Solar 2005, ANZSES Annual Conference, Dunedin NZ, 28-30 November 2005

Integrating Wind Generation into the Australian National Electricity Market

Iain MacGill and Hugh Outhred
Centre for Energy and Environmental Markets
School of Electrical Engineering and Telecommunications
University of NSW
Sydney 2052
AUSTRALIA
E-mail: i.macgill@unsw.edu.au

Wind energy has an important role to play in helping us meet ever more pressing climate change and energy security concerns within electricity industries around the world. Wind generation is, however, the first intermittent renewable energy resource that has begun to achieve significant grid penetrations in power systems. As such, it represents the frontier of managing such types of intermittent resources in power systems. Many electricity industries worldwide are also undergoing restructuring towards more competitive market-based arrangements. Australia is no exception to these parallel developments. The Centre for Energy and Environmental Markets at the University of NSW is now undertaking a three year research project exploring wind integration into the Australian National Electricity Market. In this paper we outline the underlying conceptual framework of this work both from the physical and the commercial viewpoints, and then explore this in the Australian context. We then present the two proposed research strands for the project: wind energy integration, focusing on the prediction and control of wind farm outputs to maximise their value to power system operation; and on electricity industry restructuring, exploring the technical, commercial and regulatory issues associated with facilitating wind energy in Australia.

1. INTRODUCTION

Wind energy is an emerging resource that can make a valuable contribution to meeting the pressing greenhouse and energy security challenges in electricity industries around the world. However, it represents the first intermittent energy source to reach significant penetrations in power systems and it has very different characteristics from conventional generating plant, which pose important challenges to existing power system operation. Meanwhile, many electricity industries worldwide have themselves been undergoing restructuring over the last two decades towards more commercially competitive, market-based operation and investment.

Key challenges for wind energy integration into such restructured electricity industries include:

- physical complexity in terms of the shared, non-storable, time-varying wind energy flux that is used by wind farms and the shared, non-storable, time-varying electrical energy flows that pass through the network according to the behaviour of all network elements, generators and loads,
- commercial complexity that arises because the electricity industry is infused with short- to long-term risks that are difficult to commercialise (correctly allocate to industry participants), and
- institutional complexity because of all the shared issues in planning, grid connection, network operation and management of power system security. These mean that electricity industries will always involve a mix of centralised (government and system operator) as well as decentralized (commercial) decision making, and hence require institutions that can achieve this.

There are growing efforts to better understand and manage these issues internationally and in Australia. Recent international work includes studies by the International Energy Agency (IEA, 2004; IEA, 2005), and within the United Kingdom (UK SDI, 2005), Germany (DENA, 2005), New Zealand (EECA, 2005) and the United States (CEC, 2004).

High wind energy penetrations will test the adequacy of electricity industry restructuring in all of its technical, commercial and regulatory aspects. The issues must be considered in a specific context, because wind resource, power system characteristics and institutional arrangements differ between countries. This is certainly the case for Australia's National Electricity Market (NEM) which has a large geographical scope and rather different mix of generation and loads from many other countries, and has its own particular electricity market arrangements.

In Australia, recent work includes that undertaken by the National Electricity Market Management Company (NEMMCO, 2003; NEMMCO, 2004; CSIRO, 2004), Ministerial Council on Energy's Wind Energy Policy Working Group (WETAG, 2005), South Australia's Electricity Supply Industry Planning Council (ESIPC, 2005) and the Australian Greenhouse Office (Outhred, 2003; Outhred, 2004).

The Australian Government's Wind Energy Forecasting Capability initiative (WEFC) was announced in the June 2004 Energy White Paper. The WEFC initiative is intended to facilitate the development of effective wind generation forecasting in Australia, and hence support both greater wind penetrations within Australian energy markets and more strategic development of wind farms on our electricity networks. The initiative is being administered by the Australian Greenhouse Office (AGO), with the support of the Department of Industry, Tourism and Resources (DITR).[1]

The Centre for Energy and Environmental Markets at the University of NSW is now undertaking a three year research project with support from the Australian Greenhouse Office (AGO) under the WEFC initiative. It is intended to be informed by and compliment related work being undertaken by the AGO, NEMMCO, ESIPC and WEPWG that have more specific and immediate goals. The two principle research strands of this project are:

- integration of wind energy, focusing on the behaviour of wind resources and conversion systems with particular attention to the prediction and control of the power output of appropriately aggregated groups of wind farms, and
- electricity industry restructuring, exploring the technical, commercial and regulatory issues associated with wind energy with particular attention to power system security, market design and readily acceptable levels of wind energy penetration.

In this paper, we outline the conceptual framework underpinning this research project, and the Australian context in which it sits. In the next Section we consider the physical context – characterisation of the wind resource, its conversion into electrical energy and electrical flows within a shared transmission and distribution network that connects other types of electricity generation and loads. This is done in the context of the Australian wind resource and the interconnected network of the NEM. In Section 3 we consider the commercial context of integrating wind power into the Australian electricity industry including the NEM. We conclude with some thoughts on research directions for our AGO/CEEM research project, and its proposed focus on wind generation forecasting, advanced control strategies for wind farms and appropriate electricity market design for maximising the value of wind generation in Australia.

2. THE PHYSICAL CONTEXT OF WIND INTEGRATION

2.1. Wind resources

Wind is a shared, widely distributed, highly variable energy flux with no inherent storage. The magnitude of this flux has strong temporal and locational variability. It is also somewhat unpredictable. The temporal variability of wind speed at a particular monitoring location is shown in Figure 1. Note that the wind energy flux varies as the cube of the wind speed – that is, doubling the wind speed increases wind energy eightfold. The three peaks in variability are common to most locations – short-term (less than 30 minutes) turbulence, a strong daily variation typically driven by phenomena such as sea breezes, and variability over two to seven days corresponding to the arrival and departure of particular weather systems. This has important implications for wind energy forecasting and power system operation, as discussed later.

---

[1] More information on the WEFC is available on the AGO website – www.greenhouse.gov.au.

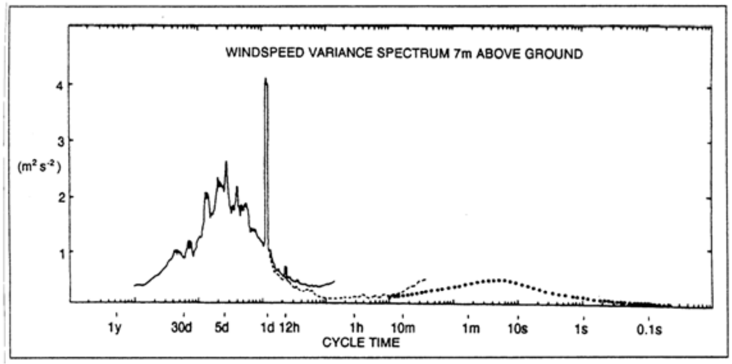

Figure 1. The variability of wind speed at a particular Danish monitoring station over 17 years of data collection (Sorensen, 2001, Fig 2.110, p194).

2.2. Wind conversion technologies

A range of wind turbine technologies are available for the conversion of wind energy flux into electrical energy. The transformation is highly non-linear as shown in Figure 2. With modern turbines it is also partially controllable. While generation is not possible for wind speeds below the cut-in rating of the unit, it is possible to downwardly control the machine's electrical output below the maximum output possible for a given wind speed.

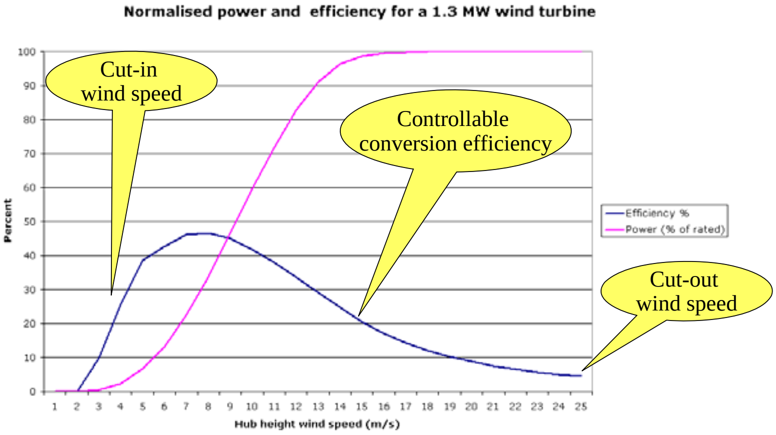

Figure 2. The wind – power characteristic for a typical modern wind turbine (taken from published data for a standard Bonus 1.3MW unit).

2.3. Aggregated wind generation

Wind turbines are normally installed in wind farms ranging from several to potentially hundreds of machines. Significant wind penetrations in power systems would normally involve numerous wind farms. A key issue then is the aggregated variability of wind generation.[2] The correlation between the outputs of separate wind farms depends largely on the time period of variation that is being considered and the distance between the wind farms as demonstrated in Figure 3. There is little correlation in the five to 30 minute average (turbulence) output of wind farms that are more than 20 to 50 kilometres apart. The 12 hour (weather related) average output of wind farms can, however, be correlated over hundreds of kilometres.

---

[2] This is typically described in terms of correlations between turbines within a wind farm, and between wind farms. Completely correlated wind generation indicates perfectly synchronized variations in output while completely uncorrelated generation means that each generator's output varies entirely independently of the others. Importantly, the average fluctuation of uncorrelated wind turbines varies as the square root of the number of turbines – that is, the average fluctuations of 100 uncorrelated turbine outputs would only be ten times greater than the average fluctuation of one turbine.

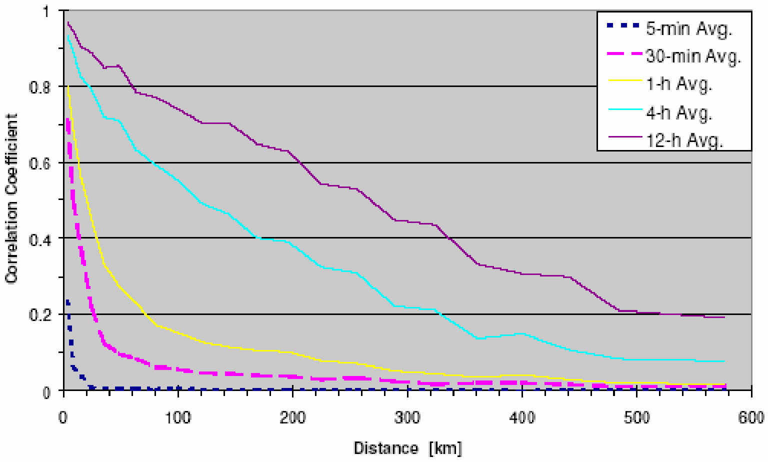

Figure 3. Cross-correlations between the power outputs of German wind farms (Giebel, 2000)

Wind generation from all these wind farms must then be integrated into a shared, geographically dispersed, electricity transmission and distribution network that delivers electricity from numerous and varied types of generators to enormously diverse end-use equipment that delivers desired energy services, as shown in Figure 4.

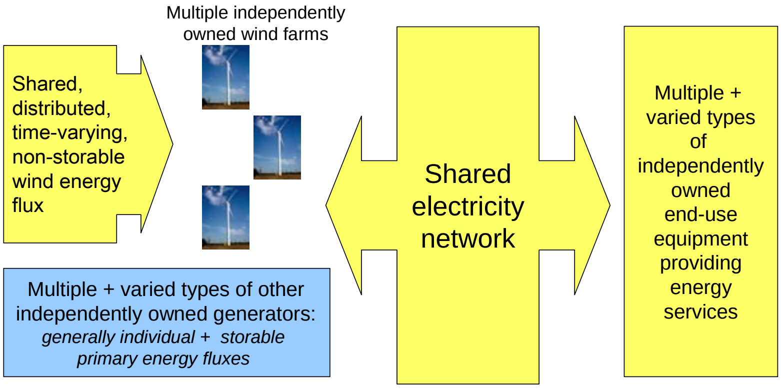

Figure 4. The physical context of wind integration into power systems.

2.4. Other power system resources – generation and loads

Note that all power system resources – loads and generation – have electrical flows that are:

- variable over time
- never more than partially controllable, and
- somewhat unpredictable.

For example, total electrical demand in most power systems varies markedly over each day, between different days of the week (particularly on the weekend) and from season to season. Most loads are independently owned and operated so overall demand is somewhat unpredictable, depending on the behaviour of end users. A large part of this unpredictability arises from the increased use of air-conditioning and heating for hot and cold temperature extremes, and our difficulties in forecasting these weather patterns.

Large coal-fired plants can usually be controlled within their minimum and maximum rated output, subject to ramp rate and startup/shutdown dynamics. They do, however, occasionally fail unexpectedly with potentially severe impacts due to their large size. Transmission and distribution network elements, such as transmission lines, are generally only partially controllable in terms of network flows and can also fail unexpectedly.

Wind generation does, however, have different characteristics from most conventional generating plant. Its technical performance is actually more predictable than most thermal plant because modern wind turbines are highly reliable, while unexpected variations in thermal plant generally represent forced outages that the operators are working hard to avoid.

2.5. The transmission and distribution network

One of the key ways that electricity networks create value is through diversification; that is, they help manage the stochastic (variability and somewhat unpredictable) electrical flows of all power system resources. For example, the power flow from a zone substation into a distribution feeder that supplies a residential suburb is far smoother than power flow into a particular house connected to that feeder.

Wind generation variability and unpredictability can therefore be at least partially managed by integrating wind farms into a shared, geographically extensive electricity network with numerous diverse electricity generation and load resources. A practical example is the network supporting the Australian National Electricity Market, which covers Queensland, New South Wales, the ACT, Victoria, South Australia and (from 2006) Tasmania.

Unfortunately power systems are also complex and time-critical systems. This is largely due to the lack of cost-effective storage of electrical energy. Therefore, while power systems can readily manage small disturbances, they are very sensitive to large and unexpected changes in the behaviour of generators, loads and network equipment. Of particular concern is the possibility that disturbances can cascade through the network leading to major blackouts. Equipment failures in large centralised power stations or the transmission network can cause large disturbances. Large changes can also arise if there is a strong correlation between the behaviour of large numbers of small generators or loads; such as air conditioners on a hot summer day, or groups of wind farms upon the arrival of a storm front. Power system operation is enhanced if we can forecast such events some time ahead.

2.6. Wind integration in power systems

One key issue for wind integration is, therefore, the potential for wind generation to create disturbances from large unexpected changes in output, and the operational arrangements within the power system for managing such events. Another issue is the ability of wind turbines to survive disturbances arising from other power system equipment.

Specific network issues at the local and potentially regional level for wind farms include:

- turbine starting and stopping transients,
- possible voltage distortions caused by the equipment,
- potentially large and unexpected variations in electrical flows through particular network elements, and
- their ability to ride through system disturbances such as temporary voltage or frequency excursions.

Power systems generally have standards for generators wishing to connect to the network that include reactive power and voltage control capability, protection requirements, remote control arrangements and ride-through capabilities. Most modern wind turbines are capable of meeting these requirements. For example, the power and voltage characteristics of sophisticated Doubly Fed Induction Generator (DFIG) and Direct Drive wind turbines are superior to earlier constant speed induction generator machines, as shown in Figure 5. These machines also offer the potential to use more sophisticated control strategies for trying to managing issues such as network flows.

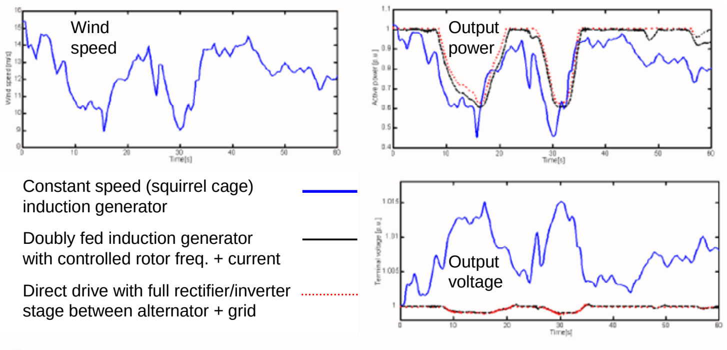

Figure 5. Output power and voltage behaviour for three different types of wind turbine technologies under variable wind conditions (Slootweg, 2003).

At the system-wide level, the alternating current frequency is a measure of overall system supply and demand balance, as shown in Figure 6. Given that power flows from all loads, generators and network availability are stochastic processes, system frequency is always varying. Power system security requires operating the system in a way that can maintain this frequency within an acceptable range under normal conditions yet also in the case of the most severe credible contingencies; for example, the sudden and unexpected loss of the largest power station or transmission line in the system. Ensuring longer-term supply-demand balance through the mix of units on-line, fuel and maintenance scheduling through to investment in new plant is also part of system security. The way these issues are managed in a power system depends on the commercial and institutional arrangements in place, as discussed in the next section.

Wind generation can certainly make frequency more variable. The issues are whether this matters in terms of normal operation (frequency regulation), significant credible contingencies for the system and longer-term security of supply issues.

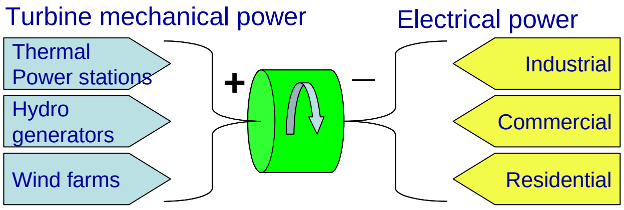

Figure 6. The relationship between supply/demand balance and frequency in power systems.

2.7. Wind forecasting

The ability to forecast wind generation at the wind farm to system-wide level over very short to longer-term time frames will play a key role in managing local, regional and system-wide impacts. Given sufficient warning of forthcoming major changes in wind generation output, it is possible to adjust the mix of other operational generation and perhaps controllable loads in order to manage supply-demand balance. The two main forecasting methods available are:

- statistical, built around real-time and historical production data from wind farms, and
- Numerical Weather Predication (NWP) systems typically applying terrain mapping to achieve higher resolution wind speed predictions than standard weather forecasting (CSIRO, 2003).

The most appropriate technique for different time-scales of forecasting is outlined in Table 1. Clearly, short-term forecasts are best done from real-time production data. The critical forecasting task of predicting the arrival of different weather systems (and in particular extreme weather events such as storm fronts) relies upon NWP systems.

Note also that the wind is a ‘public good’ resource shared by all wind farms. There are potential conflicts between the public value of wind farm production data and associated forecasts and commercial considerations of the wind farm owners and operators.

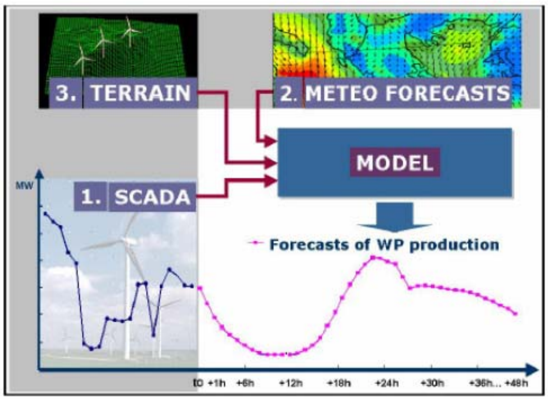

Figure 7. The available forecasting approaches for wind generation (taken from Giebel, 2003)).

Table 1. Wind generation forecasting options (adapted from CSIRO, 2003).

Time-scale	Most appropriate method	Comment
<30 minutes	Statistical, based on reported production at 1-30 minute resolution	Results strongly influenced by spatial smoothing within wind farms or groups of wind farms. Statistical methods require knowledge of wind farm characteristics or history.
30 minutes to several days	Statistical up to first 3-6 hours then Numerical Weather Prediction (NWP)	Forecasts will need to be tuned to response of each wind farm.
Days to a week	NWP	Uncertainty increases with look-ahead time.
Weeks to years	Statistical analyses of seasonal and yearly variability in wind resource on regional basis	Long-term averages are predictable with known variability. However, low forecasting capability at present.

3. THE COMMERCIAL CONTEXT OF WIND INTEGRATION

3.1. Electricity industry restructuring

The last two decades has seen worldwide efforts in restructuring national electricity industries. Generally this has included:

- structural disaggregation from monopoly (typically government owned) utilities to a mix of competing firms in generation and retail markets, yet monopoly network service providers and centralised market and system operators, and
- the introduction of far greater decentralised, commercial (market price based) decision making.

While the outcome to date of these restructuring efforts has varied and it is too soon to declare its conceptual success or failure, some principles of good electricity industry market design are clear:

- an appropriate mix of decentralised (commercial) and centralised decision making,
- a focus on embracing, and hence better managing, the inherent uncertainties within the electricity industry from the very short to longer-term - uncertainty drives competition and risk is generally best allocated to participants on the basis of who is responsible and best placed to manage it,
- allocation, as best possible, of costs and benefits to participants with respect to the costs and benefits they each provide to the industry,
- establishing a level playing field that doesn't favour incumbent technologies and participants against 'new entrants', and
- support for appropriate innovation to meet emerging challenges and change.

The way that these principles are adopted, or not adopted in specific electricity industries can have marked impacts on a technology such as wind generation, with its shared reliance on a ‘public good’ wind resource, very different operational characteristics and ‘new entrant’ status as an emerging technology for helping meet our emerging climate change and energy security challenges..

Another important issue is that traditional conceptual models may no longer be adequate. For example, concepts such as reserves are commonly adopted in traditionally structured electricity industries but are less appropriate for industries with competitive generation. In these, uncertainty plays a key role in driving competition.

3.2. The Australian National Electricity Market

The Australian NEM operates over the interconnected networks of Queensland, New South Wales, the ACT, Victoria, South Australia and (from 2006) Tasmania. It adopts a model for electricity trading in restructured electricity industries that includes:

- a spot market where energy that meets Quality of Supply criteria trading at regular and reasonably short (say half hour or less) intervals,
- derivative markets that relate to future spot market prices and convey important information for longer-term operational and investment decision making, and
- ancillary services, both market and centrally coordinated, to ensure the availability and quality of supply in the short-term between spot market dispatches, particularly with respect to unexpected contingency disturbances.

In terms of the principles of market design highlighted above, the NEM:

- has a competitive wholesale generation spot market and associated ancillary services markets, an independent market and system operator in the National Electricity Market Management Company (NEMMCO) and regulated monopoly network service providers,
- a mix of centralised and market processes for managing uncertainty (see Table 2) that impose considerable uncertainties on participants – for example, generators do not know their dispatch level beyond the next five minutes,
- a stated objective of imposing ‘causer pays’ on the costs of ancillary services, and
- formal objectives that anyone who wishes it should be able to gain access to the network while not being treated more or less favourably than incumbents, and that particular energy technologies should not be treated more or less favourably than another energy technology.

It is, however, very difficult to achieve some of these objectives in practice, and the implications of this for wind integration in the NEM are explored in the next section.

Table 2. Managing uncertainty in the Australian NEM

Time-scale	**Uncertainty issues**	**Management mechanisms**
<30 minutes	Unexpected fluctuations in generator and load power flows, network outages	Security constrained dispatch, ancillary services markets, spot market
30 minutes to several days	Variation in generator and load power flows and network outages, also inter-temporal links such as generator ramp rates, startup sequences	Security constrained dispatch, ancillary services markets, spot market and derivative markets
Weeks to years (operation)	Longer term inter-temporal links – for example, hydro scheduling, retail tariff setting, maintenance planning	Derivative markets supported by centralised system projections and security assessments
Weeks to years (investment)	Optimal investment decisions	Derivative markets supported by centralised system projections, sitting within an effective policy framework

3.3. The commercial context of wind integration into the Australian NEM

The commercial context for wind farms within the Australian NEM is outlined in Figure 8. Within the National Electricity Code that governs the NEM, a wind turbine is classified as an intermittent generator whose output is not readily predictable. As such wind farms have normally been classified as non-scheduled generation and not required to participate in the NEM processes of bidding, pre-dispatch and projected assessments of future system adequacy that apply to conventional generating plant. They do have to meet the Code's technical requirements for network connection, accept the price for electricity that applies to the connection point in each market interval and comply with operating conditions imposed by NEMMCO.

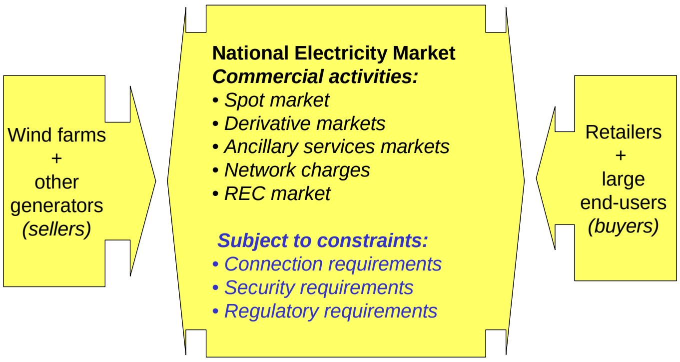

Figure 8. The commercial context of wind integration into the Australian NEM.

The design of the Australian NEM and associated arrangements for ancillary services is more favourable than many with respect to the integration of stochastic renewable energy resources. However there are still many matters of concern to the market and system operator and some other participants. In particular, the classification of wind farms as non-scheduled raises important challenges for system operators should wind penetrations become significant. They have very limited opportunities to direct the behaviour of unscheduled generation yet remain accountable for maintaining system security.

A number of changes to NEM arrangements for wind have been proposed including (NEMMCO, 2004; WETAG, 2005 and ESIPC, 2005) and there certainly appear to be potential design enhancements that could optimize the value of intermittent renewable energy resources such as wind, and facilitate high levels of penetration.

4. CONCLUSION

This paper has outlined some of the conceptual framework and specific Australian context for our research project on facilitating the uptake of wind energy resources in the Australian NEM.

The first strand of the project will investigate issues specifically associated with wind energy, including the behaviour of the atmosphere in various timescales and degrees of geographical aggregation, the design of wind energy conversion systems, and strategies for wind farm control. It will pay particular attention to the prediction and control of the behaviour of groups of wind farms, aggregated to appropriate levels for investigating power system security and quality of supply issues.

The second strand of the project will undertake a systematic investigation of the design and performance of the southern and eastern Australian electricity industry and the associated NEM from the perspective of stochastic wind energy resources. This research will pay particular attention to the implementation of power system operation and security measures, the design of ancillary service, spot and derivatives markets and market projections, and the interface between the engineering task of managing power system security and the economic task of managing operation and investment of independently owned resources.

Links between the two strands will focus on technical performance and on economic and commercial outcomes. We plan to regularly report on the results of this research over the project's three year program.

5. ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of the Australian Greenhouse Office in funding this research project as part of the Australian Government's Wind Energy Forecasting Capability initiative.

6. REFERENCES

CEC. (2004), *California Renewables Portfolio Standard Renewable Generation Integration Cost Analysis,* Californian Wind Energy Collaborative report to the Californian Energy Commission, 2004.

CSIRO. (2003), *The Feasibility of Wind Power Production Forecasting in the Australian Context,* Report to NEMMCO, December.

DENA. (2005), *Planning of the Grid Integration of Wind Energy in Germany Onshore and Offshore up to the year 2020,* Duetsche Energie-Agentur Report, Berlin.

EECA. (2005), *Wind Energy Integration in New Zealand,* Energy Link and MWH NZ Report for the Energy Efficiency and Conservation Authority, Wellington.

ESIPC. (2005), *Planning Council Wind Report to ESCOSA,* South Australian Electricity Supply Industry Planning Council, April.

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

Giebel, G., Brownsword, R. and Kariniotakis, G. (2003), *The State-of-the-Art in Short-Term Prediction of Wind Power – A Literature Overview,* Version 1.0, ANEMOS project, European Commission, available from http://anemos.cma.fr/

IEA. (2004), *Workshop on the Integration of Wind Power into Electricity Grids: Economic and Reliability Impacts,* IEA/Nuclear Energy Agency, Paris, 25 May 2004.

IEA. (2005), *International Energy Technology Collaboration and Climate Change Mitigation – Case Study 5: Wind Power Integration into Electricity Systems,* OECD/IEA, Paris.

NEMMCO. (2003), *Intermittent Generation in the National Electricity Market,* Report by the Market Development Group, March.

NEMMCO. (2004), *Forecasting Intermittent Generation in the National Electricity Market*, Report by the Wholesale Market Development Group, February.

Outhred, H.R. (2003), *Wind Energy and the National Electricity Market with particular reference to South Australia,* Report for the Australian Greenhouse Office, Canberra.

Outhred, H.R. (2004), *National Wind Power Study: An estimate of readily acceptable wind energy in the National Electricity Market,* Report for the Australian Greenhouse Office, Canberra.

Outhred, H.R. (2004b), *The Evolving Australian National Electricity Market: An Assessment,* in Power Progress: An Audit of Australia's Electricity Reform Experiment, edited by Graeme Hodge, Valarie Sands, David Hayward and David Scott.

SEI. (2004), *Operating Reserve Requirements as Wind Power Penetration Increases in the Irish Electricity System,* ILEX Energy Consulting Report to Sustainable Energy Ireland, Dublin.

Slootweg, J.G. and Kling, W.L. (2004), *Modelling Wind Turbines for Power System Dynamics Simulations: an Overview,* Wind Engineering, Volume 28, Number 1, January 2004, pp. 7-25(19)

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

UK SDI (2005), *Wind Power in the UK,* Sustainable Development Commission Report, London.

WETAG. (2005), *Integrating Wind Farms into the National Electricity Market,* A discussing paper prepared by the Wind energy Technical Advisory Group for the Ministerial Council on Energy Standing Committee of Officials, Hobart.