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National Wind Power Study

An estimate of readily accepted wind energy in the National Electricity Market

A report prepared on behalf of Unisearch Ltd
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Executive Summary

The purpose of this paper is to discuss readily accepted wind energy penetration in the Australian National Electricity Market (NEM). Here, "readily accepted" is interpreted to imply that there are technical solutions to any associated problems that are not prohibitively expensive.

Factors influencing readily accepted penetration of wind energy are first discussed and then findings of recent European and North American studies are reviewed. An estimate of readily accepted wind energy penetration in the NEM is then postulated, including estimates for each NEM region.

An analysis of international case studies and consideration of power system control strategies suggests that the NEM could readily accept 8000MW of wind farms under certain conditions. The author believes that effective operating strategies could be devised to cope with such a level of wind energy penetration, provided that:

- the wind farms were installed in a progressive manner over a period of about 10 years;
- the wind farms were widely and evenly dispersed within the NEM and, where necessary, local voltage or network flow constraints were overcome;
- the wind farms used advanced wind turbine technology, such as DFIG or alternator technology and advanced wind farm control systems that allowed the wind farm output to be remotely monitored and controlled; and
- advanced wind forecasting techniques were developed and used to predict the future behaviour of wind farms and groups of wind farms, and in particular to accurately predict significant changes in the output of regional groups of wind farms up to two days in advance.

Unfortunately, current arrangements under the National Electricity Code (NEC), including the commercial signals provided by the NEM and network charges, are not adequate to ensure such an outcome. Indications to date are that wind farms may not be being installed in a sufficiently dispersed manner to avoid network constraints and it is not clear whether developers are installing turbines of sufficient sophistication and wind farm control and protection schemes of adequate performance.

Thus the following policy options are recommended for consideration:

- Integrated regional wind development strategies should be developed, which systematically take into account resource distribution, land use issues, turbine technology and network connection requirements, network voltage and flow constraints, and other planning issues.
- Advanced wind forecasting techniques should be developed to predict the future behaviour of wind farms and groups of wind farms, and in particular to accurately predict significant changes in the output of regional groups of wind farms up to two days in advance.

Factors influencing readily accepted wind penetration

The output of any generator can vary in an uncertain manner, for example due to equipment failure, and thus should be regarded as a stochastic process. The power output of a generator such as a wind turbine, which converts an uncertain energy flux to electricity, has an additional source of uncertainty. Wind power density is a stochastic process that is a function of both space and time. Thus the output of a wind farm depends on the aggregated effect of the time-varying power density of the wind passing through the swept areas of all the wind turbines in the wind farm.

As discussed in Outhred (2003), diversity between the wind power density functions experienced by different wind turbines smooths the power output of a wind farm compared to that of an individual turbine. Likewise, diversity between different wind farms smooths the summated outputs of multiple wind farms compared to that of an individual wind farm. Thus when considering the effects of wind farms on power system behaviour, we need to consider geographically appropriate groups of wind farms, depending on whether we are considering local, regional or system-wide effects. Without appropriate management strategies, undesirable outcomes may occur in each case:

- *Local effects:* Wind farms are usually installed in rural areas, which in Australia can have relatively weak networks compared to many other countries, due to our low average rural population densities. Fluctuations in wind farm real and/or reactive power may cause fluctuating real and reactive power flows on local network elements, such as lines, transformers and switchgear. Particularly in weak rural networks, these may cause voltage fluctuations in the vicinity of a wind farm, and excessively high network flows compared to network capacity, which may exceed equipment thermal limits or cause protection schemes to operate. Wind turbines may trip in response to network voltage disturbances, leading to propagating power system disturbances. Wind turbines with power electronic interfaces may limit their short circuit current for self-protection reasons and thus not contribute significantly to local fault level, possibly hampering fault detection.

- *Regional effects:* As with local distribution networks, regional sub-transmission networks in Australia can also be relatively weak, as can interconnectors between state transmission networks. Flow constraints and voltage problems may occur in sub-transmission networks. Likewise, fluctuations in the summated output of the wind farms within a region of the National Electricity Market may cause flows between NEM regions to fluctuate, possibly causing constraints in the NEM dispatch algorithm to bind and in turn causing prices to separate between regions in the NEM energy and FCAS markets[1].

- *System-wide effects:* Fluctuations in the summated output of all wind farms connected to a power system will cause frequency to fluctuate and may change the anticipated power output of dispatchable generation (affecting dispatch in the next few hours and unit commitment in the next few days). Unexpected sudden changes in the summated output of wind farms, due to either a widespread change in wind conditions or in response to a power system disturbance are contingencies that must be assessed for their implications for reserve requirements. Wind turbines may also trip in response to power system disturbances, contributing to cascading power system disturbances.

[1] This should be regarded as a NEM design weakness rather than a problem due to wind energy per se,

Provided that advanced wind turbine technology has been used, two factors will determine readily accepted wind farm penetration levels at local, regional and system wide level: the fluctuations in wind farm power output aggregated to an appropriate level and the correlation between the time-varying aggregated wind farm power output and the time-varying aggregated demand for electricity, when considered at the same level of aggregation.

The variability of wind farm output derives from variability of the underlying resource after conversion through the wind turbine conversion function. As discussed in Outhred (2003), the wind variance spectrum can be divided into a turbulence spectrum (timescale of less than one half-hour) and weather spectrum, which covers timescales of greater than one half-hour and which peaks at a periodicity of a few days.

One factor that reduces impacts of wind variability on a power system the size of the NEM is that wind regimes experienced across the power system are unlikely to be highly correlated. Thus assuming that wind turbines were widely dispersed in the NEM, a situation where they were all operating at full output would be rare, although it would be more common at a regional or local level. At the other extreme, there would be few occasions when none of a set of widely dispersed wind turbines was producing. As suggested by Archer and Jacobson (2003):

"When multiple wind sites are considered, the number of days with no wind power and the standard deviation of the wind speed, integrated across all sites, are substantially reduced in comparison with when one wind site is considered. Therefore a network of wind farms in locations with high annual mean wind speeds may provide a reliable and abundant source of electric power."

Therefore, until a relatively high level of wind farm penetration was reached, concerns would focus more on potential local or regional network flow constraints and voltage problems than on system-wide supply-demand balance. The former should be manageable with good network design and operation (albeit at a cost that would depend on circumstances) provided that advanced wind turbine technology had been used.

As penetration of wind farms increased, the incremental economic value to the electricity industry as a whole of additional wind farms would decline. This is due to the rising cost of the additional resources and control action required to manage power system frequency and voltage, and the additional operating costs associated with committing and dispatching other generation under increasing uncertainty. Thus, as with any other form of generation, the incremental economic value of additional wind capacity would decline with increasing penetration level. However, there would be no formal "hard" limit to the readily accepted wind penetration level.

Australian examples of high wind penetration include:

- A combined wind-diesel test system installed at Malabar (Sydney) in 1988, which consisted of a 150 kW wind turbine with a standard induction generator, a 120 kW diesel generator and a resistor load bank simulating electricity demand, operated satisfactorily at 100% penetration using a load control strategy (Hart et al, 1990). Strategies of this kind have been used in practice in island wind-diesel power systems in which an over-sized wind turbine has been installed. This would not be a cost-effective strategy in a large power system for the foreseeable future.
- The King Island wind-diesel system in Tasmania has 3x250kW wind turbines that supply over 20% of the island's electricity (www.hydro.com.au). A much higher level of penetration is

expected with the commissioning of the 2 x 850 kW turbines presently under construction and the use of innovative storage technologies. The potential costs associated with high levels of penetration can be justified by the relatively high cost of diesel fuel.

- The Denham wind-diesel system in WA has a 1.7MW diesel power station and 3x 220kW wind turbines. The wind turbines are capable of supplying up to 70% of annual energy and operating at 100% wind penetration at low load. Again, the potential costs associated with high levels of penetration can be justified by the relatively high cost of diesel fuel.

- The wind-diesel system recently commissioned at the Australian Antarctic base at Mawson (2x300 kW wind turbines, with a third 300 kW turbine to come) is planned to operate at up to 100% wind penetration for up to 75% of the year with the help of short-term energy storage and a fuel cell for longer-term backup. 65% average penetration was achieved in the first month of operation with two turbines (www.pcorp.com.au; Ecogeneration Magazine, June/July 2003: 19). The high level of penetration at Mawson is facilitated by very high fuel costs and a large heating requirement that provides a controllable load.

These examples demonstrate that high levels of wind penetration are achievable under circumstances where there are high fuel costs and in some cases controllable loads. The additional costs of storage devices and/or spilt wind energy can then be justified. However, this would only apply in the NEM if the pressures for a concerted climate change response became very strong.

Thus in the NEM, the point at which it would no longer be of societal value to increase wind farm penetration further would depend on policy settings such as the MRET target and the correlation between wind farm power output and the local, regional and system-wide demand for electricity[2]. Saturation of cost-benefit could occur at a local, regional or system-wide level, although the third of these is likely to be the last to occur. At present we are at a very early stage in the progression of this process in the NEM. Thus we could envisage a situation in which localities and regions with the most attractive combination of wind resources and network capacity became saturated with respect to cost-effectiveness first. If there were appropriate planning and commercial signals, developers would then move on to other localities and/or regions.

Techniques to minimise power system disturbances due to wind farms

Techniques to reduce the size of voltage or frequency fluctuations can increase the acceptable level of wind farm penetration. These include the following:

- *Siting of wind farms to maximise the diversity between wind farm power outputs.* In general, greater and more even spacing of wind farms will enhance diversity.

[2] A high correlation coefficient between wind and load would mean that wind power was usually high when load was high, making it easier for a power system to absorb a high level of wind penetration. The reverse would apply for a negative correlation coefficient, which would mean that high wind power output usually occurred at low levels of demand. A correlation coefficient near zero would lie between these two cases and would imply that high wind power was equally likely to occur at high and low levels of demand. ESIPC (2003) suggests that the correlation between wind farm output and electricity demand is relatively near to zero for South Australia when considered as a whole.

- *Control of groups of wind farms to limit combined power output or rate of increase of output.* Control could be exercised on a local, regional and system-wide basis to depending on need, and it could be centralised or, where appropriate, decentralised in response to a local variable such as voltage or frequency. This strategy could be used for the infrequent occasions when all turbines were at or near their rated output but would be commercially unattractive if used on a regular basis.

- *Control of other resources in response to fluctuations in wind farm output.* Suitable resources include responsive generation such as hydro (eg Tasmania; Snowy Mountains) and standby generators, reversible storage such as a battery (as being tested on King Island), controllable loads such as storage water or space heating (Mawson), or dump load (Malabar). Again, control could be centralised or, where appropriate, decentralised in response to a local variable such as voltage or frequency. The more flexible that these resources were, the higher the wind penetration that could be tolerated.

- *Use of wind turbine control systems to provide an "inertial response" to perturbations in power system frequency.* Within limits, the dynamic behaviour of wind turbines with power electronic interfaces (those that use a doubly fed induction generator or an alternator) can be tailored according to power system operating requirements.

- *Use of voltage control devices to reduce voltage disturbances in the vicinity of wind turbines.* Static VAr compensators (SVCs) and the power electronic interfaces associated with the wind turbines can be used to reduce voltage disturbances in the vicinity of wind turbines and to enhance the ride-through capability of wind farms.

The acceptable level of wind energy penetration will depend on the cost of implementing strategies of this kind as compared to the benefits derived from increased wind energy penetration. It will vary from one power system to another and from one type of wind turbine to another.

Doherty and O'Malley (2003) explore the effect of increasing wind energy penetration on reserve requirements, showing that distributing a given wind penetration over a greater number of wind farms and shortening the time horizon for reserve scheduling (for example by using more flexible reserve plant or better forecasting techniques) both reduce the amount of reserves required.

Nunes et al (2003) suggest that wind turbines with doubly fed induction generator (DFIG) are more robust to power system faults than those with conventional squirrel cage induction generators. Koch et al (2003) corroborate these conclusions and illustrate that appropriately controlled DFIG wind turbines can also contribute to frequency control by modulating rotational kinetic energy in such a way as to reduce frequency perturbations.

Wind power forecasting techniques

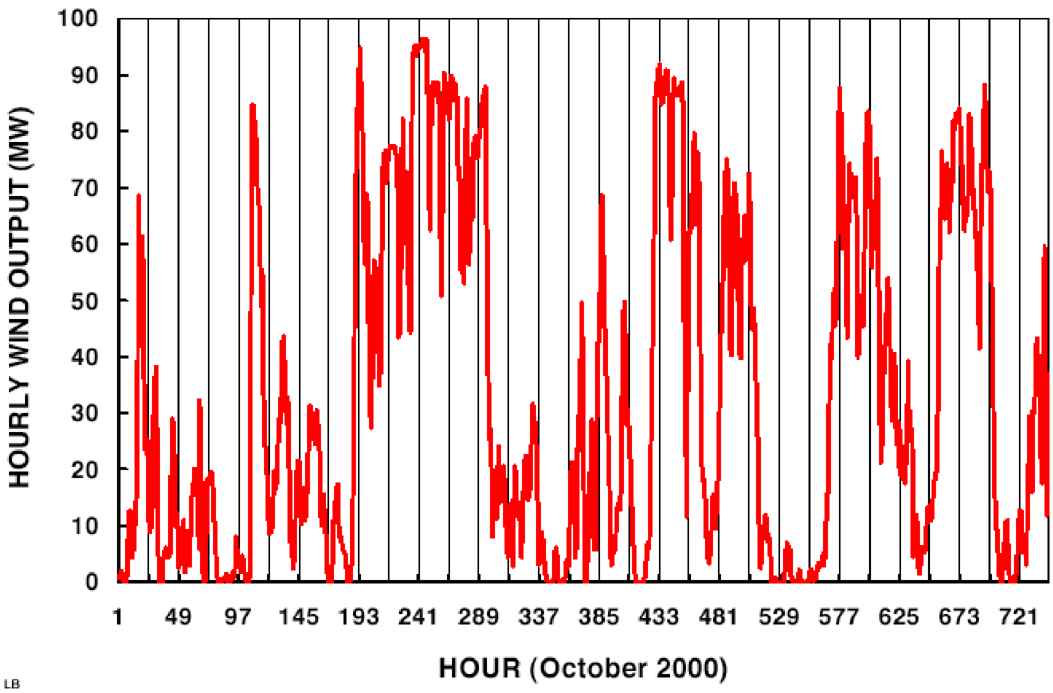
Reliable wind power forecasting has the potential to considerably improve the cost-effectiveness of wind farms in main grid applications by reducing dispatch and commitment errors and by reducing the need for spinning reserve. Accurate forecasts a few hours ahead would reduce the costs of maintaining short-term reserves and accurate day-ahead forecasts would reduce costs associated with inappropriate unit commitment. Accurate longer-term forecasts would assist in network planning and in generation investment. Because of the effects of diversity, it is important to be able to predict changes that affect wind farms in a correlated manner. In particular:

- Accurate prediction of the timing of large changes of either sign up to one day ahead would assist in making unit commitment and spinning reserve decisions[3]
- Accurate prediction of diurnal patterns would assist in unit commitment
- Accurate prediction of seasonal patterns would assist the management of hydro reservoirs and fuel stockpiles
- Accurate prediction of multi-year variability and trends would assist investment decision making for wind farms and other generation resources.

Experience with wind forecasting techniques suggests that persistence techniques (extrapolation of past behaviour) are appropriate for prediction intervals of up to about three hours and that techniques based on weather forecasting models have better predictive accuracy for longer prediction intervals (Outhred, 2003).

For example, Figure 1 shows the hourly power output of the 104 MW Lake Benton wind farm for October 2000 (Hirst, 2001). It can be seen that significant changes to the pattern of short-term behaviour occur from time to time as weather patterns move through.

Changes due to weather pattern effects may not always be predictable merely by extrapolating past behaviour This is illustrated in Figure 2, which is a moving average prediction two hours ahead of the hourly output of Lake Benton wind farm extrapolated from previous hourly power outputs (Hirst, 2001). Figure 2 shows that on many occasions useful predictions are made (perfect predictions would lie on the dashed red line). The outliers represent situations where past behaviour is not a good prediction of the future. Under those circumstances, information from weather forecasting models would improve forecast accuracy.



[3] Spilling a small amount of energy to slow the rate of rise could ameliorate a rapid increase in wind farm power output.

Figure 1. Hourly power output of the Lake Benton wind farm for October 2000 (Hirst, 2001)

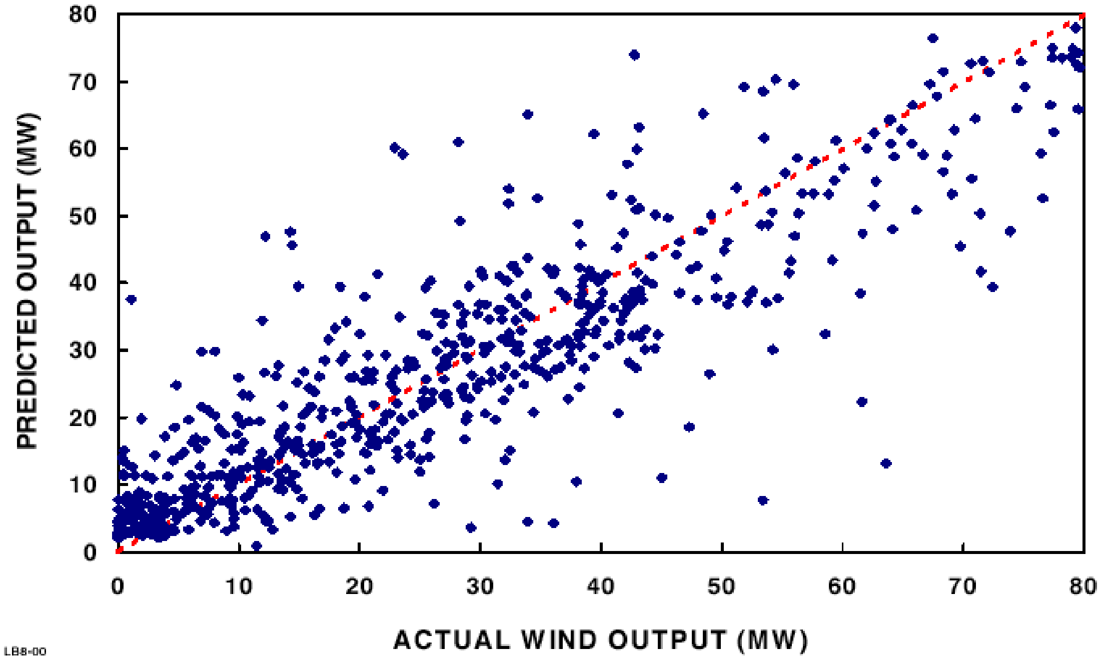


Figure 2. Two-hour predictions of power output from the Lake Benton wind farm compared to actual power output, with the red line corresponding to a perfect prediction (Hirst, 2001)

The California Independent System Operator uses an auto regressive moving average extrapolation technique to produce forecasts up to 3 hours ahead. Based on its experience, it has determined that a more refined forecasting tool should have the following characteristics (Pinson and Kariniotakis, 2003):

(a) the model should incorporate local weather forecasts and de-rate data in order to minimize maximum average error (MAE);

(b) a bias compensation algorithm should be a part of the model;

(c) the algorithm should be adaptive in terms of its ability of self-tuning based on its past performance and changing generation patterns;

(d) the model should provide the probabilistic confidence intervals for its forecasting errors, and

(e) the algorithm should be able do detect inconsistencies in real-time production data caused by unscheduled events such as unit outages or metering equipment failures.

A hybrid forecasting technique has been developed that combines numerical weather predictions with on-line wind farm power measurements to predict wind farm power production up to 48 hours ahead with an on-line measure of prediction risk (Pinson and Kariniotakis, 2003). Such techniques show promise in reducing the uncertainty in the amount of reserve capacity required, thus reducing unit commitment and dispatch costs for fossil fuel plant used in 'back-up" capacity.

Foken et al (2002) illustrate the potential value of forecasts derived from Numerical Weather Prediction (NWP) models. Figure 3, taken from Foken et al (2002), shows the actual power output of a wind turbine together with a series of forecasts made 6, 12, 18, 24, 36 and 48 hours ahead. The 6 and 12-hour forecasts in this study are always accurate and even the 48-hour forecasts provide useful information in most forecasting runs. However, the forecast run on day 324 does not predict the magnitude of the storm on day 326 very well 36 or 48 hours ahead. Similarly the 36 and 48-hour predictions made on day 328 have a timing error of a few hours in the arrival of a storm front on day 330. In both cases, the forecast run on the following day is more accurate in predicting these events.

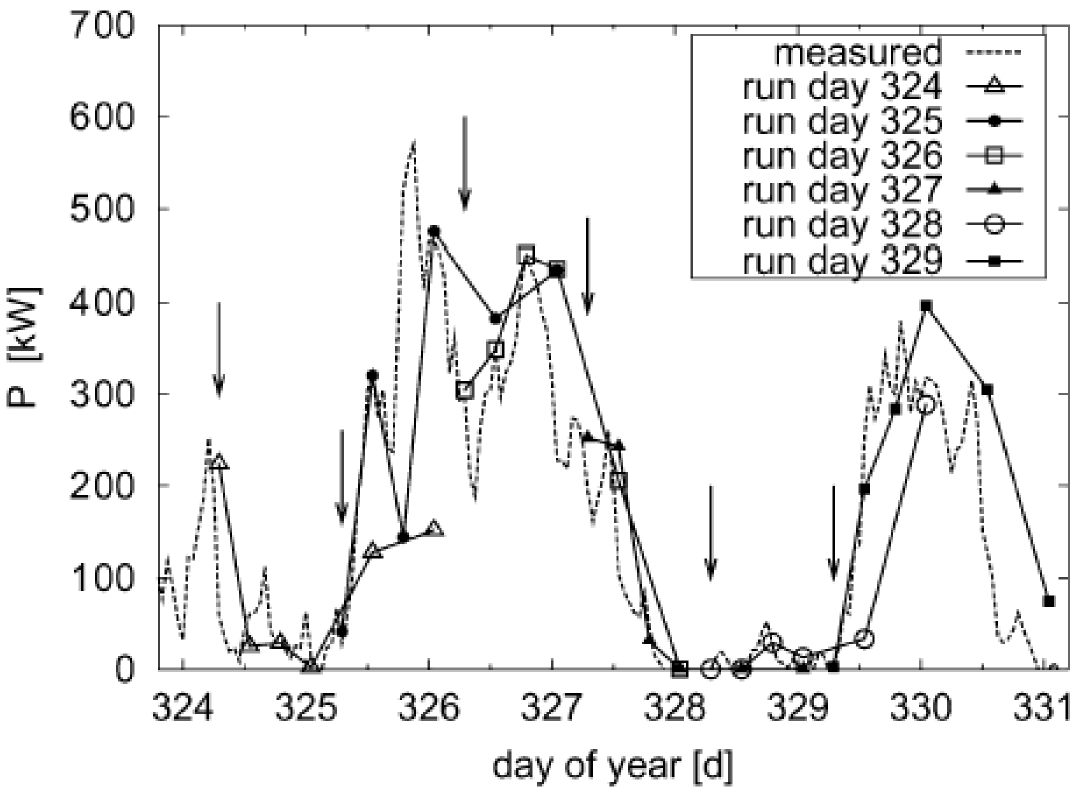


Figure 3. Comparison of measured and predicted output of a wind turbine (Focken et al, 2002). The downward pointing arrows show the first (6 hour) forecast in each set of 6, 12, 18, 24, 36 and 48-hour forecasts. The 6 and 12-hour forecasts are always accurate in this example.

Review of recent studies of wind-power penetration levels and system impacts in Europe and North America

1) A recent study for the UK Department of Trade and Industry (Ilex Energy Consulting, 2002) investigated the cost associated with increasing the penetration of renewable energy in the UK grid to 30% on the basis of generated energy. As documented in Table 9 of that report, Ilex Energy Consulting considered scenarios with up to 38 GW of installed wind farm capacity in a

power system with a peak demand of 62 GW and minimum demand of 25 GW (that is, a penetration level of 60% of maximum demand and over 100% of minimum demand). They estimated the cost penalty associated with such a high level of penetration at £2.2/MWH when spread over all energy generated per year. This penalty allowed for the additional flexible generating capacity required to meet the normal reliability target for the power system.

2) A recent study for the Ireland electricity system suggests that up to 800 MW of wind farms could be accepted before curtailment would be likely to be required at minimum load, in a power system with approximately 5000 MW peak demand and 2200 MW minimum demand (Garrad and Partners, 2003). This implies a penetration of 16% of max demand and 36% of minimum demand. For estimating the maximum allowable penetration, it was assumed that the summated output of the wind farms could change by 100% in an unpredicted manner over several hours. Given that the size of Ireland (including Northern Ireland) is approximately 100,000 km^2, or roughly half the size of Victoria, there is limited scope to take advantage of temporal diversity in wind farm output compared to the NEM.

3) In a study for WE Energies, a utility in Wisconsin, USA, Electrotek Concepts (2003a) estimates the additional ancillary service costs associated with four different levels of installed wind farm capacity – 250 MW, 500 MW, 1000 MW and 2000 MW – for a utility with peak load of about 7000 MW and average load of about 4000 MW, which forms part of a larger power pool. They identify costs, which they estimate total between 1.9 and 2.9 US$/MWH depending on penetration level (from 6% to 50% of average load), as being of three kinds:

- The cost of dispatchable generation tracking wind power fluctuations at timescales of several minutes
- The cost of additional generation reserves to cover uncertainty in future forecast wind production (they assume a day-ahead forecast error in wind farm output of ±50%).
- The cost of tracking minute-by-minute fluctuations in wind farm output.

However, no wind farms were yet installed and this simulation study relied on wind data from four potential wind farm sites. Thus it is unlikely to correctly represent aggregation effects.

4) In a related study, Electrotek Concepts (2003b) estimates the operating cost impact of incorporating an existing 280 MW wind farm in a 7000 MW utility as 1.9 US$/MWH, assuming a day-ahead forecast error in wind farm output of ±50%.

NEMMCO Intermittent Generation Paper

The National Electricity Code defines an "intermittent generator" as "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). The NEMMCO paper on Intermittent Generation in the National Electricity Market (NEMMCO, 2003a) identifies the following key issues, to which the following responses can be made:

- **Forecasting:** *"the variable nature of intermittent generation presents a new dimension to the central forecasting processes managed by NEMMCO for the operation of the market and management of supply adequacy" (NEMMCO, 2003: 3).* As previously discussed, forecasting techniques can reduce the uncertainty surrounding the future output of wind turbines, wind farms and groups of wind farms. It will be important to determine how effective such forecasting techniques are in the context of the NEM.

- **Frequency control ancillary services (FCAS):** *"as the amount of intermittent generation in the power system increases, there is likely to be an increase in the usage and cost of these ancillary services" (NEMMCO, 2003: 3).* Because FCAS deals with short-term fluctuations, diversity between wind farms should considerably reduce the need for additional frequency control ancillary services compared to that predicted by observing the output of a single wind farm alone. For example, the power outputs of wind farms that are widely dispersed in South Australia should be largely uncorrelated for the turbulence spectrum (<30-minute period).

- **Voltage control:** *" the variability of intermittent generation causes additional variability of voltage, particularly in connected to distribution networks that may be more sensitive to load variations" (NEMMCO, 2003: 3).* Wind turbine control systems or complementary devices such as Static VAr Compensators (SVCs) should be able to reduce the voltage disturbances in the vicinity of wind farms. However, wind farm developers will always wish to minimise their expenditure on network connection assets due to competitive pressures.

- **Network management:** "*increased variation in generation is likely to result in increased sub 5-minute variation of flows on network elements and interconnectors" (NEMMCO, 2003: 4).* There will be significant sub 5-minute variations in flows on network elements within NEM regions, and the associated voltage fluctuations may have to be ameliorated by control action (eg SVCs). However, diversity between wind farms should reduce sub 5-minute variations (in relative terms) at the level of aggregation equivalent to regional interconnectors as currently modelled in the NEM[4].

- **System inertia:** "*some intermittent generation technologies also have the potential to reduce system inertia by displacing plant with higher inertia" (NEMMCO, 2003: 4).* As discussed previously, the control systems of modern wind turbines can in principle be programmed to emulate an inertial response at little additional cost.

Thus, while the issues raised by NEMMCO are of great importance, they can be managed at least to some extent by installing appropriate wind turbine technology and control schemes, and by exploiting diversity. NEMMCO (2003b) sets out proposed data requirements for wind farms connected to the National Electricity Market. These would collect sufficient data to investigate the above issues at a wind farm level.

Western Power Issues Paper

Figure 4 shows an operating charge for wind farms in the South West Interconnected Power System (SWIS) that Western Power has proposed to take account of the anticipated increase in operating costs associated with unit commitment and dispatch in the presence of wind farms compared to dispatch without wind farms (Western Power, 2002). While it is clear that such costs will increase, Western Power's analysis did not allow for diversity between wind farms at different locations nor for advanced wind farm operating strategies. Nor does it appear to have allowed for the potential of wind forecasting techniques to provide useful predictions of wind

[4] There are likely to be variations in interconnector flows at timescales > 5 minutes, which may cause variations between the spot prices in neighbouring NEM regions. Price separation may occur under some circumstances. These can be regarded as matters for the market to resolve and may lead to complementary investment in flexible generation or reversible storage.

farm output up to three days ahead (Outhred, 2003). When these are taken into account, the cost impost should be less severe than the Western Power paper suggests.

Readily accepted wind farm penetration in the NEM

For the purposes of this study, a readily acceptable penetration level has been estimated to be 50% of minimum demand, based on the following reasoning:

- The Western Power study concluded that 150 MW of wind farms could be "reasonably accommodated" on the South West Interconnected Power System (SWIS) without taking account of wind farm diversity, forecasting or power limiting strategies (Western Power, 2002). Assuming that 450 MW of wind (about 50% of minimum load in the SWIS) was spread among 9 wind farms spaced sufficiently far apart to have little correlation in turbulence spectrum, their combined turbulence spectrum fluctuations would reduced by a factor of $9^{0.5}$ or 3 compared to those of a single 450MW wind farm. Thus, the turbulence spectrum fluctuations of the dispersed 450MW of wind turbines, when expressed as a fraction of combined power output, would be equivalent to those of 150 MW of wind turbines concentrated in one location, as modelled in the Western Power study. If we also assume that forecasting techniques can provide useful predictions of summated wind farm output up to two days ahead, then it should be possible to substantially reduce the cost of inappropriate unit commitment and dispatch compared to the outcome without forecasting.

- Ilex Energy Consulting (2003) predicted satisfactory operation of the UK grid at a penetration level of 61% of maximum demand and over 100% of minimum demand. Clearly, this would require effective control strategies.

- Garrad Hassan (2003) suggested that up to 800 MW of wind farms could be accepted without curtailment in the Irish power system, which has about 5000MW peak and 2200MW minimum demand, to give a penetration level of about 36% of minimum demand. Recalling that the land area of Ireland (including Northern Ireland) is approximately 100,000 km^2, or about half the area of Victoria, it should be possible to achieve greater diversity benefits in the NEM than could be achieved in Ireland.

- ESIPC (2003) studied penetration levels of up to 1000 MW of wind in the South Australian NEM region, which has approximately 1000 MW minimum demand. While this study did not investigate sub-half hour phenomena or network flow and voltage limitations, it did demonstrate that the system could be dispatched at that level of penetration assuming that good predictions of wind farm output were available. Network-related effects can in principle be managed by appropriate selection of wind farm sites, connection configurations, wind turbine control capabilities and control strategies.

- Australia has a number of examples of effective high wind penetration in diesel mini-grids. The wind-diesel studies at Malabar (Hart et al, 1990) demonstrated satisfactory operation at up to 100% penetration (120 kW) using a load control strategy. The experience at Denham and Mawson demonstrates that this is an achievable goal in actual diesel power systems of larger size. While small wind diesel systems are simpler and more robust than large power systems, they cannot take advantage of the geographical diversity of the wind resource to nearly the same extent. Also, the NEM has yet to take full advantage of demand-side participation in energy markets and ancillary service provision.

- Spain had 4800MW of wind capacity installed at December 2002, supplying approximately 4% of generated electricity. It also has a target of 13,000 MW by 2011 (IDEA, 2003). The Spanish power system had a total electricity production of about 210 TWH per year in 2002, which is a little larger than the NEM, and it also has a relatively weak interconnection to France and a stronger one to Portugal. Peak demand in the Spanish power system in 2002 was about 34000 MW and minimum demand was about 20,000 MW (Red Electrica de Espana, 2003). 13,000 MW of wind capacity would probably still correspond to > 50% of minimum demand in 2011.

Table 1 shows key parameters for the regions of the NEM for the Quarter January-March 2003 (NECA, 2003). Figure 5 shows demand duration curves for the same regions for the same period (NECA, 2003). From Figure 5, we can compute the level exceeded 95% of the time. It is appropriate to use these 95% levels for forward-looking projections and they are shown in Table 2 along with estimates of readily acceptable levels of wind penetration based on 50% of typical minimum demand.

Note: This report suggests possible levels of installed wind capacity in different States that are considered plausible/acceptable from power network management perspective only. It is meant to provide a guideline, given current knowledge and experience of wind in the NEM. It in no way recommends or advocates reaching these State levels and recognises that many other local and state planning considerations, such as community needs, environmental risks and broader economics, will drive a varied level of development. It is an individual State policy decision as to what targets should be proposed for wind developments in that State.

Table 1. Key parameters of NEM Region Demand for January – March 2003 (NECA, 2003)

Demand in MW	QLD	NSW	VIC	SA
Maximum demand in the period Jan-Mar 03	7095	12467	8188	2787
Maximum demand since NEM start (Dec 98)	7109	12467	8188	2833
Date of maximum since NEM start	4/12/02	30/1/03	24/2/03	07/1/01
Minimum demand in the period Jan-Mar 03	3966	5419	3816	976
Minimum demand since NEM start (Dec 98)	2894	4624	2614	853
Date of minimum since NEM start	26/12/98	26/12/99	27/12/98	01/1/00

Table 2. Maximum demand, demand exceed 95% of the time and estimate of readily accepted wind penetration (NECA, 2003; Western Power, 2002; & private correspondence)

	QLD	NSW	VIC	SA	Tas	WA*
Maximum demand (MW)	7095	12467	8188	2787	1700	2700
Demand exceeded 95% of time (MW)	4257	6233	4500	1115	1000	1040
Demand exceeded 95% of time (% Pk)	60%	50%	55%	40%	58%	38%
Plausibly acceptable wind (MW)	2100	3100	2200	500	500	500

*South West Interconnected System in WA

This implies that approximately 8000 MW of wind energy could be readily accepted in the NEM if it was distributed among the existing NEM regions in approximately the above proportions and in the absence of significant amounts of other forms of intermittent generation. Approximately 500 MW more could be accepted if Tasmania enters the NEM. Additional wind farms could be tolerated, however the combined output may have to be limited under some circumstances. In general, the incremental value derived from installing wind farms would decline with increasing penetration.

Table 3 compares a recent summary of existing and planned wind energy projects in Australia (Woolnough, 2003, updated from AusWEA web site, 23/9/03) with the estimate of readily accepted wind capacity estimated above. This shows that currently installed wind farm capacity is well below the readily acceptable level in all states.

Table 3 also shows that plans for wind farms significantly exceed the readily accepted capacity in South Australia. However, a higher level of wind capacity in SA may be readily accepted if a significant fraction of the South Australian wind farms is installed close to the border with Victoria assuming that there is adequate physical capacity to Victoria to provide support if wind farm output falls rapidly.[5]

Table 3. Comparison of installed & planned wind capacity with readily acceptable wind capacity

	QLD	NSW	Vic	SA	Tas	WA	Total
Readily acceptable wind (MW)	2100	3100	2200	500	500	500	8900
Installed wind (MW)*	13	17	92	35	11	28	196
Proposed (MW)*	40	115	437	1190	570	347	2699
Installed or proposed (MW)*	53	132	529	1225	581	375	2895

*Source for updated installed & proposed wind MW: www.auswea.com.au (23/9/03)

Table 4 shows interconnection capacity in the National Electricity Market. This shows that there is approximately 680 MW transfer capability from Victoria to South Australia and 420 MW from South Australia to Victoria, the former number being the more important in the context of providing support in the event of an unpredicted rapid decline in wind farm output. Network augmentation in the southeast of South Australia could increase this support capability.

Basslink could provide similar back-up support for wind farms in Tasmania. In principle, it could move rapidly from transmitting 600 MW from Tasmania to Victoria, to transmitting 300 MW from Victoria to Tasmania, a range of 900 MW.

Table 4. Interconnection in the National Electricity Market (NEMMCO, 2003c)

Interconnection	**MW**
Queensland to NSW (QNI AC)	950
NSW to Queensland (QNI AC)	700
NSW to/from Qld (Direct Link DC)	180
NSW-Snowy (AC)	1150
Snowy-NSW (AC)	3200
Snowy-Vic (AC)	1900
Vic-Snowy (AC)	1100

[5] The interconnection capacity modelled in the NEM is, of necessity, an abstraction of the physical power system.

Vic-SA (AC)	460
SA-Vic (AC)	300
Vic-SA (Murraylink DC)	220
SA-Vic (Murraylink DC)	120
Vic-Tas (Basslink DC, 2005?)	300
Tas-Vic (Basslink DC, 2005?)	600

Geographical factors affecting wind penetration

Table 5 shows the installed wind capacities in Denmark and Germany and their respective land areas. These land use figures imply that the Eyre Peninsula at 45000 km^2 could absorb 1,500 MW of wind turbines at the present average German land-use density or 3,000 MW at the present average Danish land-use density[6].

Also, the land with good wind resources accessible to the NEM in SA, Victoria and NSW and not quarantined by urban areas or national parks is roughly 200,000 km^2, which could absorb 7,000 to 14,000 MW of wind power at similar average densities to the present situation in Germany and Denmark respectively.

Table 5. Land area, installed wind capacity and wind power density in Denmark and Germany
(sources: European Wind Energy Association and Greenpeace (2003), The Times Concise Atlas of the World, 1983)

Country or region	Area (km^2)	MW wind (end 2002)	MW/km^2
Denmark	43,000	2900	0.067
Germany	360,000	12000	0.033

Focken et al (2002) suggest that the ability to exploit diversity between the stochastic outputs of evenly distributed wind turbines depends primarily on the land area involved. Wind power density (MW/km^2) thus becomes an inverse measure of the ability to exploit diversity.

On this reasoning, assuming similar wind behaviour in Australia and Europe, 8000 MW spread evenly over 200,000 km^2 (0.04 MW/km^2) could be expected to give greater diversity benefits than the present situation in Denmark, and probably also more than in Germany, where wind farms are concentrated in a region close to the North Sea. Moreover, the land with good wind resources accessible to the NEM in SA, Victoria and NSW is not contiguous but rather distributed across a much greater land area, adding to the diversity when considered for the NEM as a whole. This reinforces the view that local network constraints are more likely to be restrictive than NEM-wide constraints in the near term. However, these should be technically solvable. For example, 3000 MW of wind capacity on the Eyre Peninsular would raise comparable network design issues to those already solved in Denmark. Whether it would be cost effective to do so is, of course, another matter.

[6] Wind farms are actually distributed more evenly in Denmark than in Germany, where they are concentrated in areas close to the North Sea.

Conclusions

This preliminary review of the issues suggests that the NEM could readily accept 8000MW of wind farms provided that:

- the wind farms were installed in a progressive manner over a period of about 10 years;
- the wind farms were widely dispersed within the NEM and, where necessary, local voltage or network flow constraints were overcome;
- the wind farms used advanced wind turbine technology, such as DFIG or alternator technology and advanced wind farm control systems that allowed the wind farm output to be remotely monitored and controlled; and
- advanced wind forecasting techniques were developed and used to predict the future behaviour of wind farms and groups of wind farms, and in particular to accurately predict significant changes in the output of regional groups of wind farms hours or preferably days in advance.

Unfortunately, current arrangements under the National Electricity Code (NEC), including the commercial signals provided by the NEM and network charges, are not adequate to ensure such an outcome. Indications to date are that wind farms may not be being installed in a sufficiently dispersed manner to avoid network constraints and it is not clear whether developers are installing turbines of sufficient sophistication and wind farm control and protection schemes of adequate performance.

Thus the following policy options are recommended for consideration:

- Integrated regional wind development strategies should be developed, which systematically take into account resource distribution, land use issues, turbine technology and connection requirements, network voltage and flow constraints and other planning issues.

- Advanced wind forecasting techniques should be developed to predict the future behaviour of wind farms and groups of wind farms, and in particular to accurately predict significant changes in the output of regional groups of wind farms up to two days in advance.

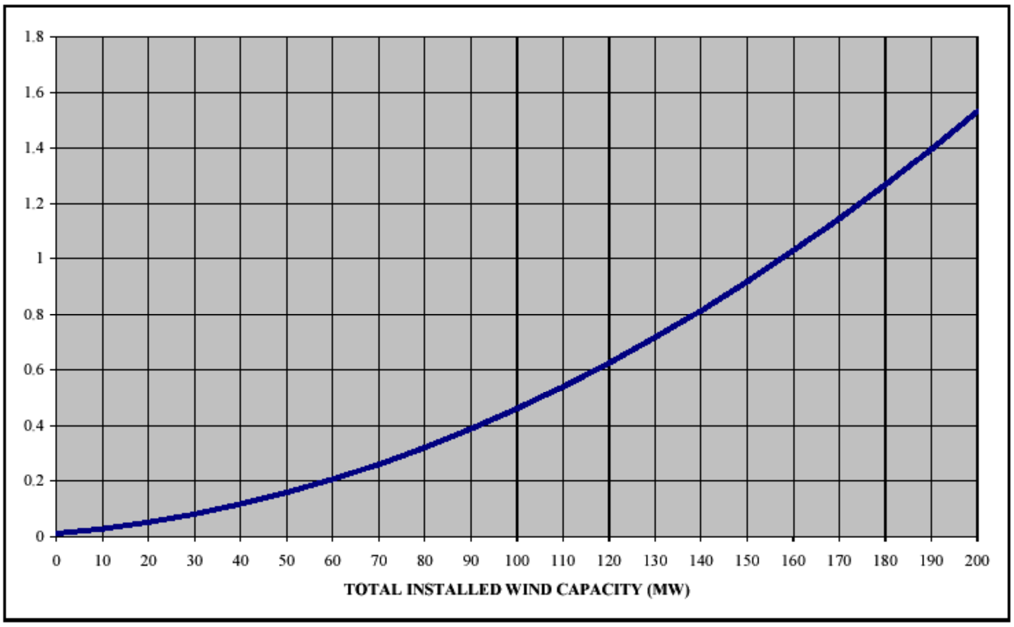


Figure 4. Proposed penalty charge (c/kWh) for wind energy in Western Australian South Western Interconnected Power System (Western Power, 2002)

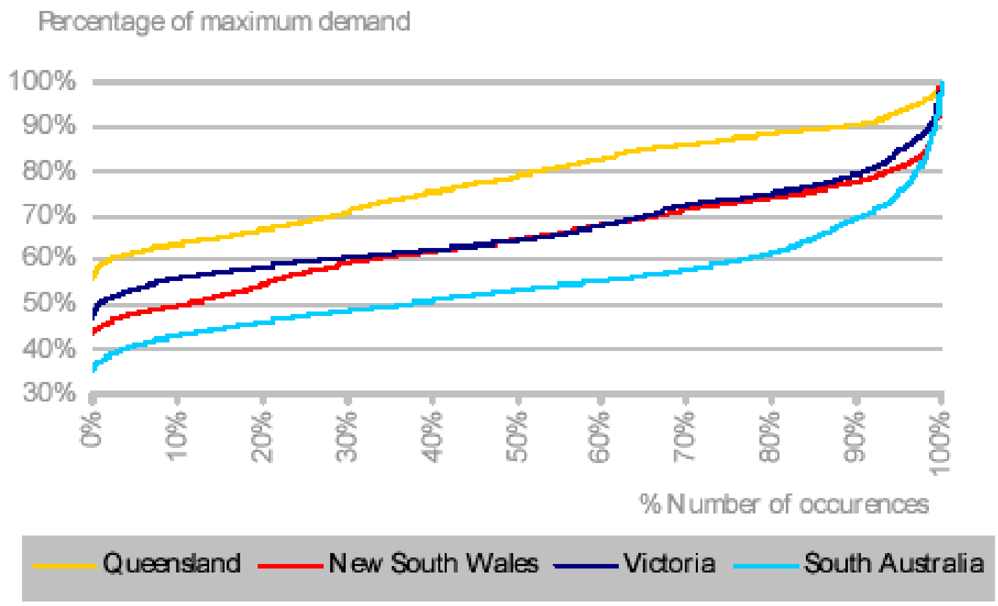


Figure 5. Demand duration curves for the States participating in the NEM. The lines represent the percentage of time spent (horizontal axis) below the demand level indicated (vertical axis). The data is half-hourly demand for January-March 2003 (NECA, 2003)

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