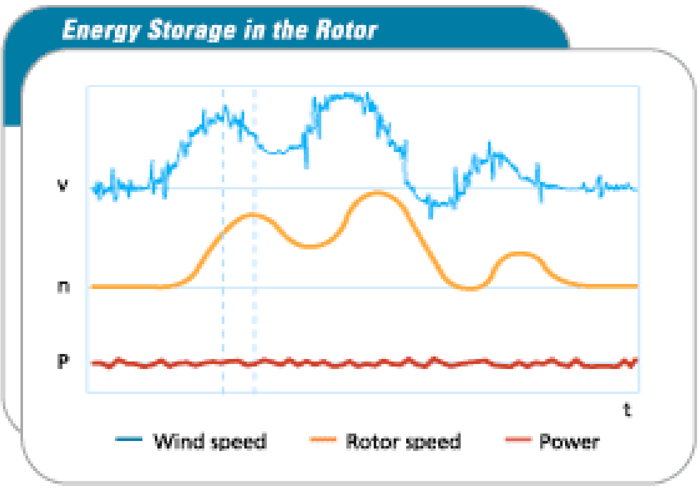

Figure 5. Turbulence smoothing using active blade pitch and rotor speed control (www.gepower.com/dhtml/wind)

The power output of a wind turbine is a function of wind power density and conversion efficiency. The power curve (power output versus wind speed) is produced by plotting turbine electrical power measurements that have been averaged over a period of several minutes against wind speed measurements that have been averaged over the corresponding periods.

Figure 6 shows the (averaged) wind power and conversion efficiency curves based on manufacturer's data for the wind turbines used in the Codrington wind farm.

The key features of the power curve are:

- Cut-in wind speed (typically 3 m/s), at which the wind turbine commences operation
- Rated wind speed (typically 12-15 m/s), above which the conversion efficiency of the wind turbine is deliberately reduced to prevent the turbine power exceeding its rated value
- Cut-out wind speed (typically 25 m/s), at which the wind turbine is shut down to avoid damage

The cube-law relationship of wind power density is reflected in the section of the wind-power curve between 5 and 10 m/s in Figure 6, where the turbine is working at a near-uniform conversion efficiency of 40-45% for weather spectrum energy. Conversion efficiency falls off on either side of this speed range as shown in the efficiency curve in Figure 6. This turbine design uses a two-speed rotor rather than continuous speed control. The latter might increase low wind speed efficiency slightly but would have little effect on annual energy yield as this is mostly accumulated during high wind speed conditions. Conversion efficiency will generally be lower for turbulence spectrum wind energy than weather spectrum wind energy because rapid fluctuations in speed and direction are difficult to track and may not be uniform across the swept area.

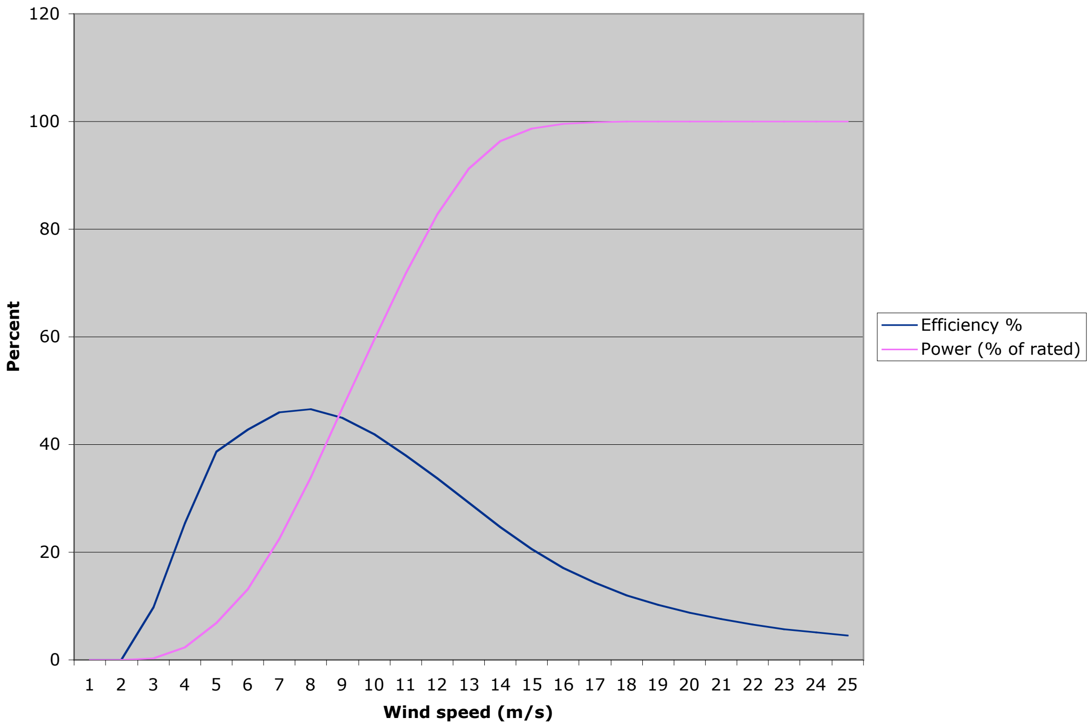

Figure 6. Averaged output power and conversion efficiency curves for the 1.3 MW wind turbines used in Codrington wind farm based on manufacturer's power curve data

Generally, a wind turbine will not experience a uniform wind regime across the swept area of its rotor due to wind shear and turbulence effects, and the mechanical power exerted by the rotor on the shaft will represent the averaged effect of this "micro-scale" wind behaviour. The electrical power produced by the turbine will be a filtered version of the mechanical power, taking into account the effects of rotor inertia, blade pitch, rotor speed and inverter (if present) control systems, and the dynamic interactions between the wind turbine and the rest of the power system.

Figure 7 shows simulated and measured electrical power from a test on a wind turbine in Denmark (Sorensen et al, 2001). The data is presented in the frequency domain and shows a typical "low-pass filter" characteristic with very little energy in electrical power above a frequency of about 0.1 Hz (equivalent to an oscillation period of 10 seconds). As indicated in Figure 7, there is always a resonant peak at a frequency related to the speed of rotation of the rotor. The size of the resonant peak may be higher in wind turbines controlled to maximise turbulence energy capture (Morcos & Gomez, 2002).

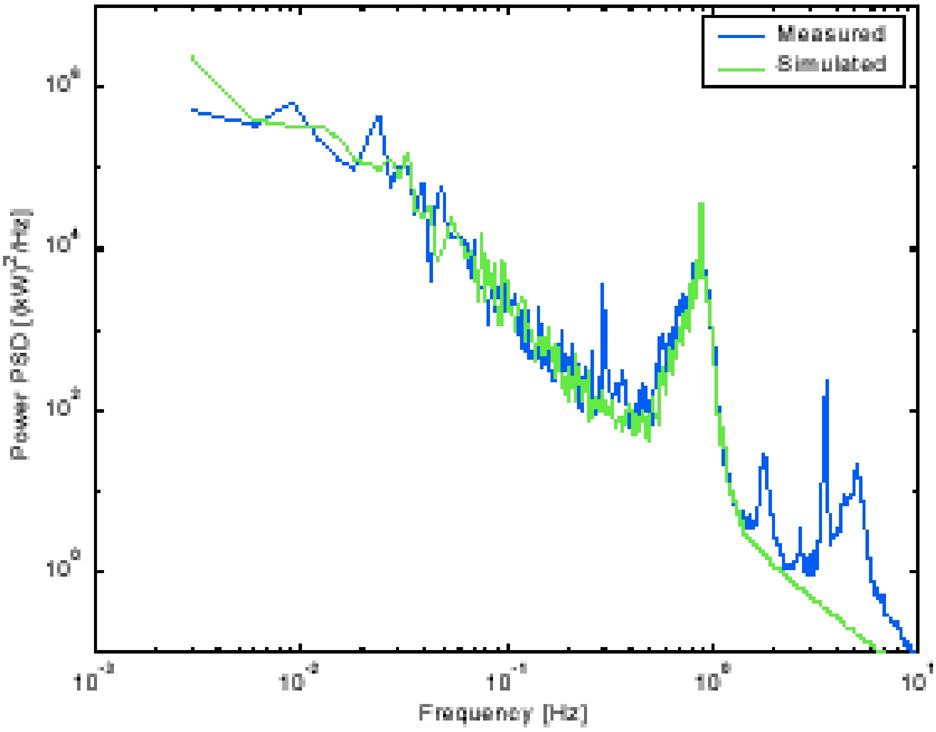

Figure 7. Frequency domain behaviour of the electrical power output of a wind turbine (Sorensen et al, 2001)

An electricity industry consists of generator, network and load equipment. It operates as single, tightly coupled entity rather than as a set of connected but autonomous parts. The key aspects of wind turbine behaviour from the electricity industry perspective are as follows:

- *Starting transients*, when the wind speed picks up sufficiently to cause the wind turbine to automatically start. These can occur frequently if the wind speed fluctuates above and below cut-in speed. Starting transients arise from the initial imbalance between mechanical and electrical power flows and from the "magnetic inrush" phenomenon for induction generators. Starting transients can be reduced by "soft-start" techniques.
- *Fluctuations in power output while operating,* due to fluctuations in wind speed and direction or fluctuations in terminal voltage or frequency.
- *Stopping transients,* when a wind turbine is disconnected from an electricity network. Stopping transients are most severe when the wind turbine must be shut down from full power output. This may occur if the cut out wind speed is reached and the turbine control system automatically disconnects the wind turbine. A shut down may also occur because of a voltage and/or frequency disturbance propagating through the network, which may exceed voltage ratings or expose the rotor to unacceptable accelerating power.

Thus wind turbines may cause voltage and frequency fluctuations that reflect characteristics of the wind turbine and its control systems as well as the wind regime. Such fluctuations may have commercial implications for a wind farm operator as will be discussed later.

Wind turbines with synchronous generators, particularly those with a “braking resistor” connected to the DC bus of a DC-link inverter may be less susceptible to high-power shutdowns than other designs. Dynamic reactive power compensation (provided by an appropriately designed inverter or a separate SVC) may reduce the susceptibility of induction machine designs to high-power shutdowns and also reduce shock loadings on the turbine. Coordinated design may be necessary to avoid the possibility of dynamic interactions between wind turbines and with the rest of the power system.

A wind farm can be defined to consist of a number of wind turbines in proximity that are electrically connected with a common point of connection to an electricity network. The wind turbines are usually sited to maximise the output of the wind farm as a whole taking into account interference between wind turbines and subject to siting constraints, network connection costs and visual and environmental impacts.

A large modern wind turbine usually has a step-up transformer either at the base of the tower or in the nacelle, and electrical connections between wind turbines are usually at a voltage level of 11 kV or above. A wind farm is usually connected through a further step-up transformer to the electricity network at a voltage level of 33-132 kV. The transformer impedances reduce the extent to which voltage fluctuations and waveform distortions propagate from the wind turbines into the network.

Each wind turbine in a wind farm sees a different wind regime and as a result of diversity between these regimes, the stochastic process that represents total electrical power output of a group of turbines will have smaller normalised fluctuations than the stochastic process that represents the electrical power output of an individual wind turbine.

The extent of this smoothing effect depends on the context but will be bounded by the following relationships for a set of identical wind turbines in one or more wind farms experiencing wind regimes of comparable power density:

- If the wind regimes experienced by each of the wind turbines were fully correlated in time (that is, each turbine experienced an identical pattern of wind power as a function of time) the summated power output of all the wind turbines would have the same normalised standard deviation as the power output of a single turbine.
- If the wind regimes experienced by each of the wind turbines were fully uncorrelated in time (that is, each turbine experienced an independently varying pattern of wind power as a function of time) the summated power output of all the wind turbines would have a normalised standard deviation that was inversely proportional to the square root of the number of wind turbines in the set ($n^{-0.5}$) compared to the normalised standard deviation of the power output of a single turbine.

Rosser (1995) reports on the effects of diversity on smoothing short-term power fluctuations for the 2MW Esperance wind farm, which consists of 9 Vestas V27 225 kW wind turbines. He showed that the one-second changes in output for individual turbines were uncorrelated over 200 hours of data (that is proportional to $n^{-0.5}$, where n is the number of turbines in operation). This result is shown in Figure 8. He also found that correlation between the wind turbine power fluctuations increased for longer averaging times.

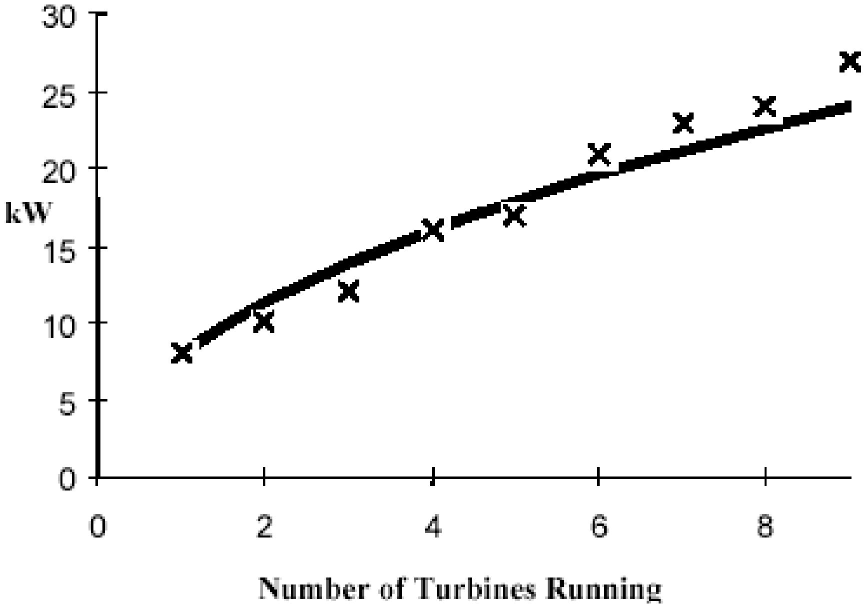

Figure 8. One-second power fluctuations for the Esperance 2MW wind farm as a function of the number of turbines running. The solid line is the $n^{-0.5}$ approximation (Rosser, 1995)

The effectiveness of the smoothing process is a function of wind farm layout and wind regime. For example, the wind farm layout on the left of Figure 9 may be less effective than the wind farm layout on the right in smoothing wind farm power output fluctuations due to multi-second wind gusts associated with sea breezes.

Figure 9. Contrasting wind farm layouts with respect to the effectiveness of smoothing of wind farm power output (www.windpower.org)

The size of starting and stopping transients for a wind farm depends on the size (and design) of the individual wind turbines rather than the wind farm. However the frequency of starting and stopping transients is a function of the number of wind turbines in a wind farm. Problems with voltage flicker on the local network may increase with the number of wind turbines in a wind farm due to the increased frequency of starting transients (Morcos and Gomez, 2002).

Figure 10 shows the real and reactive power output of the Esperance 2MW wind farm during a starting sequence of the nine wind turbines. The spikes in reactive power are associated with magnetic inrush currents to establish magnetic fields in the squirrel cage induction generators as they are connected to the network. There are no corresponding spikes in real power. These turbines use a "soft start" mechanism.

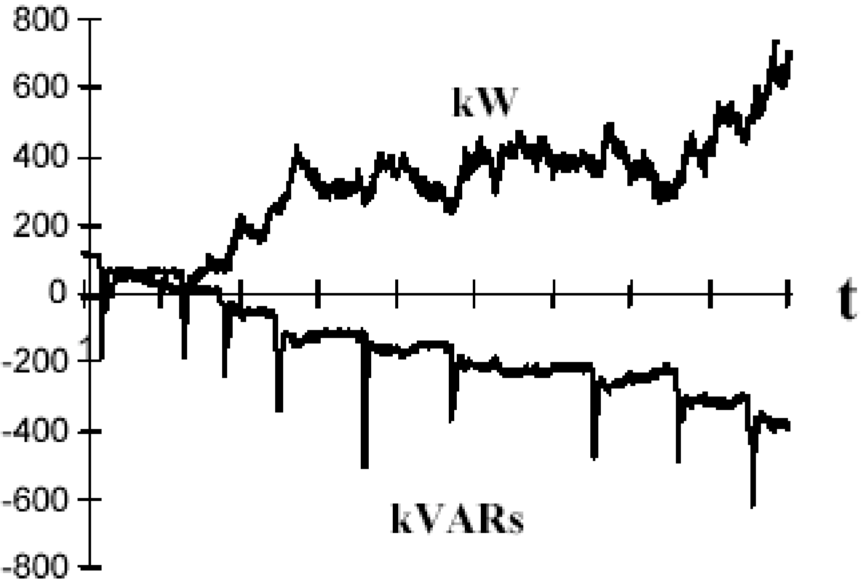

Figure 10. Starting sequence for the nine turbines in the 2MW Esperance wind farm (Rosser, 1995)

At a larger scale there will be smoothing effects between the electrical power outputs of wind farms, with smoothing being more pronounced as the separation between the wind farms is increased. This effect is illustrated in Figure 11 for wind farms in Germany. The graphs show the cross-correlation coefficients for different averaging times between the power outputs of wind farms as a function of wind farm separation. They show that the cross-correlation coefficients fall-off much more quickly with wind farm separation for short averaging times, when localised turbulence effects dominate the calculated correlation coefficient, than for long averaging times, when localised turbulence effects have been filtered out.

Figure 12 shows cross-correlation coefficients for simulated wind farms across Northern Europe using data derived from meteorological models. These results are consistent in form with Figure 11 and suggest that the summated output from widely spaced wind farms should be significantly smoother than that of individual wind farms.

There is likely to be a different relationship between wind farm separation and cross-correlation coefficient in Australia compared to Europe because of differing weather patterns. Therefore, Figures 11 and 12 are not directly relevant to the Australian context.

It would be valuable to undertake similar correlation studies for Australian wind farms and this would be facilitated by the collection of synchronised 30-second data from all wind farms in Australia. It is worth noting that in terms of scale, the "National Electricity Grid" in Southern and Eastern Australia extends over a distance of approximately 4000 km.

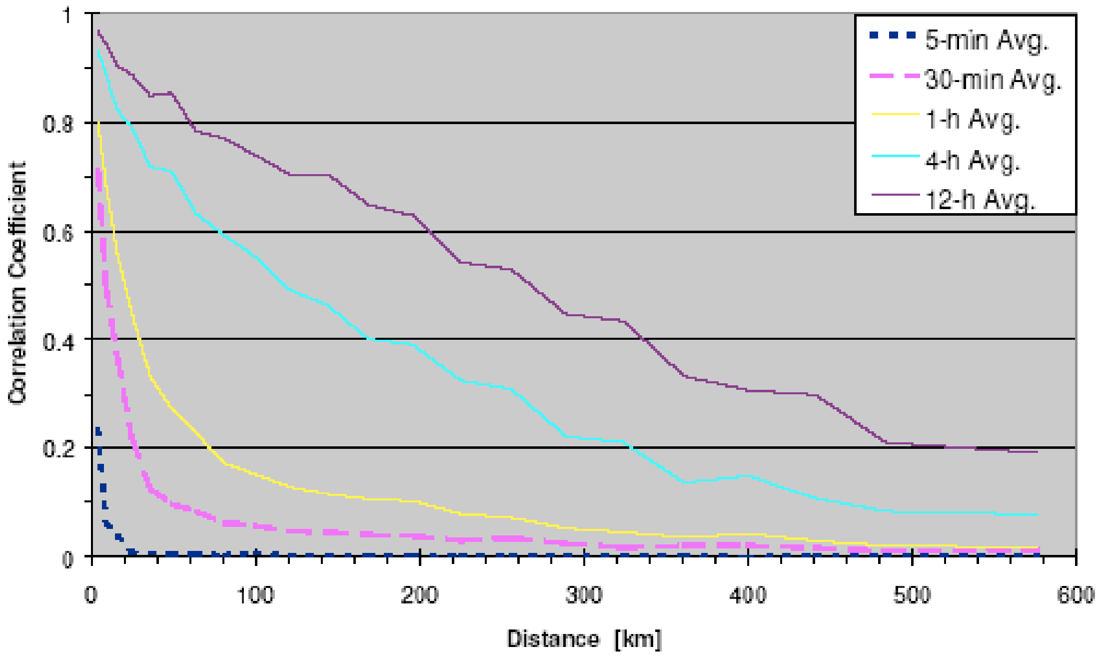

Figure 11. Cross-correlation coefficients for different averaging times for the power outputs of German wind farms as a function of wind farm separation up to 600 km (Ernst, reproduced in Giebel, 2000)

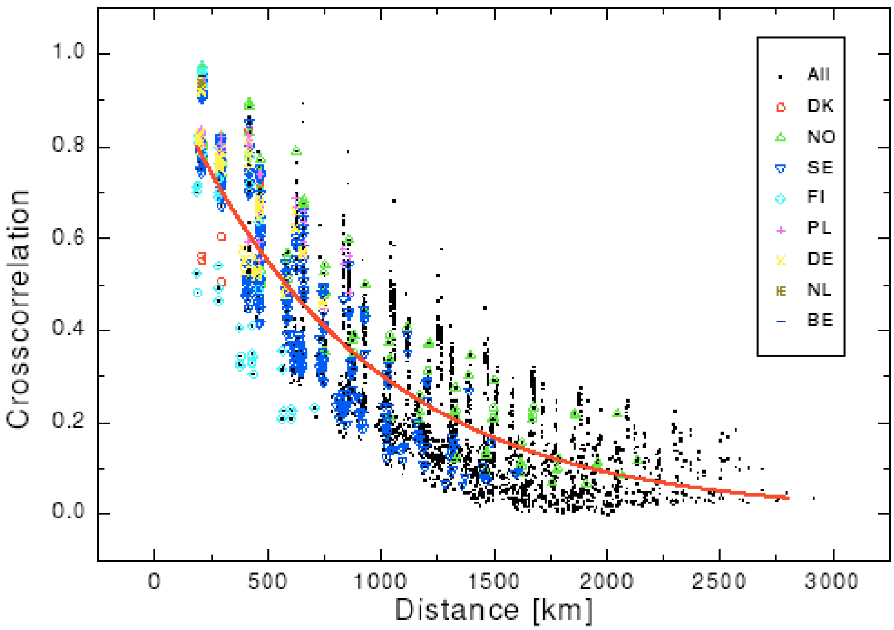

Figure 12. Cross-correlation coefficients for 12-hourly data between the output powers of simulated wind farms in Northern Europe as a function of separation up to 3000 km (Giebel, 2000)

Gardner et al (2003) investigated the relationship between the output powers of two wind farms in Scotland. One wind farm (Hare Hill) consisted of 16 660kW wind turbines, the other (Dunlaw) 26 660kW wind turbines. All the turbines were pitch regulated with variable rotor speed within a limited range. Dunlaw is about 80km NE of Hare Hill, and is usually down-wind of it. Gardner et al had access to nearly one year of concurrent data for wind farm output power at a 10-minute sampling interval.

Figure 13 shows a sample of the data set for a 14-day period in June 2001, while Figure 14 shows the first 2.5 days of this period in more detail. There are three data series in each figure – one for the output power of each wind farm and a summated data set, each series being expressed as a percentage of rated power.

These figures illustrate the lack of correlation in the short-term (turbulence) power fluctuations as well as the lag between the weather-related variations in output power. The summated power is clearly smoother than the output power of either wind farm.

The lag in weather-related fluctuations is brought out more clearly in Figure 15, which shows the cross-correlation function between the output powers of the wind farm. The peak of the cross-correlation function is at a lag of about 2 hours.

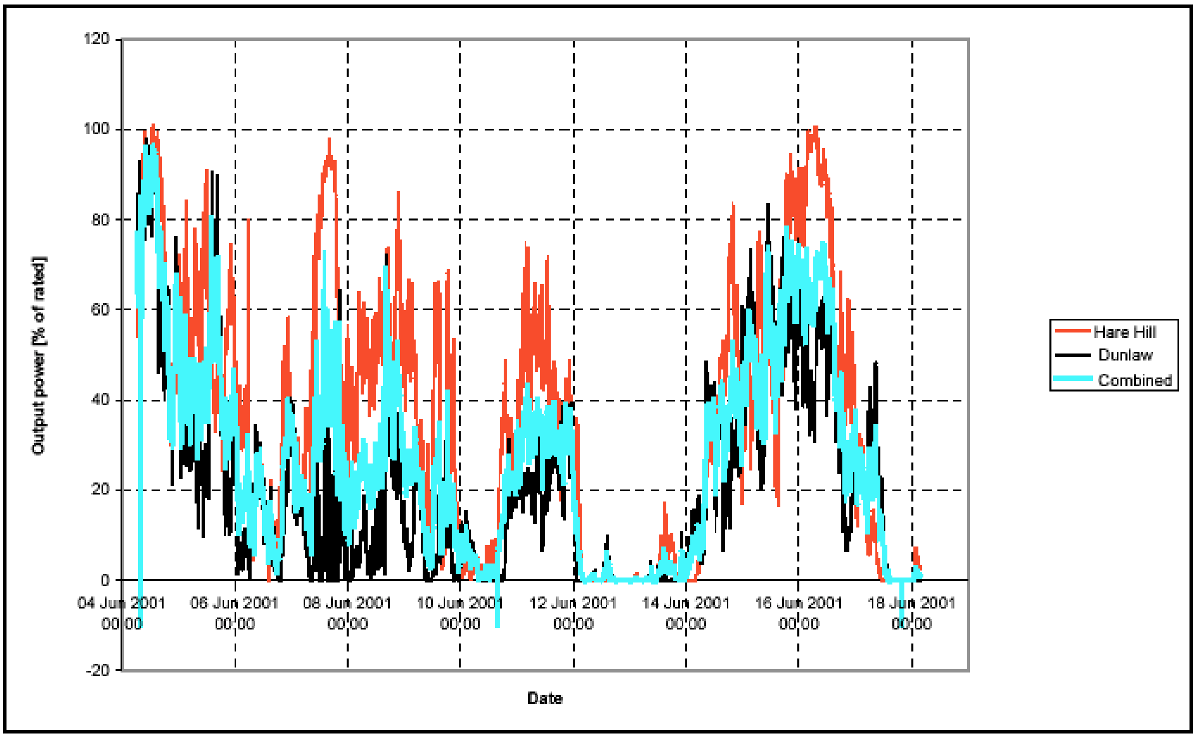

Figure 13 Output power of two wind farms located 80km apart over a 14-day period (Gardner et al, 2003)

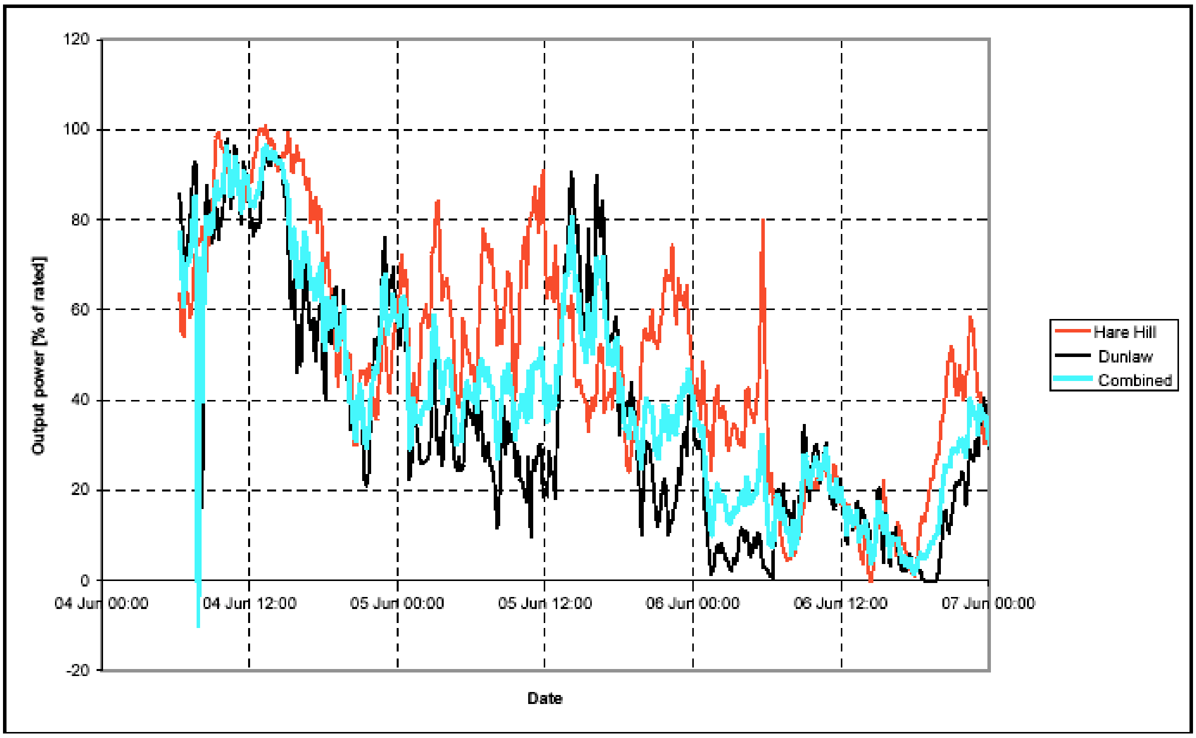

Figure 14. Output power of two wind farms located 80km apart over a 3-day period (Gardner et al, 2003)

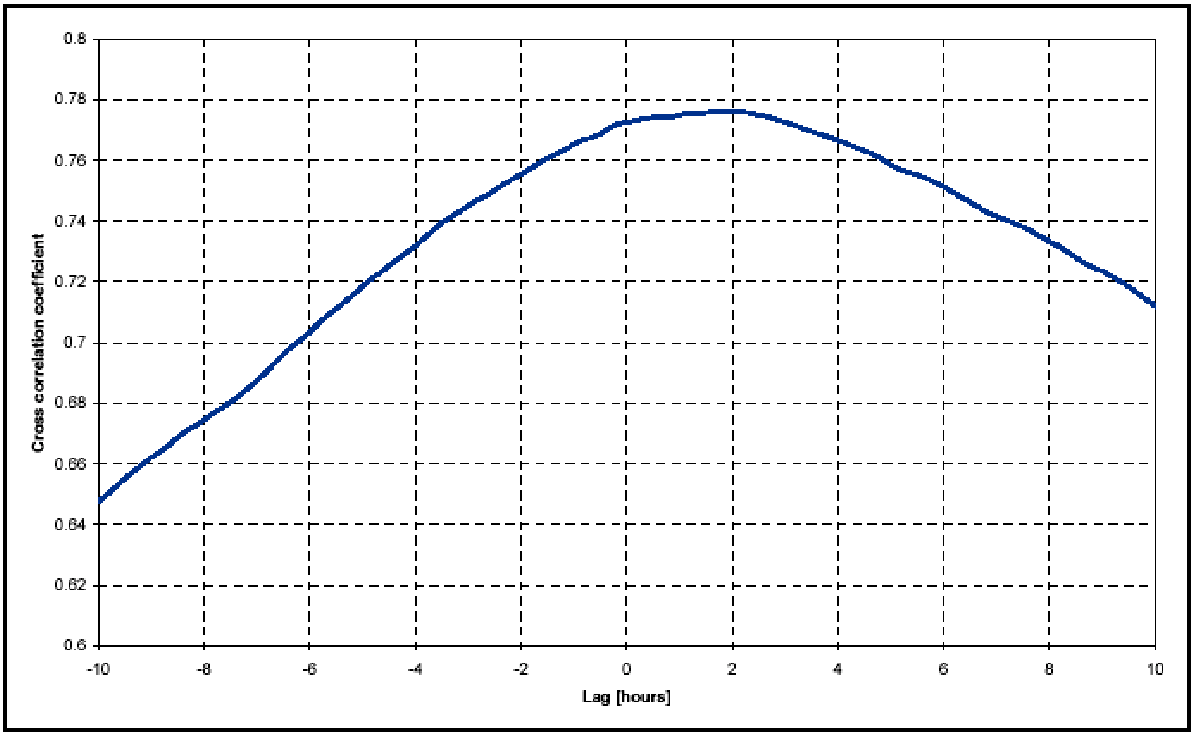

Figure 15 Cross-correlation function between the output powers of two wind farms located 80 km apart over one year of data (Gardner et al, 2003)

Predicting the output of wind farms and groups of wind farms

There are a number of reasons for predicting the power output of wind farms and groups of wind farms:

- Design of the layout of a wind farm, taking into account local topography, interference between the turbines within the wind farm and (if relevant) interference from nearby (existing or anticipated) wind farms.
- Determination of the rating of network connection assets, taking into account the diversity between the outputs of wind turbines within a wind farm and (if relevant) the diversity between the outputs of multiple wind farms that share the same connection assets.
- Assessing the commercial viability of a wind farm, which should take account of both income and expenditure associated with ancillary services, spot energy, financial instruments and (if relevant) environmental instruments.
- Considering the acceptable level of penetration of wind energy in an electricity industry at a local, regional or industry level due to voltage, frequency or security related phenomena.

Thus prediction should consider both short-term and longer-term behaviour, taking into account turbulence, diurnal, weather and climatic phenomena. Prediction studies should commence early in the planning phase of a wind farm and continue throughout its operating life. In the planning phase, prediction can only be model-based but model predictions should be augmented by physical measurements once a wind farm commences operation.

Turbulence depends on local topography, whereas atmospheric phenomena occur on a larger geographical scale. Therefore prediction techniques should combine models that are appropriate at each scale and incorporate information from wind farm power measurements. As discussed earlier, it is important to estimate the fraction of total energy that appears in the turbulence spectrum, because this should be correlated over relatively small distances only.

As reported in Hirst (2002), there are two main categories of wind forecasting methods:

- Methods that predict future wind speed or wind farm power output by either assuming it remains identical to the current value (persistence model) or by extrapolating recent behaviour using a more sophisticated time series model (ARMA model). These models are useful for up to a few hours.
- Methods based on meteorological models (Numerical Weather Prediction or NWP) that can produce useful forecasts up to a day or two ahead, depending on the predictability of weather patterns.

ESD Ltd (2000) discusses forecasting methods for both categories and suggests that the breakeven point between ARMA and NWP models occurs at about 3.5 hours projection time.

Figure 16 shows a comparison of simple persistence and NWP models for a particular wind farm based on one year of data (Gardner et al, 2003), which suggests that the breakeven projection point as measured by RMS error is about one hour ahead. This is consistent with ESD's figure of 3.5 hours when a more sophisticated ARMA forecast is used instead of an assumption of persistence. Note that in practice the error bound would be important as well as the RMS error.

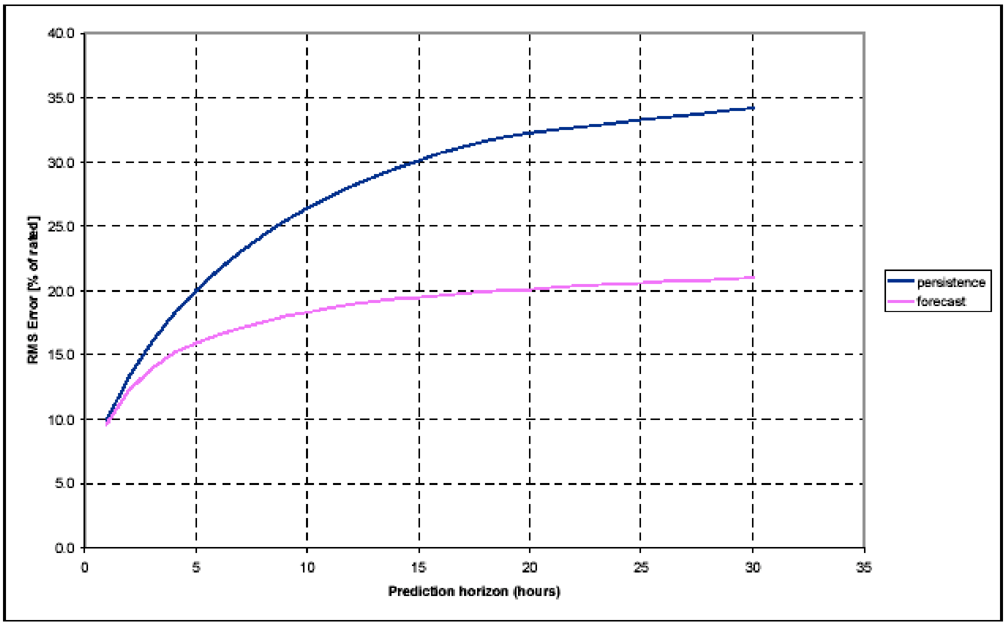

Figure 16. Comparison of the RMS error of persistence and NWP forecasts for a particular wind farm based on one year of data (Gardner et al, 2003)

The US National Renewable Energy Laboratory has developed wind forecasting techniques based on meteorological models that are capable of producing "high-resolution (1 km2) wind maps for essentially anywhere in the world" (Elliot, 2002). In Australia, CSIRO has developed the *Windscape*™ model (Steggel et al, 2002; Wilkinson, 2002), in which a fine-scale boundary layer model is nested within regional meteorological (NWP) models of successively finer resolution, as illustrated in Figure 17.

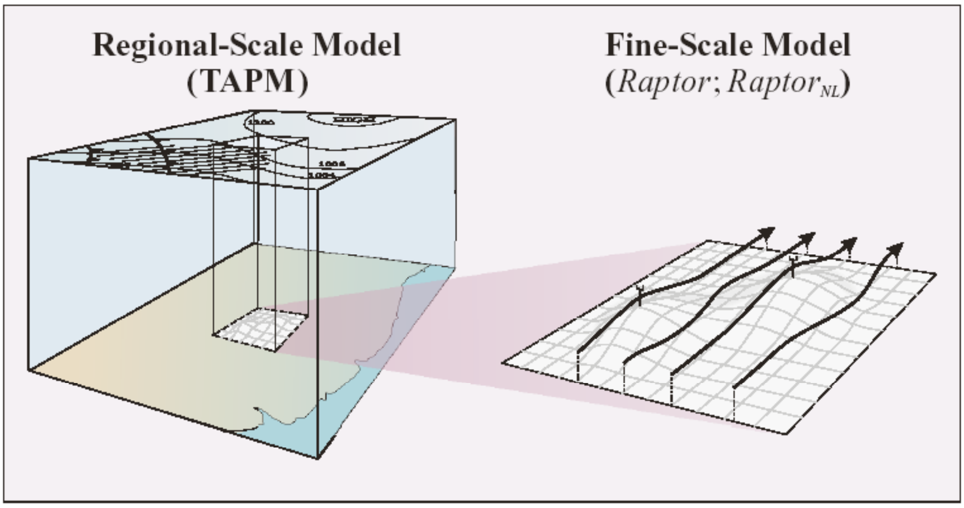

Figure 17. Nested modelling approach used in *Windscape*™ (Steggel et al, 2002)

To date *Windscape*™ appears to be aimed more at the wind farm project evaluation phase than at the operating phase, and it may not yet have been used to produce forecasts of the power output of operating wind farms or groups of wind farms. The value of *Windscape*™ in the operating phase would benefit from the augmentation of atmospheric modelling with models derived from measured wind farm outputs. This is another important reason for collecting synchronised 30-second data on the operating output of all Australian wind farms.

The results of a recent US study demonstrate that useful short-term predictions can be made from extrapolation-style models based on measured power. Figure 18 shows a comparison of two-hour ahead prediction with actual wind farm power output for a 103.5 MW wind farm consisting of 138 wind turbines (Hirst, 2001). The predictions are based on a simple first-order extrapolation model.

Another important type of prediction is the likelihood of significant change in wind farm output from one time to another. Figure 19 shows the probability density function for predicted changes over a period of twelve hours in the power output of groups of wind farms. The outermost curve is for the combined power output of simulated wind farms in Denmark alone, while the two inner curves are for the combined output of simulated wind farms in the Nordic countries and for Northern Europe as a whole. Figure 19 indicates that there is a probability of approximately 1% that the output of the simulated wind farms will change by more than ± 20% for each grouping in a twelve-hour period. Similar studies should be undertaken for Australia.

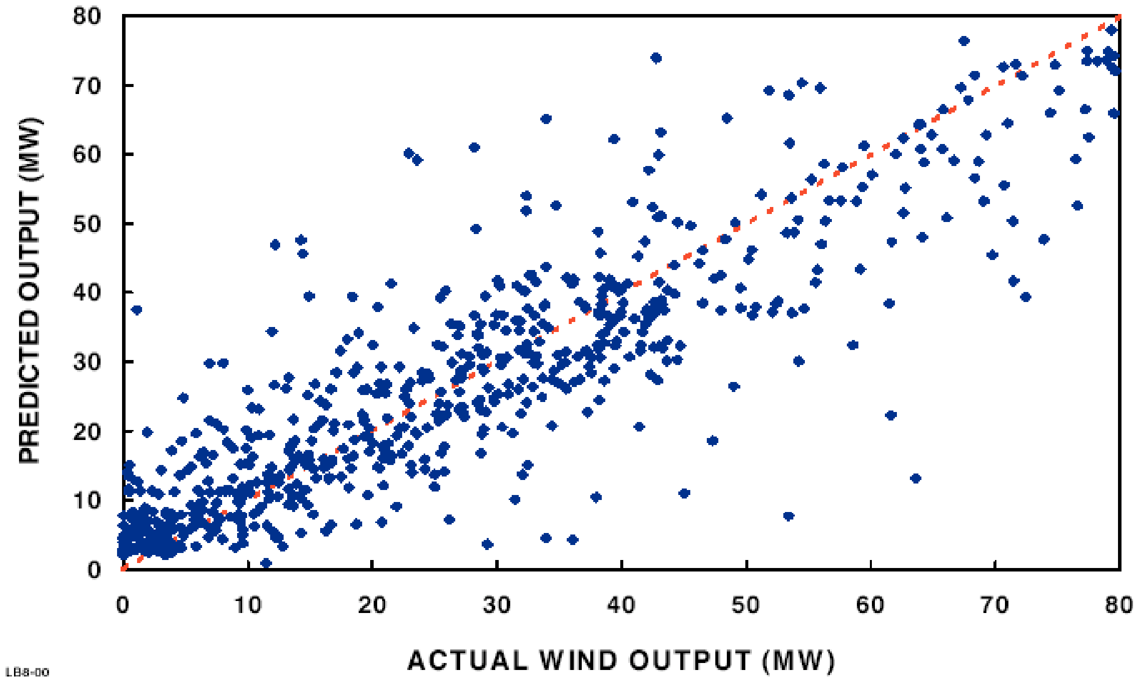

Figure 18. Comparison of two-hour ahead prediction with actual wind farm power output for a 103.5 MW wind farm consisting of 138 wind turbines (Hirst, 2001)

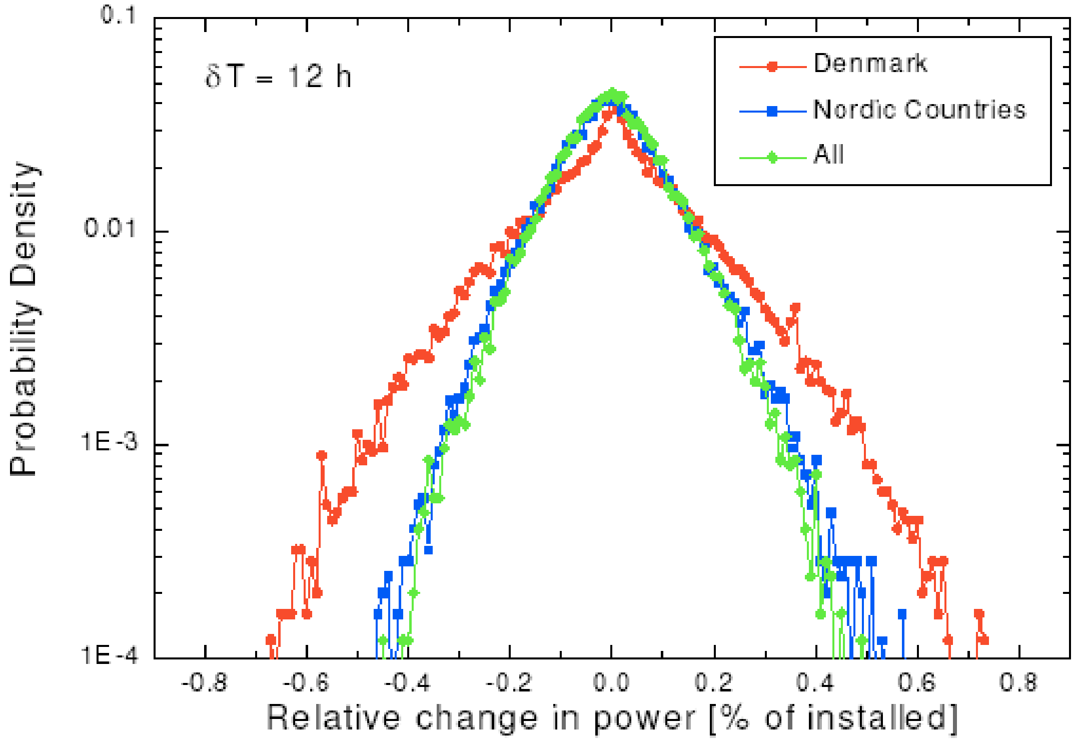

Figure 19. Probability density function for predicted changes in the power output of various groups of simulated wind farms over a period of twelve hours (Giebel, 2000)

The European Union ANEMOS research project, which is currently underway, aims to combine atmospheric and measurement-based modelling to develop forecasting software that can provide accurate forecasts at the "national, regional or at single wind farm level and for time horizons ranging from minutes up to several days ahead" (http:/anemos.cma.fr/). This would provide additional functionality beyond programs such as Prediktor, developed by the Risø National Laboratory in Denmark (Prediktor, 2002), which combines on-line weather forecasting information from a NWP model with on-line measurements of wind farm output to produce a prediction of wind farm power output up to 48 hours ahead in 1 to 3 hour time steps, using the approach illustrated in Figure 20.

Thus, in response to growing development of the global wind energy industry, sophisticated modelling techniques have been developed (and continue to evolve) that can support cost-effective selection of wind farm sites and provide useful predictions of the power output of individual wind farms and groups of wind farms.

These tools have value to wind farm developers, electricity industry operators, electricity market operators and policy makers, and one question that arises is how responsibility for different types of forecasting studies should be assigned among the various stakeholders. One important consideration is that the continuous spatial and temporal nature of wind energy means there are important shared costs in wind energy forecasting.

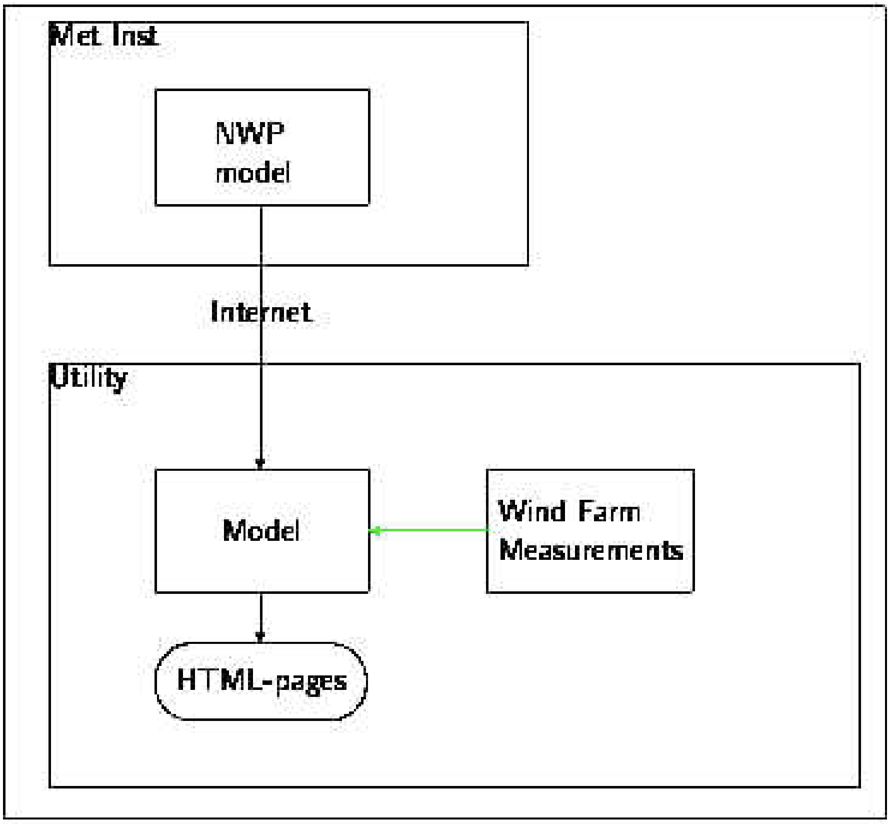

Figure 20. Functional block diagram for the Prediktor wind farm power forecasting tool (Prediktor, 2002)

The technical and commercial context for wind farms in a restructured electricity industry

Wind energy raises the following issues in the context of a restructured electricity industry:

- It introduces new technologies or uses existing technologies in unfamiliar ways, for example the use of induction machines as generators rather than motors and the use of power electronic interfaces for generators.
- There is significant uncertainty in, and thus a value in predicting, the power injected into an electricity network by a wind turbine, a wind farm or a group of wind farms.
- There are doubts about the ability of existing engineering operation and planning models to successfully predict important consequences of introducing wind energy technology. For example, there is uncertainty about the extent of diversity between wind turbine power outputs and the ability of wind turbines to ride through system disturbances and to contribute to fault level (Arnott, 2002; Western Power, 2002).

Wind farms have resource and technology characteristics that differ from those of the large fossil fuel power stations that have traditionally been used in the Australian electricity industry. The most important differences are as follows:

- Wind resources are time-varying and non-storable, therefore wind farm output is non-dispatchable except at the cost of spilling wind resources.
- The generators used in modern wind turbines often employ induction generators and power electronic interfaces are frequently used.

- A wind farm typically consists of many turbines of relatively small rating, making it less cost-effective to install expensive turbine control mechanisms than on a single large machine.
- Wind turbines automatically start and stop when the wind speed reaches cut-in and cut-out speeds respectively, with associated transients that depend on the technology and control algorithms employed. Wind turbines may also stop unexpectedly due to disturbances on the electricity network to which they are connected.

The holistic nature of electricity industry operation implies that issues arising from the above characteristics may limit the acceptable level of penetration of wind farms in a region of an electricity industry or an electricity industry as a whole. There is the potential for:

- Excessive voltage or frequency fluctuations or network power flow swings due to wind farm power fluctuations during operation
- Excessive or insufficient fault levels in the vicinity of wind farms, or difficulties in maintaining acceptable network voltage profiles
- Excessive reserve requirements due to the risk of sudden wind farm shut downs from high power output.

Practical problems of this kind are already emerging in Denmark, where the installed wind farm capacity is 50% of peak demand and it supplies 16% of annual energy (Hilger, 2002). However, it should be noted that the Danish electric power system forms part of a much larger European electric power system, so that from an engineering perspective, penetration levels are much lower than these figures would suggest. By contrast, Rosser (1995) reports that the Esperance wind-diesel system in Western Australia has operated satisfactorily at up to 70% penetration under light load conditions.

Voltage and frequency related implications of wind farms

The electricity industry has the following important characteristics:

- Electrical energy cannot be stored cost-effectively, and is transferred instantaneously through an electricity network from generators where it is “produced” to end-use equipment where it is “consumed”. The industry works in a holistic manner and total electricity generation and total consumption (including network losses) are in balance at all times.
- Imbalances between the power being delivered to electricity generators by their prime-movers (eg a wind turbine) and the electric power that they generate are mainly absorbed by changes in the rotational kinetic energy of electrical machines, with consequential changes in frequency. Wind turbines may have lower inertias than some other kinds of generating equipment, so that frequency perturbations may increase for this reason as well as fluctuating wind turbine power.
- Electrical energy flows through an electricity network according to the laws of circuit theory, delivering energy from a mix of all generators to each item of end-use equipment. The voltage profile in an electricity network is a function of network impedances and the pattern of “real” and “reactive” power flows. Voltages at nodes away from near-ideal voltage sources (such as synchronous machines of significant size) will fluctuate if real and/or reactive power flows fluctuate.

Network connection issues for wind farms

Large wind farms will often be located away from load centres and existing power stations, and may thus require substantial network augmentation or extension to connect them to the existing network, with associated network losses in conveying the energy to loads. By contrast, small wind farms connected to existing distribution networks may, if their output is strongly correlated with local demand, offer opportunities to defer network augmentation costs and reduce network losses. Wind farm projects may require new network control or protection regimes, and other supply, network or demand-side projects might significantly change the network context in which they are placed.

It may be possible to reduce the connection costs for remote wind farms by capturing economies of scale in network augmentation. For example Hackney (2002) states that new 132 kV construction would be required if significant wind farm development occurred in the NSW tablelands due to lack of capacity in the existing sub-transmission network, which is designed to serve limited rural load. At the same workshop, Tanner (2002) suggested that the cost of connection to the NSW 330 kV grid could fall from $2,500/kW to connect a 5 MW wind farm to $150/kW to connect four 50MW wind farms sharing the same substation. Similarly, the data in Meritec (2002) suggests that the cost of strengthening the Eyre Peninsula transmission network to accommodate wind farms could fall to about $200/kW for total wind farm capacity of 400-500 MW. The South Australian context is discussed more fully later in this report.

Ackermann (2002) discusses transmission issues for offshore wind farms and points to the potential use of actively commutated, pulse width modulation DC conversion and DC transmision in those circumstances. This technology can provide control over real and reactive power flow and may also have on-shore application because underground cables can be used, making it easier to obtain transmission easements. The main drawbacks are the high cost and switching loss of the converter stations and, for on-shore use, the high cost of cables compared to overhead lines.

Joint ventures between wind farm operators/developers and perhaps other network users (eg local end-users) may be the best way to capture economies of scale. Governments could assist by guiding the development of wind resources within their jurisdictions in a staged manner.

Treatment of wind farms under the National Electricity Code

The National Electricity Code (NECA, 2002) is a set of rules that determines the way in which the electricity industry operates in the southern and eastern states of South Australia, Victoria, New South Wales, Queensland and the Australian Capital Territory. Amongst other things, the Code contains rules that define the operation of the National Electricity Market (NEM), as well as rules for defining, procuring and paying for ancillary services (additional technical requirements that are not represented in the electricity spot market) and for connection to and augmentation of the network. One of the primary objectives of the Code is that “a particular energy source or technology should not be treated more favourably or less favourably than another energy source or technology” (NECA, 2002: Clause 1.3).

The Code also contains provisions for “pre-dispatch”, “projections of system adequacy” and “statements of opportunity”, which involve short, medium and long-term forecasts of supply-demand balance. As wind penetration grows, it will be important to have sound forecasts of future power output and energy production by individual wind farms and by geographical groupings of wind farms (Arnott, 2002).

Under the Code, a wind turbine is classified as an intermittent generator: "a *generating unit* whose output is not readily predictable, including, without limitation, solar generators, wave turbine generators, wind turbine generators and hydro-generators without any material storage capability" (NECA, 2002: Chapter 10, p 27A). This classification means that the National Electricity Market Management Company (NEMMCO) would not normally centrally dispatch wind farms, although NEMMCO has the right to impose conditions on intermittent generation if needed to facilitate operation of the National Electricity Market (Arnott, 2002).

Thus wind turbines would normally start and stop automatically and vary in power output according to the wind speed. However, wind farm operators would have to accept the price for electricity that applied to their point of connection in each market interval and would have to comply with operating conditions imposed by NEMMCO.

Wind farms would have to meet the Code's technical requirements for connection to the network (NECA, 2002, Chapter 5). These requirements are in principle technology neutral but take into account the holistic nature of industry operation. They include requirements for operability within specified ranges of voltage and frequency and the ability to ride-through specified disturbances. They are currently under review (see www.neca.com.au).

Wind farm operation in the National Electricity Market

Electricity industry operators aim to keep deviations in frequency and voltage from their nominal values within acceptable bounds by a combination of automatic control actions and direct operator intervention. Under the National Electricity Code, this is managed by "market related ancillary services" using resources that are dispatched jointly with the electricity spot market dispatch.

Wind farms are not well placed to provide these ancillary services because of the intermittent nature of their power output. However, the operators of wind farms with advanced turbine designs and wind farm control schemes could implement control strategies to automatically reduce wind farm power output when frequency or local voltage exceeded nominated trigger values, or to smooth power output if wind power fluctuations were causing excessive voltage or frequency fluctuations.

The costs of providing ancillary services are shared amongst market participants according to the principle that they should be "allocated to provide incentives to lower overall costs of the national electricity market" (NEC, Chapter 3, p 2). If ancillary service costs increase with increasing wind farm penetration, and causality can be demonstrated, then wind farms may be asked to pay an increasing share of ancillary service costs in accordance with the above principle. Western Power (2002) proposes such an arrangement.

Electricity industry operators attempt to maintain "secure" industry operation, that is, ensure satisfactory industry operation in the face of "contingencies", possible future events such as the failure of a generator or network element that may place industry operation at risk. Security is managed by constraining industry operation to states that are robust against plausible contingencies.

One important concern for industry operators is that contingencies may lead to cascading failures because other generation or network resources may not be able to "ride-through" temporary disturbances associated with a contingency (Arnott, 2002). For example, a voltage dip may occur following the unexpected trip of a large thermal generating unit. A wind turbine exposed to that voltage dip would be unable to maintain its normal electrical power output during the voltage dip and would thus experience a large accelerating power that may lead to an over-speed shut down. One or more large wind farms shutting down in this manner would represent a cascading failure triggered by the original generator trip.

It should be possible to design wind turbines to provide adequate ride-through for disturbances, and to reduce starting and stopping transients to acceptable levels. Industry and wind farm operators could collaborate on characterising the relevant disturbances (which may be site dependent) and undertaking tests of ride-through capability and of the disturbances associated with starting and stopping transients.

Electricity industry operation has traditionally been implemented as a "supply-side" problem, in which operators rely on their ability to control the output of dispatchable (that is controllable) generators to manage frequency deviations and dispatchable reactive power resources to manage network voltage profiles. Wind farms are a form of non-dispatchable generation, and it would become increasingly desirable to encourage cost-effective demand-side participation in frequency and voltage management as the penetration of non-dispatchable generation grew.

Voltage control and its implications for wind farms

Voltages in an electricity network must be maintained within acceptable limits. As previously indicated, synchronous generators and to a lesser extent wound rotor induction generators with inverters can act as near-ideal voltage sources whereas standard induction generators cannot. Thus wind farms may exacerbate voltage control problems for one or more of the following reasons:

- They use standard induction generators (rarely used in modern large wind turbines) and are located in relatively weak parts of the network with regard to voltage control
- Their power output is intermittent, with the possibility of frequent starting and stopping transients (a function of wind regime and wind farm control strategy).

NEMMCO and network service providers manage voltage control in the NEM using a category of non-market ancillary services called network control ancillary services (NCAS). These are acquired under tendering processes and, in some instances wind farm operators may be able to participate in their provision. However they may be liable to pay for NCAS if they are contributing to, rather than ameliorating, voltage fluctuations.

Wind farm investment in the National Electricity Market

The commercial viability of wind farms in the NEM requires that adequate income be derived both from the sale of energy and the sale of Renewable Energy Certificates (RECs) (Wilkinson, 2002). As discussed in (PriceWaterhouseCoopers, 2002), to satisfy their project financiers, wind farm developers usually prefer to sell both energy and RECs to a single buyer (typically an electricity retailer) under a long term Power Purchase Agreement (PPA) covering a period of 5 to 15 years.

In the NEM, a PPA can be thought of as a forward contract that has spot and derivative components for both electrical energy and RECs. In negotiating a PPA of this kind, a retailer will take a number of factors into account in assessing the value of the energy and REC components:

- The short term variability of wind farm output, its diurnal and seasonal characteristics, network loss factor and other factors that might conceivably affect the average annual spot market price that the wind farm energy achieves
- The match between the pattern of wind farm power production and the aggregate pattern of demand of the retailers' customers in the same NEM market region.
- The variability of wind farm production from year to year
- Forward price curves for both electricity derivatives and RECs and the liquidity of the associated forward markets.

The uncertainty associated with each of these factors may mean that retailers may be less willing to offer as much on a rolled-in MWH basis for wind energy than for renewable energy from dispatchable generators such as storage hydro. Sophisticated forecasting techniques should be able to reduce the present levels of uncertainty associated with wind energy and so improve the rolled-in price that wind farms can achieve under PPAs.

Other electricity-related issues that influence the financial outcomes for wind farms include:

- Ancillary service payments (already discussed)
- Connection costs and network charges
- Possible replacement of the MRET scheme by an emission-trading scheme as proposed in the COAG energy market review final report (COAG Energy Market Review, 2002).

Connection costs and network charges
Wind farms will be required to pay for dedicated network assets, including radial lines that connect the wind farm to the shared network unless they can demonstrate, under the ACCC Regulatory Test (ACCC, 1999), a positive net benefit to the market that is also a greater benefit than all alternatives under most scenarios. This can be a difficult test to meet.

Generators are not required to contribute to the cost of the shared network under the Code, however they may also be expected to contribute to "deep" connection costs - that is any modifications to the shared network that are required to accommodate the generator. Deep connection costs are more subjective and should be reviewable by the relevant regulator.

Small wind farms connected to distribution networks are classified as distributed generators and are entitled to the amount of "transmission use of service charge" that the distribution network service provider avoids due to the presence of the wind farm (IPART, 2002). This amount would usually be small due to the intermittent nature of wind farm output.

To isolate voltage disturbances, it is desirable to connect a wind farm via its own transformer to a sub-transmission or transmission network. For large wind farms, this will usually be necessary because of limited HV distribution and/or sub-transmission network ratings, as previously discussed.

Possible replacement of the MRET scheme by an emission-trading scheme
Under an emission-trading scheme, wind farms would receive supplementary income according to the emissions that they displaced. The way in which the income was received would depend on the design of the emission trading scheme but would be either "rolled-in" to the price of electrical energy or through sales of "emission credits". In either case, the supplementary income achieved by a wind farm would depend on the mix of fossil fuels displaced by the wind farm and the cost of alternative ways of meeting the emission reduction target. It would be substantially less than the present price for RECs unless a challenging emission reduction target was set.

Specific issues for South Australia

Regulatory context

The Electricity Supply Industry Planning Council (ESIPC) of South Australia is responsible for preparing Annual Planning Reviews and advising on future development strategies. The Transmission Network Service Provider (TNSP) is responsible for preparing specific transmission network augmentation plans and submitting them to the ACCC for approval in its role as economic regulator for the South Australia transmission network.

The Eyre Peninsula

Meretic (2002) is the result of an investigation undertaken for ESIPC "to outline the infrastructure requirements to service any large-scale generation that might be developed on the Eyre Peninsula, including comment on the capability of the existing network and highlighting any broad issues" (p i). The key findings of this investigation were:

- The existing Eyre Peninsula 132 kV network is not suitable for large scale generation (>50 MW)
- The assumed network augmentation approach would be a backbone development of two 275 kV circuits from the Port Augusta region to a location relatively central within Eyre Peninsula such as Yadnarie.
- Assuming development costs of $1M/MW for the wind generation, the transmission investment required will seem out of proportion for the smaller generation scenarios
- The remoteness from load will lead to high losses, and voltage limitations will restrict power flows
- Power factor correction will need to be designed into the generator units to ensure unity pf at point of connection
- Dynamic reactive support (ie SVC) is likely to be required within the Eyre Peninsula network to ensure stable operation of the network.

These findings illustrate important issues that have been raised in this report:

- Wind resources are often located in areas remote from existing generation and load centres, thus connection costs and network losses can be high, and there may be problems with voltage control and security that could be reduced by careful selection of wind turbine technology.
- There can be significant economies of scale for network connection that extend beyond the scale of an individual wind farm.

Thus it would be desirable to coordinate and stage the development of the wind resources of the Eyre Peninsula. As much as 500 MW of wind farms would be required to fully network capture economies of scale. This would appear to require the formation of a joint venture between wind farm developers to share the costs and benefits, which might be facilitated by government guidance.

The South-east

"The South Eastern Transmission System of South Australia (SETS) extends from the southern and eastern suburbs of Adelaide in a south-easterly direction through Mt Gambier and over the state border to Heywood in Victoria. This is a strategic component of Australia's high voltage transmission network." (Burns and Roe Worley, 2002:1).

The report by Burns and Roe Worley is the result of an investigation undertaken for ESIPC to "analyse the SETS and identify the augmentations needed, so that the transmission system will continue to operate satisfactorily under 'N-1' operating conditions" taking into account "potential new wind farm, biomass and gas generation proposed between Adelaide and Mt Gambier and to supply the projected increases in South East region customer demand over the next fifteen years" (Burns and Roe Worley, 2002:1).

The report concludes that generation rather than load requirements will drive transmission network augmentation, and that a significant program of network upgrades would be required over the next 15 years "in order to accommodate projects planned by electricity market participants". These upgrades involve "deep" upgrading of the 275 kV transmission corridor as well as "shallow" generator connection projects. It would be difficult to identify accountabilities for some of the individual network projects, which would benefit a number of generators and load centres. Moreover, these network upgrade projects would be best designed and implemented as a coordinated development program.

Once again, improvements in cost-effectiveness would flow from a coordinated wind farm development program that might be facilitated by government guidance.

Implications for electricity industry restructuring

The National Electricity Code has the objective of technology neutrality. This has largely been achieved for existing generation technologies and resources. However it would be largely a matter of chance if the Code were fully neutral with respect to the wide range of new technologies and resources that might be introduced in the future. The following issues arise in the case of wind farms:

- Conditions for wind farms are often most prospective in areas remote from existing generation and load centres, involving significant network connection costs. However, individual wind farms are likely to be too small to fully capture the economies of scale available from coordinated network development.
- Wind energy is a stochastic primary energy resource and as penetration of wind energy increases, it will become more important to formulate electricity industry operation as the fundamentally stochastic problem that it is, rather than as an approximately deterministic problem that it has been traditionally assumed to be. This has broad implications for the Code including ancillary service, spot energy and derivative trading arrangements.
- The introduction of large amounts of intermittent generation will increase the likelihood of frequency perturbations and frequency control targets should be reviewed in this context. Many items of end-use equipment already contribute to frequency and/or voltage control due to passive frequency and/or voltage responsiveness, which could often be further enhanced if there were appropriate commercial signals.

- Within their operating limits, large synchronous generators can provide voltage control services at very low cost. Induction generators with inverters can provide equivalent capability for some functions if they are designed to do so. Therefore, there is a growing need to provide clear commercial signals as to the value of voltage control capability.

Recent Australian initiatives

The MRET scheme is the primary Federal government support mechanism for the Australian wind energy industry. This is to be reviewed next year, however the final report of the COAG Energy Market Review (2002) has recommended its termination.

A number of state governments have issued wind farm planning guidelines. These are aimed at the individual wind farm developer and complement the good-practice guidelines released by the Australian Wind Energy Association (AusWEA, 2002). The New South Wales government has recently released a wind atlas for NSW, which is available on the SEDA web site (www.seda.nsw.gov.au) and is based on analysis by CSIRO. The atlas still primarily aimed at the individual wind farm developer. However it represents an important step towards regional planning for wind farms in that state, and being GIS based, it can be readily combined with other overlays to create an effective regional planning tool. Interestingly the spatial variability of the wind resource illustrated in the atlas, which is reproduced in Figure 21, may indicate that the wind regime on parts of the NSW tablelands has a relatively high turbulence component.

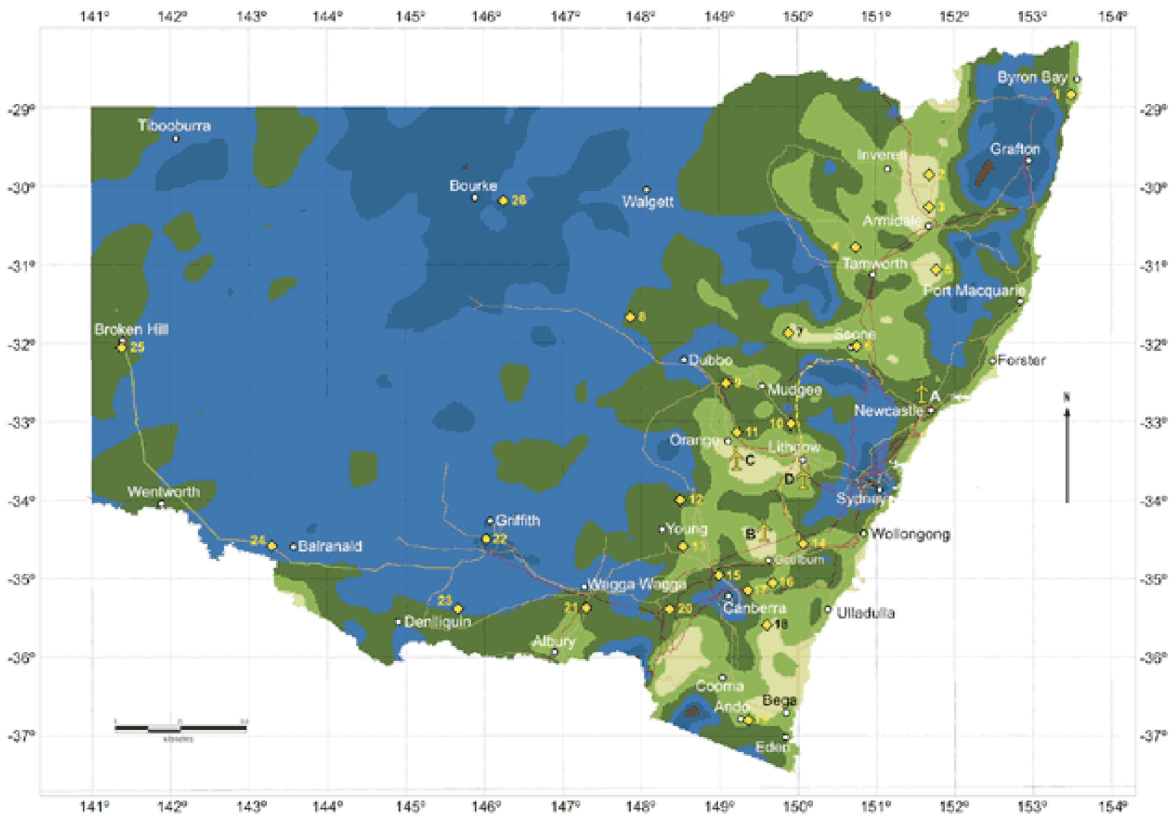

Figure 21. Wind Atlas for New South Wales (SEDA, 2002) available from www.seda.nsw.gov.au

Western Power has recently released an Information Paper on technical and commercial issues for renewable energy generation in that state (Western Power, 2002). This paper places particular emphasis on wind energy and raises similar issues to those raised in (Arnott, 2002). It suggests that it may be difficult to accept more than 10-15% wind power penetration in a power system for voltage and frequency management and spinning reserve reasons and proposes an interim maximum wind farm target of 150MW for WA.

The Western Power paper also foreshadows an energy charge for wind farms that is a function of total installed wind capacity as shown in Figure 22. The paper notes that its studies are based on extrapolation of the behaviour of a single wind farm, highlighting the importance of improving our knowledge about wind diversity and power system interaction issues before implementing charging regimes of this kind.

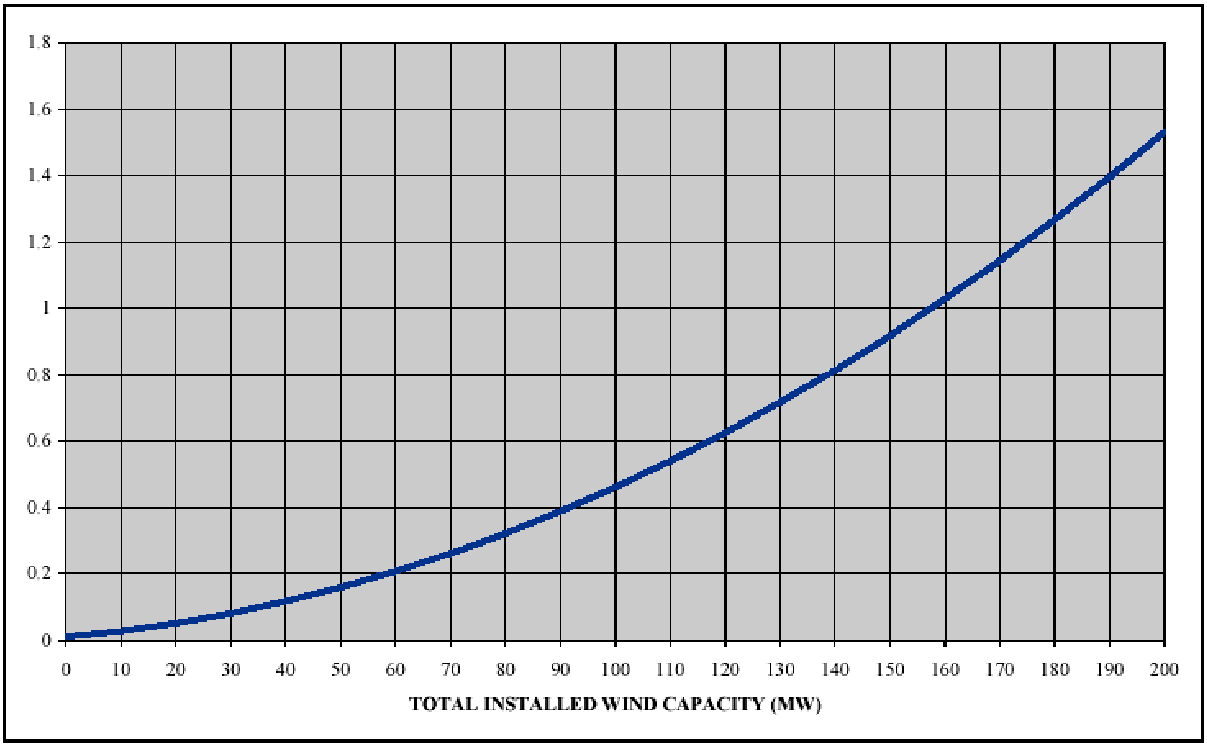

Figure 22. Suggested initial wind spinning reserve prices (c/kWh) in Western Australia as a function of total installed wind capacity ((Western Power, 2002)

Trends in wind turbine technology and wind farm control strategies

The technology on offer in the global wind market is evolving rapidly. Gipe (2002) provides a recent report on the global wind energy market and notes that the average turbine rating continues to rise, exceeding 900 kW for wind turbines installed in 2001. The largest machines currently operating are Enercon's 4.5MW prototype and GE Wind Energy's 3.6 MW prototype, both of the order of 100m diameter on towers of height 100m or taller, with 5MW turbines in advanced stages of design.

Gipe (2002) identifies the top six global wind turbine suppliers (in order) as Vestas, Enercon, NEG Micon, Enron (recently purchased by General Electric and now called GE Wind Energy), Gamesa and Bonus. Most of those companies are active in the Australian market and all offer wind turbines with ratings greater than 1 MW. The largest wind turbines installed in Australia to date are the Enercon 1.8 MW turbines in Western Power's Albany wind farm and the Vestas 1.75 MW turbines used in Toora and Woolnorth wind farms.

In the recent wind turbine designs offered by these market leading companies, all make use of active blade pitch control to adjust the blade angle of attack as wind speed varies and most use rotor speed control with a speed range of about 2:1, allowing stored rotor kinetic energy to be varied by 4:1.

Enercon is the only market leader to use a direct drive configuration. It uses a wound rotor alternator with sliprings, and a DC link variable frequency inverter with voltage or power factor control capability (www.enercon.de). However, companies with smaller market share have recently introduced direct-drive turbines with permanent magnet alternators, which are claimed to give improved part-load conversion efficiency as well as design simplification compared to a wound rotor alternator (de Vries, 2002). They may also have a weight advantage.

The rest of the market leaders use a gearbox and induction generator combination. In their most recent designs for large machines, Vestas, NEG Micon and GE Wind Energy all use wound rotor induction generators with sliprings and variable-frequency rotor-injection inverters with voltage or power factor control capability (de Vries, 2002 and company web sites). Thus wind turbines from all of these manufacturers should have (or should soon have) similar power output smoothing capability to that illustrated in Figure 5 for GE Wind Energy's 3.6MW turbine.

It is likely that the remaining wind turbine companies will follow the trend towards combined variable pitch and variable speed operation and voltage control capability. It is also likely that these features will be retrofitted in smaller turbines in due course.

Wind farm control strategies are also evolving and now allow wind farm power output to be controlled in response to power system requirements (see for example "Vestas Online" at www.vestas.com).

Conclusions and recommendations

Wind energy appears likely to be the first stochastic resource to be widely used for generating electricity. For that reason alone, wind energy brings new issues that should be addressed prior to its extensive deployment. However, the exploitation of wind energy also brings innovative use of generator technologies, including widespread use of induction generators and power electronic interfaces, which may have implications for electricity industry operation. The key issues that arise are:

- *Uncertainty in the future power output and energy production of wind turbines, wind farms and groups of wind farms*, arising from effects such as topographic features, short-term turbulence, diurnal, weather and seasonal patterns, and long-term phenomena such as climate change.
- *Voltage and frequency disturbances* due to starting transients, power fluctuations during operation and stopping transients initiated by high wind speeds or network disturbances.
- *Potential problems in fault detection and/or fault clearance* caused by either inadequate or excessive fault level in the vicinity of a wind farm.

- *Potential difficulties in managing frequency and/or voltage* in power systems with a high penetration of wind turbines due to low inertia and/or lack of voltage control capability.
- *Difficulties in capturing economies of scale in network connection for wind farms,* because the network rating that minimises per-unit network connection cost may exceed the effective network rating required by a single wind farm (which will usually be less than the nameplate rating of the wind farm due to diversity effects).

These issues have technical and commercial implications for both wind farm developers and other industry participants. However, wind turbines can be designed to ride-through network disturbances, reduce starting and stopping transients and contribute to voltage and frequency control. Also, there are useful diversity effects and short and long-term wind farm production forecasts can be produced. Finally, appropriate planning protocols could capture economies of scale in network connection costs. Therefore, the following recommendations are made:

- Wind power forecasting techniques should be further refined by systematically combining meteorological models with fine-scale boundary layer models and measurements of wind farm production. To investigate diversity effects, it would be desirable to collect synchronised 30-second data on the power outputs of all wind farms in Australia.
- These enhanced forecasting techniques should be used to forecast wind power and energy production for timescales and degrees of spatial aggregation that are appropriate for ancillary services, spot energy and derivative markets and the REC market.
- Advanced wind turbine designs and control strategies should be used and tests should be conducted of the ability of wind farms to ride-through plausible network disturbances.
- Planning protocols should be developed that facilitate the deployment of wind farms in a manner that minimises grid connection costs while maximising the benefits of diversity between wind farm power outputs, for example by encouraging joint ventures.
- The National Electricity Code should be reviewed with respect to the neutrality of implementation of ancillary services, spot and derivative markets and projections of system adequacy in the context of stochastic energy resources such as wind energy.

These recommendations would require governments to take a more active role in the wind energy industry than they have taken to date. The minerals industry provides a precedent, although there would be differences in the specific roles that government would play.

References

Ackermann T (2002), "Transmission systems for offshore wind farms", *IEEE Power Engineering Review*, December, pp 23-27.

Arnott I (2002), *The participation of wind energy in the National Electricity Market*, A paper presented to Australian Wind Energy Conference, Melbourne, 29-30 April.

Australian Competition and Consumer Commission (ACCC, 1999), *Regulatory test for new interconnectors and network augmentations,* December.

Australian Wind Energy Association (AusWEA, 2002), *Best Practice Guidelines for the implementation on wind energy projects in Australia,* available from www.auswea.com.au.

British Wind Energy Association (BWEA, 1982), *Wind energy for the eighties*, Peter Peregrinus.

Burns and Roe Worley (2002), *South eastern transmission system development concept plan,* Report prepared for the Electricity Supply Industry Planning Council of South Australia. Available from www.esipc.sa.gov.au.

COAG Energy Market Review (2002), *Towards a truly national and efficient energy market,* Commonwealth of Australia, Final Report, December.

Danish Wind Industry Association (2002), *Guided tour,* www.windpower.org

Elliot D (2002), *Assessing the world's wind resources,* IEEE Power Engineering Review, September, p 4-9.

ESD Ltd (2000), *Maximising the commercial value of wind energy through forecasting,* Report ETSU W/11/00555/REP prepared for ETSU under funding of the DTI, UK, 110 pp.

Gardner P, Snodin H, Higgins A and McGoldrick S (2003), The impacts of increased levels of wind penetration on the electricity systems of the Republic of Ireland and Northern Ireland: Final Report, prepared for the Commission for Energy Regulation (CER), Ireland and the Office for the Regulation of Electricity and Gas (OFREG), Northern Ireland. Available from: www.cer.ie/cerdocs/cer03024.pdf.

Giebel G (2000), *Equalizing effects of the wind energy production in Northern Europe determined from reanalysis data,* Risø R-1182 available from: http://www.risoe.dk/

Gipe P (2002), "Soaring to new heights. The world wind energy market", *Renewable Energy World,* Vol. 5, No. 4, July-August, pp 33-47.

Hackney C (2002), *Wind connection workshop case studies,* Presentation to Transgrid-Country Energy Workshop on Grid Connection of Wind Farms, Sydney, 11 September.

Hilger C (2002), Impact of decentralized generation on system operation, VGB PowerTech, June, pp 53-56.

Hirst E (2001), *Interactions of wind farms with bulk power operations and markets,* available from: http://www.ehirst.com/

Hirst E (2002), *Integrating wind energy with the BPA system - Preliminary Study*, a report prepared for Bonneville Power Administration, available from: http://www.ehirst.com/

Ilex Energy Consulting (2002), *Quantifying the system costs of additional renewables in 2020,* a report for the Department of Trade and Industry (UK), available from: http://www2.dti.gov.uk/energy/developep/support.shtml.

Independent Pricing and Regulatory Tribunal (IPART, 2002), *Inquiry into the Role of Demand Management and Other Options in the Provision of Energy Services Final Report,* October, www.ipart.nsw.gov.au.

Leonhard W and Muller, K (2002), Balancing fluctuating wind energy with fossil power stations – where are the limits? *Electra* 204, October.

Meritec (2002), *Eyre Peninsula infrastructure investigation,* A report prepared for the Electricity Supply Industry Planning Council of South Australia. Available from: www.esipc.sa.gov.au.

Milligan M, Porter K, Parson B, and Caldwell J (2002), Wind Energy and Power System Operations: A Survey of Current Research and Regulatory Actions, *The Electricity Journal,* **15**(2), 56_67, March.

Morcos M and Gomez J (2002), Flicker Sources and Mitigation, *IEEE Power Engineering Review,* November, pp 5-10.

National Electricity Code Administrator (NECA, 2002), *National Electricity Code,* Version 1.0 Amendment 7).

Prediktor Fact Sheet (2002), Wind Power Research Program, Risø National Laboratory, http://www.prediktor.dk/

PriceWaterHouseCoopers (2002), *Changing locations: Impacts on the financial viability of a hypothetical wind farm development in Victoria,* A report prepared for the Sustainable Energy Authority of Victoria.

Rosser, M (1995*), Fluctuations in real and reactive power from a 2MW Wind Farm interconnected with a 14MW diesel power station,* Proceedings AUPEC 95, Perth.

Sørensen P et al (2001), *Simulation of interaction between wind farm and power system,* Risø R-1281 available from: http://www.risoe.dk/

Steggel N, Ayotte K, Davey R, Coppin P (2002), *Wind prospecting in Australia with Windscape™,* Internal Report CSIRO Land and Water, March, available from: www.clw.csiro.au/products/windenergy/.

Tanner P (2002), *Wind farm grid connection technical issues,* Presentation to Transgrid-Country Energy Workshop on Grid Connection of Wind Farms, Sydney, 11 September.

de Vries E (2002), "Where to next? Developments and Trends in wind turbines", *Renewable Energy World,* Vol. 5, No. 4, July-August, pp 63-71.

Western Power (2002), *Technical and commercial issues for access of renewable generation to the Western Power South West System,* Information Paper, November. Available from www.westernpower.com.au.

Wilkinson R (2002), Trying to catch the wind: mapping the nation's key new renewable generation resource, ESAA Electricity Supply Magazine, November, pp 10-11.