LESSONS LEARNED FROM INTERNATIONAL WIND INTEGRATION STUDIES

AEMO WIND INTEGRATION WP4(A)

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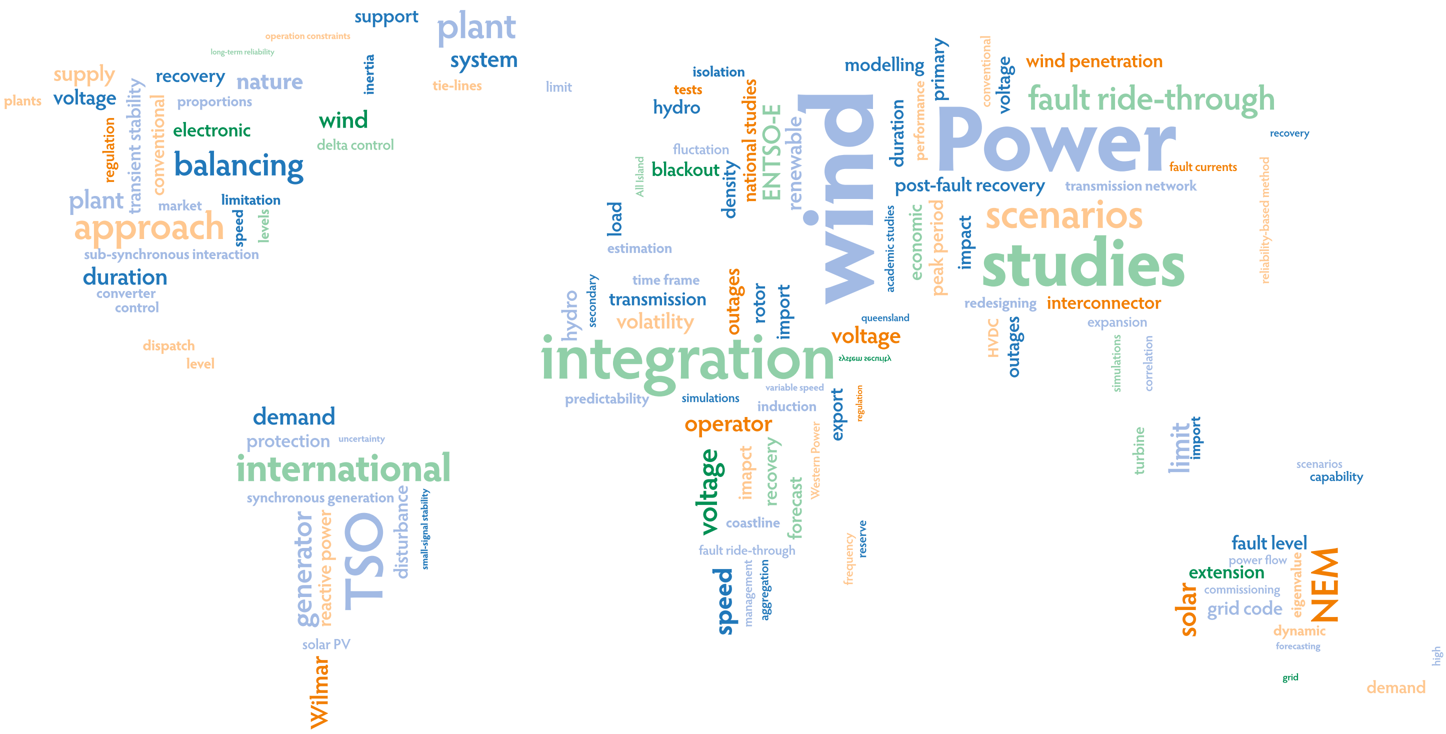

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EXECUTIVE SUMMARY

The Australian Energy Market Operator (AEMO) is expecting a significant increase in wind power generation in the Australian National Electricity Market (NEM). To accurately identify issues that might affect the NEM and adequately deal with the integration of wind power, AEMO solicited assistance from a number of international experts to research and report on international experiences and work being done on wind power integration. The work was divided into three work packages, to summarise and put into the context of the NEM:

1) experiences in wind integration across the world (WP1);
2) the implications on grid codes (WP2); and
3) the approaches used to assess the impact of increasing wind power generation on power system operations (WP4(A)).

energy**nautics** was selected to carry out the third task (Work Package 4(A)), to review experiences reported in various wind integration studies, with a specific focus on technical power system issues.

Issues that are considered major challenges for high penetration of wind power in a power system vary from region to region. Some of them may affect the security of the entire system while some of them may only affect local operation. In this context, the objectives of Work Package 4(A) are to:

- assess the key issues treated in wind integration studies worldwide;
- summarise the methodologies and general results of wind integration studies; and
- report on key lessons learned.

This work package is also to determine in conjunction with AEMO which of the key results and lessons are relevant to the NEM for consideration in future wind integration studies.

A. Technical issues typically considered

A broad review of wind integration studies around the world identified the issues commonly investigated, as listed in Figure 1 below.

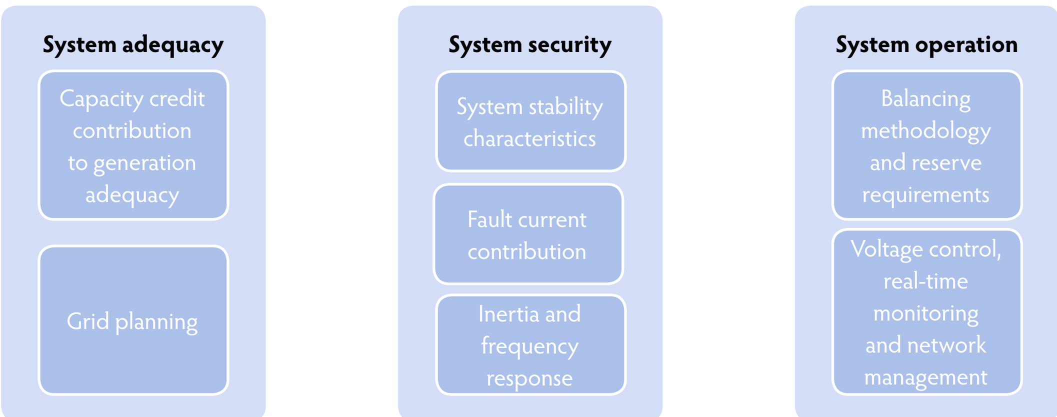

Figure 1: Overview of technical issues considered by wind integration studies. Source: energynautics

System adequacy: As wind power is added to a generation mix it may introduce an extra level of uncertainty in the ability of the power supply to meet load. This is particularly relevant for power systems where the peak load is expected to increase at the same time as conventional power plants to be replaced by intermittent renewable power generation. It is important that a reasonable estimation of the capacity credit of wind power is made so that adequate generation capacity can be secured to meet the future load. Furthermore, because wind power plants are often built in remote areas, grid extension and/or reinforcements are also often required. Since the lead time for construction of wind power plants is much shorter than that of transmission lines and conventional power plants, it becomes critical that grid augmentations are planned with significant foresight into political and industry intentions for the development of renewable energy based generation.

Capacity credit of wind power

Transmission planning for renewables integration

System security: Like all new generation, the addition of wind power may affect system stability and frequency response characteristics. The impact depends on the location, size, connection voltage level, and technical performance of the wind power plant. Most wind turbines use converters which decouple them from the grid, so direct impact on rotor angle stability is negligible. However, if the turbines displace significant proportions of synchronous generation they may have an indirect impact. The most significant impacts are seen following a voltage dip, which can cause wind power plants to disconnect if they do not have low voltage fault ride-through (FRT) capability (which is nowadays mandated by many Grid Codes around the world). When wind power generation is high and conventional power generation is displaced, the predominant oscillatory mode may be changed, or minimum system inertia might be required to control frequency excursions and maintain rotor angle stability. To ensure good security, the contribution that wind power plants make to fault currents must be assessed to ensure that the fault levels are adequate for the proper functioning of protection equipment and HVDC devices. Depending on the finding, this may require redesigning the protection scheme.

Fault ride-through and voltage support capability

Wind power plant contribution to fault levels

System inertia and frequency control

System operation: Wind power output depends on the wind speed (and weather) which is constantly changing. Wind forecasting helps to reduce the uncertainty inherent in nature and give a certain level of predictability for short-term planning and the generation dispatch process. Forecasting systems have improved significantly over the past years, however, forecast errors still exist, and may impact balancing and the requirements for reserves. While most systems are designed to handle some degree of uncertainty, it is prudent to assess the reserve requirements with wind power added to the system and make sure that the balancing procedures in place can manage the additional level of uncertainty. Many studies on wind integration found that high penetration rates are likely to increase both secondary and tertiary reserve requirements[1], even if forecast errors are minimised. The impact on secondary reserve is less compared to the latter, due to the fact that forecast errors get smaller the closer to dispatch. In some cases, especially in shorter time frames, price volatility in the power market may also cause severe impacts on reserve requirements.

Reserve requirements

Voltage control

1 The terminology for reserves varies between countries. In this report, secondary reserve corresponds to regulation reserve, defined as reserves made available in 5-15 minutes. Tertiary reserve corresponds to dispatch or load following reserve, available in 15-30 minutes and short-term capacity reserve, available in 30 minutes to some hours (and up to a day).

B. Measures that support wind integration

Several solutions are suggested to deal with the technical issues investigated. Some of the common measures are listed below:

- **Aggregating wind power plants** over a larger area to reduce the variability of wind power output and improve the capacity credit. This also improves the accuracy of wind power output forecasting, therefore reducing the requirements on balancing reserves.

- **Augmenting the grid** to increase access to wind power resources and share balancing resources over a wider area. This includes transmission reinforcements to relieve congestion, strengthening of tie-lines to facilitate power exchange between regions and extending the network to provide access to areas with excellent wind resources. Since it takes time to build transmission assets however, optimising the use of existing infrastructure using dynamic line rating, Flexible Alternating Current Transmission System (FACTS) devices and phase shifting transformers are suggested as a possible intermediate measure.

- **Implementing operation constraints** to secure minimum contingency and balancing reserves, system inertia, voltage support, fault current level and dynamic stability, so that synchronous generators can adequately provide these services. However, modern wind power plants can also provide many of these services and they should be included in the Grid Code if not already the case.

- **Real-time network management** based on wind power output can facilitate the transition from the current system to the future one. A good example is the control centre for renewable energies (CECRE) in Spain and Portugal, where aggregated control of wind power plants and other renewable energy generation such as solar power are used to calculate dynamic operating constraints.

Some studies evaluate the effectiveness of these measures, through market simulations in simple financial and environmental terms, such as the likely impact on market performance (costs and price volatility), and the resulting CO_2 emissions. In some studies operation efficiency is measured by network losses, the amount of unused (or curtailed) wind energy, and the cost impacts that high wind power generation has on the performance requirements of conventional power plants.

C. Relevance to NEM

Given the characteristics of the NEM and the expected wind power development in the NEM area, it was identified that some technical issues are likely to be more important than others. Figure 2 summarises the technical issues that have highest significance for future wind integration studies in the NEM.

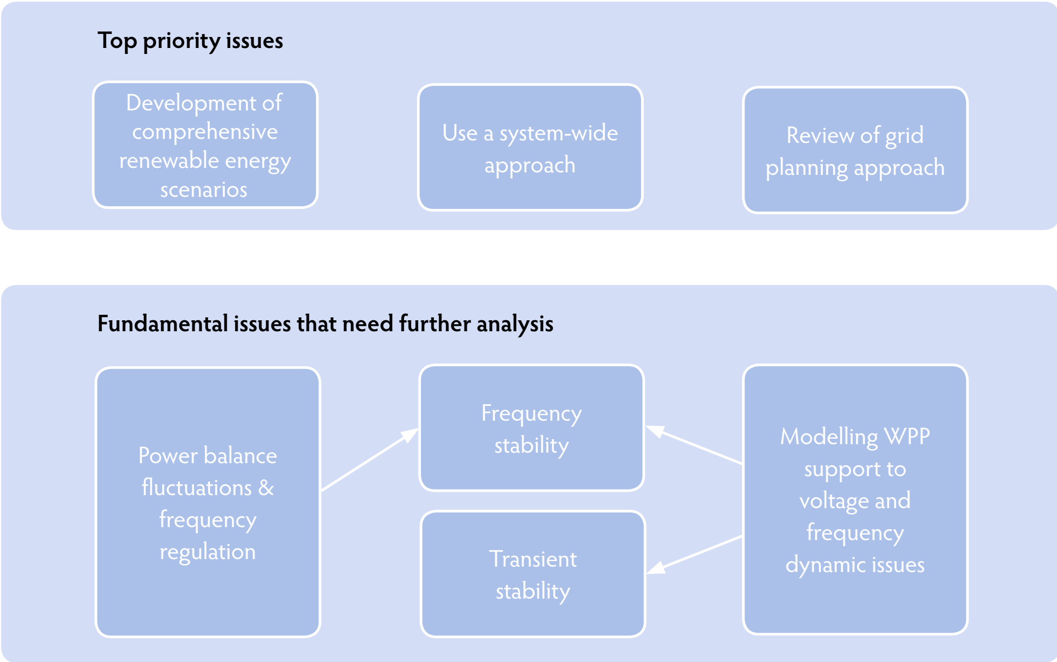

Figure 2: Overview of topics that should be considered by the NEM. Source: energynautics

Development of comprehensive renewable energy scenarios

In particular, discussions with various transmission systems operators indicated that solar PV growth should also be considered in renewable integration studies. For example, in Germany and Italy, the growth of solar PV has been so rapid that some giga-watts are connected in the distribution networks, and considerable challenges have been observed affecting voltage stability and balancing issues similar to those of wind.

Include solar PV in future studies

The Australian NEM only has a few hundred megawatts of solar PV power installed to date, however, policy support and development of larger scale solar PV plants in the planning pipeline could mean fast expansion in a short time frame. This could raise challenges in distribution and possibly transmission levels and it is recommended that solar PV is included in any future renewable energy integration studies for the NEM area.

Use a system-wide approach

It is recommended that generation adequacy, balancing and dynamic stability impacts of wind power are evaluated across the NEM rather than for individual states. Even though interconnections between states are currently limited, there are benefits that system-wide studies can bring in certain situations. For example, in the case of a storm front hitting the coastline of South Australia, there might be the risk that a large amount of wind power plants in the state are shut down consecutively within a few hours due to extremely high wind speeds exceeding the safe operating limits of the wind turbines. In this situation it may be more beneficial to allow import of reserve generation from another state rather than to secure it locally.

Investigate the benefits of a system-wide approach

Review of grid planning approach

The grid planning approach in the NEM is also important in integrating wind energy. With the current approach, much of the wind power resources that are available at remote areas will not be able to access the grid because they are likely to require grid extensions which are deemed more expensive than building conventional generation closer to the demand centre. However, in other countries and regions grid augmentations are considered in a broader policy context, with long-term security of supply and renewables integration as the primary objective. Unless the way the NEM plans grid augmentation is revised, long-term security of supply may be compromised.

Renewables integration as primary objective

Modelling wind power plant support capabilities

It is important that the ability of the wind power plant to support voltage and frequency are modelled appropriately when assessing frequency response and transient stability aspects. Some studies performed in the NEM assume the "worst case" scenario, that wind power generation is expanded using old turbine technology without voltage support capabilities. This is an unrealistic assumption, as the technology is developing towards providing more and more grid support capability options. Many turbines can now offer not only FRT capabilities but frequency control and virtual inertia capabilities. Therefore, it is recommended that a system-wide study is performed with a variety of turbine technology capabilities, and to test if the current Grid Code is sufficient for mixed turbines scenarios.

Wind turbine technology for grid support

Balancing and frequency regulation

Compared to many other power systems which settle generation bidding in a day-ahead market and manage the balancing with ancillary services, balancing issues in the NEM will be easier to deal with since it has a 5-minute dispatch market. However, this also indicates that the market prices will be subject to higher volatility with low prices resulting from high wind power generation and high prices from moments of low wind power generation. Therefore, it is important to investigate the impact on long-term price in markets for high penetration of wind power.

Market price volatility

Other issues

Other issues that may be investigated if the particular circumstances require it, are small-signal stability (for example, to test power system stabiliser capability of wind power plants), sub-synchronous interaction (if series-compensated lines are introduced to connect remote wind power plants) and the impact of wind power plant contribution to short-circuit fault current, especially for weakly connected parts of the network and to ensure correct operation of HVDC devices.

CONTENTS

ABBREVIATED TERMS

AEMO	Australian Energy Market Operator
CECRE	Control Centre of Renewable Energies
CREZ	Competitive Renewable Energy Zone
DFIG	Doubly Fed Induction Generator
DSM	Demand-side Management
DSO	Distribution System Operator
ENTSO-E	European Network of Transmission System Operators for Electricity
ERCOT	Electricity Reliability Council of Texas
FACTS	Flexible Alternating Current Transmission System
FCAS	Frequency Control Ancillary Services
FRT	Fault ride-through
FSFC	Full Scale Frequency Converters
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IMO	Independent Market Operator
ISO	Independent System Operator
LVRT	Low voltage ride-through
NEM	National Electricity Market
NTNDP	National Transmission Network Development Plan
NYISO	New York Independent System Operator
NYSERDA	New York State Energy Research and Development Authority
OPF	Optimal Power Flow
PSS	Power System Stabiliser
PUCT	Public Utility Commission of Texas
RES-E	Electricity from Renewable Energy Source
SCIG	Squirrel Cage Induction Generator
SSCI	Sub Synchronous Control Interaction
SSI	Sub Synchronous Interaction
SSR	Sub Synchronous Resonance
SSTI	Sub Synchronous Torsional Interaction
SVC	Static VAR Compensator
TSO	Transmission System Operator
TYNDP	Ten Year Network Development Plan
UPS	Uninterruptible Power Supply
VAR	Voltage-ampere Reactive
WPP	Wind Power Plant
WTG	Wind Turbine Generator

GLOSSARY

ASYNCHRONOUS GENERATOR	An asynchronous or induction generator is a type of AC electrical generator that uses the principles of induction motors to produce power.
CAPACITY CREDIT	See CAPACITY VALUE
CAPACITY VALUE	Also denoted as CAPACITY CREDIT. The amount of conventional generation that can be replaced by wind power capacity while maintaining existing level of supply security.
DELTA CONTROL	Fast secondary reserve made available by first down regulating the wind turbine by a certain delta applying pitch control, which can then be used to very fast up-regulate the wind turbine if needed.
DYNAMIC VOLTAGE CONTROL	Continuous voltage control by different generation resources.
FIRM GENERATION/ SUPPLY	Firm generation is the percentage of a generator's maximum capacity that is counted toward calculation of the reserve margin.
GENERATION RESERVE	Reserves to mitigate a contingency, which is defined as the unexpected failure or outage of a system component such as a generator, transmission line, circuit breaker, switch, or other electrical element.
HARMONIC DISTORTION	Harmonic distortion is found in both the voltage and the current waveform. Most current distortion is generated by electronic loads, also called non-linear loads. As the current distortion is conducted through the normal system wiring, it creates voltage distortion according to Ohm's Law.
INSTANTANEOUS MAXIMUM PENETRATION RATE	The instantaneous maximum penetration rate of wind power is calculated as the installed wind capacity divided by the off-peak demand.
INTERCONNECTORS	Interconnectors are transmission links (e.g. tie-line or transformer) which connect two control areas.

MAXIMUM FAULT	Largest possible single loss of generating capacity resulting from either forced outage of generation or transmission equipment.
MINIMUM SYSTEM INERTIA	The minimum system inertial constraint is analogous to imposing a constraint whereby a minimum number of synchronous generators must be online at all times ("must run units").
N1- SITUATION	The N-1 criterion is a rule according to which elements remaining in operation after failure of a single network element (such as transmission line/transformer or generating unit, or in certain instances a bus bar) must be capable of accommodating the change of flows in the network caused by that single failure.
POWER FLOW SIMULATIONS	Power flow simulations involve numerical analysis applied to a power system. It usually uses simplified notation such as a one-line diagram and per-unit system, and focuses on various forms of AC power (ie: voltages, voltage angles, real power and reactive power). A number of software power flow simulation tools exist such as DIgSILENT PowerFactory and Siemens PSS/E.
POWER VOLTAGE/ REACTIVE POWER VOLTAGE	Steady-state analysis of voltage stability limits is done by calculating the active power versus voltage (PV) curves and reactive power versus voltage (QV) curves for dispatches with zero exchange over interconnector.
PRIMARY, SECONDARY AND TERTIARY RESERVES	**Primary reserve** is to mitigate a contingency, which is defined as the unexpected failure or outage of a system component such as a generator, transmission line, circuit breaker, switch, or other electrical element. **Secondary reserve** is an amount of reserve that is sufficient to allow for normal regulating margins. Regulating reserves, which are responsive to AGC, are the primary tool for maintaining the frequency. **Tertiary reserve:** Capability above firm system demand required for regulation, load forecasting error, forced and scheduled equipment outages, and local area protection. This type of reserve consists of both generation synchronized to the grid and generation that can be synchronized and made capable of serving load within a specified period of time.

REACTIVE POWER	Reactive power is an imaginary component of the apparent power. It is the portion of electricity that establishes and sustains the electric magnetic fields of alternating-current equipment such as motors and transformers and causes reactive losses on transmission facilities. It is provided by generators, synchronous condensers, or electrostatic equipment such as capacitors and directly influences the electric system voltage.
REGULATION RESERVE	See SECONDARY RESERVE.
ROTATING INERTIA	The sum of all rotating mass inertias of the connected synchronous generation opposing a change of system frequency. The rotational speed of synchronous generators is an exact representation of the system frequency.
ROTOR ANGLE STABILITY	Rotor angle stability refers to the ability of synchronous machines of an interconnected power system to remain in synchronism after being subjected to a disturbance.
SINUSOIDAL VOLTAGE	A sinusoidal voltage waveform is one where the voltage as a function of time follows the trigonometric function sin(x).
STEADY-STATE ANALYSIS	Using power flow simulations to investigate the risk of system overload, voltage instability and (N-1)-safety problems.
STEADY-STATE STABILITY, TRANSIENT STABILITY AND OSCILLATORY STABILITY	Stability is the ability of an electric system to maintain a state of equilibrium during normal (steady-state) and abnormal system conditions or disturbances (transient). Oscillatory stability refers to the ability of the power system to damp oscillatory modes created by the interaction of generators connected to the power system.
SUB SYNCHRONOUS OSCILLATIONS	Shaft mechanical systems for large synchronous or induction motors and turbine generators can be subjected to severe torsional stresses due to triggered sub synchronous resonance (SSR) especially in electric grid networks with heavily series-compensated transmission lines.

SYNCHRONOUS GENERATOR	Synchronous generators are capable of converting mechanical energy into electricity when operated as a generator and power mechanics when operated as a motor. Synchronous generators are used in the majority of hydroelectric and thermoelectric plants.
TAP CHANGERS	A transformer tap is a connection point along a transformer winding that allows a certain number of turns to be selected. This means that a transformer with variable turns ratio is produced, enabling voltage regulation of the output. The tap selection is made via a tap changer mechanism.
TRANSIENT OVERVOLTAGE	Transient overvoltages are brief, high-frequency increases in voltage on AC mains.
TRANSIENT STABILITY	The ability of an electric system to maintain synchronism between its parts when subjected to a disturbance of specified severity and to regain a state of equilibrium following that disturbance.
UNITY POWER FACTORS	The power factor of an AC electric power system is defined as the ratio of the real power flowing to the load over the apparent power in the circuit, and is a dimensionless number between 0 and 1 (frequently expressed as a percentage, e.g. 0.5 pf = 50% pf).

1

INTRODUCTION

1. INTRODUCTION

The use of wind power for electricity generation is growing in many places around the world. Countries such as Denmark, Germany and Spain deal with a high penetration of wind power already today and are leading in their integration to the grid. Other countries which are showing strong growth and significant research activities are Ireland, UK, Scandinavia, South Australia and the USA. Although the current rate of penetration may be low, wind power is growing rapidly in China and India, and should be kept in mind.

Based on planning studies conducted by AEMO, wind power production is predicted to grow further in Australia. This is due to a combination of factors, namely the government's goal to achieve 20% of electric energy supply from renewables by 2020, the introduction of carbon tax, necessity to build more supply to cater for rising demand, and falling costs of building wind power plants which is making the investment more attractive.

According to the latest National Transmission Network Development Plan (NTNDP) published by AEMO in December 2010, the NEM could see up to 5,480 MW of wind power by 2020, with 2,177 MW in South Australia and 1,298 MW in Tasmania (1).

Like most power systems, the NEM is designed to deliver electricity from large-scale power plants with controllable outputs to large load centres located around the country. When intermittent power sources such as wind power are introduced in large quantities, this may impact certain existing regulatory, technical and market aspects.

To gain a better understanding of the possible impacts of increasing wind penetration in the NEM, AEMO contracted energynautics to investigate how other system operators around the world approach the uncertainty of possible wind integration, in particular, regarding technical issues related to power system operation.

Technical issues are typically investigated using power system studies based on simulation models of the power system in question, considering the expected future development, for instance future wind power installations. The details of the simulation model as well as the scenarios vary depending on the technical issues to be investigated.

To identify the relevant technical issues and possible methods to investigate them, as well their relevance to the NEM context, energynautics has reviewed selected power system studies performed by different Transmission System Operators (TSOs) and similar organisations around the world. Based on the review findings, this report develops key suggestions for possible similar studies to be conducted by AEMO in the near future.

This report (corresponding to work package 4(A)) forms part of the **AEMO Wind Integration Study: International Experience**, together with work packages 1 and 2, which cover general experience and grid codes for wind integration around the world respectively. Together these studies can be used to formulate future wind integration studies for the NEM.

2

STUDY APPROACH

2. STUDY APPROACH

A. Overview of NEM

In Australia, the National Electricity Market (NEM) is expecting significant growth in wind power generation. According to the latest figures from the NTNDP[2], up to 5,480 MW of wind is expected by 2020 predominantly in southern regions covering the states of Tasmania (TAS), Victoria (VIC) and South Australia (SA).

Since the geographic locations where wind power development is expected are remote from major demand centres (Figure 3), it is expected that much of the energy will have to flow through the high voltage transmission network. The transmission system of the NEM covers a very large distance and has relatively weak interconnection between states.

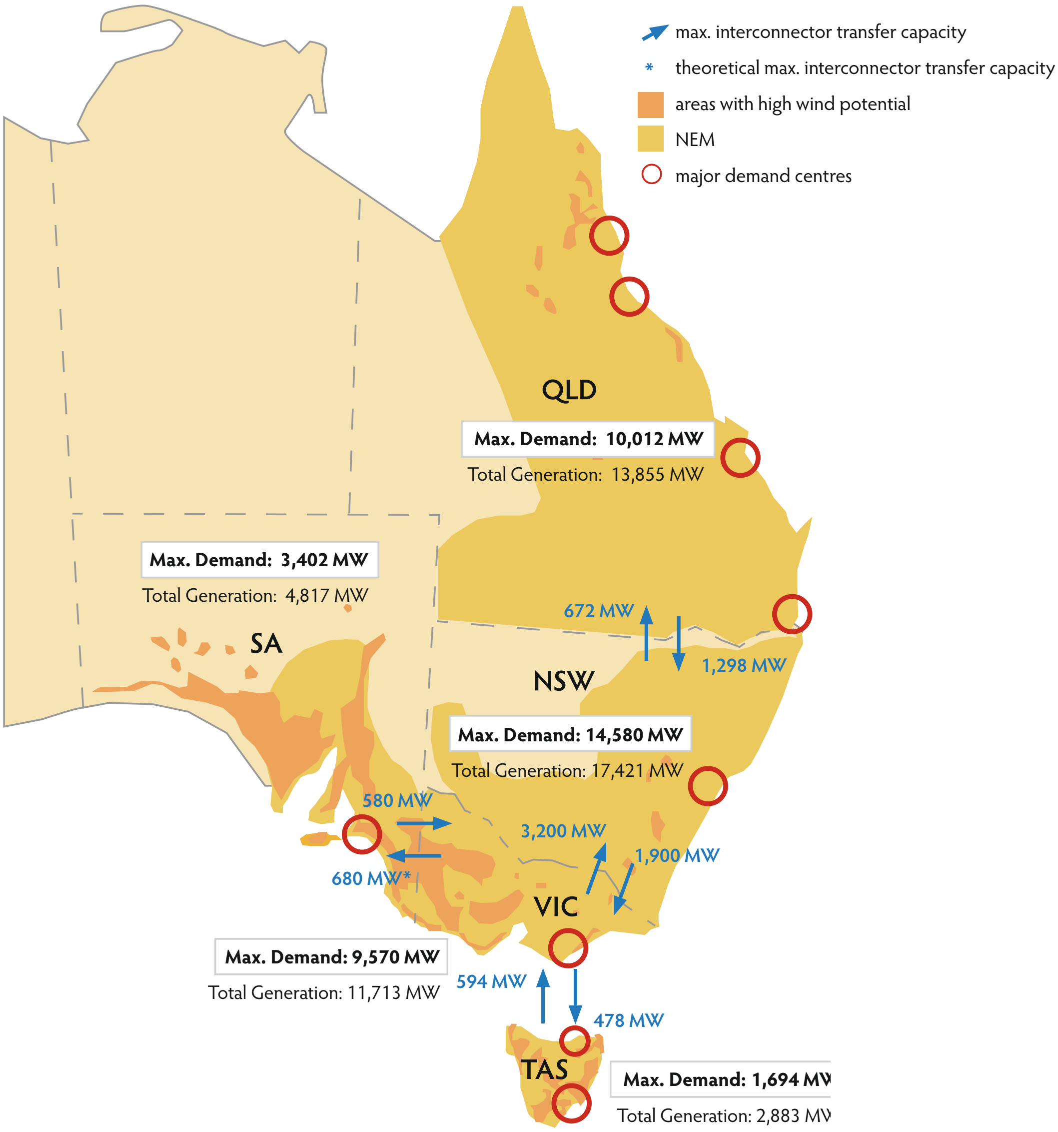

Figure 3: Map of interconnected regions of the NEM, with highlighted regions of expected wind development and demand centres. Modified from (1)

2 NTNDP is the National Transmission Network Development Plan published on a yearly base by AEMO. The latest version is available on: http://www.aemo.com.au/planning/ntndp.html

In the states where large wind power development is expected (SA and VIC), the high voltage transmission system will be subject to extremely high penetration rates. In fact, the instantaneous maximum penetration rate[3] in South Australia is already today one of the highest in the world for weakly interconnected network areas, with over 80% instant penetration level (without considering interconnector flow) observed. This can be seen in Table 1, where the instantaneous maximum penetration with and without interconnectors are compared for the states within the NEM and a number of selected power systems which are known to be almost island systems with high penetration of wind power generation. As it stands in 2011, the instantaneous maximum penetration of wind power in South Australia is comparable to that experienced in the interconnected power system of Ireland and Northern Ireland.

Year	System[4]	Installed wind capacity (MW)	Off-peak demand (MW)	Theoretical instantaneous maximum penetration without interconnector[5]	Theoretical instantaneous maximum penetration with maximum export[6]
2011	SA	1,019	859	119% (observed: >80%)	71% (observed: 54%)
	TAS	223	776	29% (observed: 17%)	16% (observed: 10%)
	VIC	531	3,718	14% (observed: 8%)	7% (observed: 6%)
	NSW	186	5,739	3%	2%
	QLD	12	4,371	0%	0%
2020	SA	2,177	1,247	175%	105%
	TAS	1,298	948	137%	84%
	VIC	1,390	5,062	27%	14%
	NSW	536	6,935	8%	5%
	QLD	79	6,918	1%	1%

3 The instantaneous maximum penetration rate of wind power is calculated as the installed wind capacity divided by the off-peak demand.

4 Information corresponding to the NEM was taken from (122) or through correspondence with AEMO.

5 Calculated values: Installed wind capacity / Off-peak demand

6 Calculated values: Installed wind capacity / (Off-peak demand + Maximum export capacity)

Year	System[4]	Installed wind capacity (MW)	Off-peak demand (MW)	Theoretical instantaneous maximum penetration without interconnector[5]	Theoretical instantaneous maximum penetration with maximum export[6]
2011	All Island[7]	1,889[8]	1,664[9]	114%	108%
	Iberian Peninsula	24,378[10]	19,205[11]	127%	118%
	ERCOT[12]	9,500[13]	22,426[14]	42%	41%
	Québec	675[15]	19,143[16]	4%	2%
2020	All Island	5,962[17]	1,678	355%	264%
	Iberian Peninsula	38,000[18]	19,205	198%	184%
	ERCOT	19,500[19]	22,426	87%	69%
	Québec	4,000	19,143	21%	14%

Table 1: Installed wind power capacity and penetration with and without interconnectors for the NEM and some selected systems. Source: Various, see footnotes.

Without any substantial plans for increasing the interconnector capacity, the theoretical maximum penetration rates in Tasmania and South Australia will reach levels comparable to those of the Iberian Peninsula[20] by 2020, where concrete plans already exist for increasing the interconnector transfer capability. While there are some tentative plans in the NEM to enhance the interconnection between states (Table 2), wind power penetration levels in selected states will be some of the highest in the world.

7 All Island refers to the interconnected power system of Ireland and Northern Island.

8 Source: http://www.iwea.com/index.cfm/page/barchart (Accessed 26/9/2011)

9 Source: http://www.eirgrid.com/media/Transmission%20Forecast%20Statement%202011-2017-web%20version2.pdf

10 Figures at end of 2010 according to GWEC: http://www.gwec.net/index.php?id=9 (Accessed 26/9/2011)

11 Corresponding to 24/4/2011, RED ELECTRICA: http://www.ree.es/ingles/operacion/curvas_demanda.asp and REN: http://www.centrodeinformacao.ren.pt/EN/InformacaoExploracao/Pages/DiagramadeCargadaRNT.aspx

12 ERCOT (Electricity Reliability Council of Texas) refers to the interconnected system of Texas, USA.

13 Source: http://www.ercot.com/content/news/presentations/2011/ERCOT%20Quick%20Facts%20-%20March%202011.pdf

14 According to the Ancillary Services Requirement Report by GE Energy (70) Page 3-28.

15 Source: http://www.hydroquebec.com/generation/index.html

16 Peak: 38,286 MW according to Annual Report 2010 (http://www.hydroquebec.com/publications/en/annual_report/pdf/rapport-annuel-2010.pdf), (110) estimates minimum load to be half of maximum, therefore 38,286/2 = 19,143 MW.

17 4350 MW in Ireland + 1012 MW onshore + 600 MW offshore wind in Northern Ireland. Source: http://www.eirgrid.com/media/GCS%202011-2020%20as%20published%2022%20Dec.pdf

18 Source: http://www.gwec.net/index.php?id=131 (Accessed 26/9/2011)

19 Source: http://www.seco.cpa.state.tx.us/re_rps-portfolio.htm (Accessed 26/9/2011)

20 Iberian Peninsula refers to the interconnected region of Spain and Portugal.

Interconnection[21]	Maximum export/import capacity for 2011 (MW)	Export/import upgrade (MW)	Expected commissioning
NSW to QLD	672/1,298	300/600	2010/11 to 2014/15
VIC to NSW	3,200/1,900	0/500	2010/11 to 2014/15
VIC to SA	680/580	240/250	2025/26 to 2029/30
TAS to VIC	594/478	0	Not applicable
All Island	80/450[22]	500	2011[22]
Iberian Peninsula	500 (+900)/1,300 (+600) [23]	1,500 2,700	2014[24] 2020 +
ERCOT	860[25]	5,000[26]	Information not available
Québec	8,060/11,050[27]	1,200[28]	2015

Table 2: NEM interconnector upgrade plans compared with other selected regions. Source: Various, see footnotes.

21 Information corresponding to the NEM was provided by James Lindley based on NTNDP modelling data.

22 NTC values for winter 2010/2011 published by ENTSO-E: https://www.entsoe.eu/fileadmin/user_upload/_library/ntc/archive/NTC-Values-Winter-2010-2011.pdf

23 NTC values for winter 2010/2011 published by ENTSO-E. Figures in brackets correspond to export/import to Morocco.

24 Expected commissioning according to the Ten Year Network Development Plan published by ENTSO-E, available on: https://www.entsoe.eu/index.php?id=232

25 The ERCOT control area is not synchronously connected to the Eastern or Western Interconnection but it can exchange about 860 MW with the Southwest Power Pool and Mexico through DC links. Source: http://www.ferc.gov/market-oversight/mkt-electric/texas.asp#inter (Accessed 26/9/2011)

26 This figure corresponds to the proposed Tres Amigas project, which will link the Eastern Interconnection, Western Interconnection and the ERCOT system. Source: http://www.tresamigasllc.com/docs/ERCOT_TA.pdf

27 Values published by Hydro Québec on: http://www.hydroquebec.com/transenergie/en/index.html (Accessed 26/9/2011)

28 Project to increase the energy interchange capacity between Québec and New England by building a 1,200-MW interconnection to link Québec's power grid with new Hampshire's. Commissioning is scheduled for 2015. Source: http://www.hydroquebec.com/projects/new-hampshire.html (Accessed 26/9/2011)

B. Wind power integration studies

Wind power integration studies are important for power systems expecting large wind power developments. Prominent studies have been performed in Europe and North America covering system-wide issues as well as country (or state) based issues, while a myriad of academic studies has been published in journals dealing with specific issues on a more general basis.

The approach used in WP4(A) for the review of international wind integration studies is shown in Figure 4.

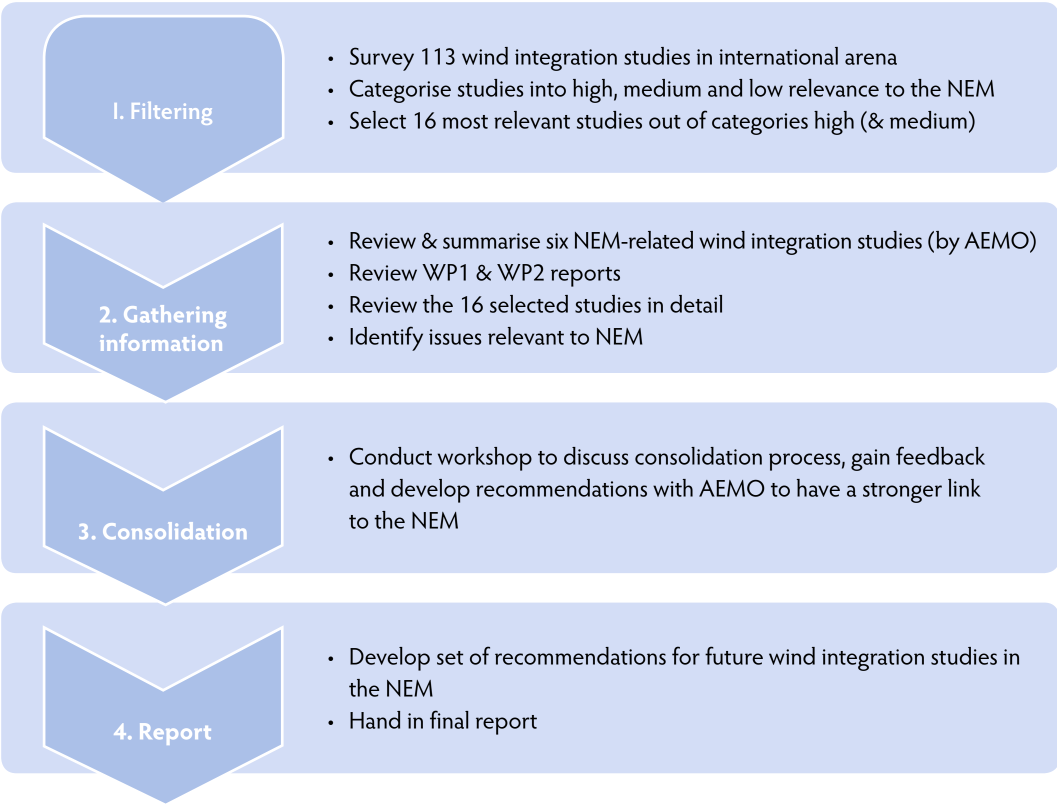

Figure 4: Outline of approach for WP4(A). Source: energynautics

First, studies investigating wind integration issues were surveyed from various regions of the world where wind power has seen significant growth. In total 113 studies were selected, varying from region-wide system studies to academic papers on specific integration issues. Step 1

These studies were ranked as having a high, medium or low relevance to the purpose of this work package, which is to identify technical issues and approaches that are likely to be important for a wind integration study for the NEM. In determining the ranking, factors such as the level of similarity of the study region to the NEM (island systems or weakly interconnected power systems), the level of wind penetration assessed in the study and the level of coverage of technical issues were considered. AEMO staff were involved in this process, to add an insight based on actual experience with the NEM.

From the complete list of studies, 16 were selected to ensure that all key technical issues were discussed in some way. In this process, focus was placed on island systems with weak interconnections to neighbouring systems like Ireland, Spain and Portugal, Texas, Québec, Western Australia and New Zealand.

In addition, studies from the New York ISO were reviewed due its similarity with the NEM, in having a 5-minute real-time market in conjunction with a day-ahead market.

Table 3 lists the selected 16 studies selected. A more detailed list can be viewed in Appendix 8.1.

Study Area	Organisation (and consultant)	Date published	Name
NATIONAL/SINGLE AREA STUDIES			
ERCOT (Texas, USA)	Electricity Reliability Council of Texas (GE Energy, ABB)	2008-03 2010-12	Analysis of Wind Generation Impact on ERCOT Ancillary Services Requirements, GE Energy. ERCOT CREZ Reactive Power Compensation Study, ABB.
Hydro Québec (Canada)	Hydro Québec (Hydro Québec , RE Power)	2009-10 2010-10	Assessment of AGC and Load Following Definitions for Wind Integration Studies in Québec, I. Kamwa, et al., Article in Proceedings: 8th International Workshop on Large Scale Integration of Wind Power and on Transmission Networks for Offshore Wind Farms 255-265. A New Simulation Approach for the Assessment of Wind Integration Impacts on System Operations, M. de Montigny, et al., Article in Proceedings: 9th International Workshop on Large Scale Integration of Wind Power and on Transmission Networks for Offshore Wind Farms 460-467. Frequency Control in Québec with DFIG Wind Turbines, M. Dernbach, et al., Article in Proceedings: 9th International Workshop on Large Scale Integration of Wind Power and on Transmission Networks for Offshore Wind Farms 342-347.
Transpower (New Zealand)	New Zealand Electricity Commission (Transpower System Operator)	2007-03 – 2008-06	Wind Generation Investigation Project (WGIP), Transpower NZ.
Western Power (Western Australia)	Western Power	2010-01	Effects of increased penetration of intermittent generation in the SWIS.

Study Area	Organisation (and consultant)	Date published	Name
Germany	Deutsche Energie-Agentur GmbH (DEWI, E-ON Netz, EWI, RWE, Vatenfall)	2005-02 2010-11	DENA Grid Study I: Energy Management Planning for DENA Grid Study I: Energy Management Planning for the Integration of Wind Energy into the Grid in Germany, Onshore and Offshore by 2020. DENA Grid Study II: Integration of Renewable Energy Sources in the German Power Supply System from 2015-2020 with an Outlook to 2025.
NYISO (New York, USA)	The New York State Energy Research and Development Authority and New York Independent System Operator (GE Energy, NYISO)	2005-03 2010-09	The Effect of Integrating Wind Power on Transmission System Planning, Reliability and Operations, GE Energy. Growing Wind: Final Report of the NYISO 2010 Wind Generation Study, NYISO.
Minnesota (USA)	Minnesota Department of Commerce Office of Energy Security (The Minnesota Transmission Owners)	2008-06	Minnesota Dispersed Renewable Generation Transmission Study Vol. I, II and III.
IMO (Western Australia)	Independent Market Operator (ROAM Consulting, McLennan Magasanik Associates, Sinclair Knight Merz)	2010-08 – 2010-11	Renewable Energy Generation Working Group: Summary of Processes and Outcomes, IMO Work Package 1: Scenarios for Modelling Renewable Generation in the SWIS, ROAM Consulting. Work Package 2: Reserve Capacity and Reliability Impacts, McLennan Magasanik Associates. Work Package 3: Assessment of FCS and Technical Rules, ROAM Consulting. Work Package 4: Technical Rules, Sinclair Knight Merz.

REGIONAL STUDIES			
Iberian Peninsula (Spain and Portugal)	Red Eléctrica España, Spain Rede Eléctrica Nacional, Portugal	2005-05	Study of Wind Energy Stability in the Iberian Peninsula (Confidential)[29]
All Island (Ireland and North Ireland)	Governments of Ireland and North Ireland (TNEI) EirGrid (Ecofys and DIgSILENT)	2008-01 2010-06	All Island Grid Study: Transmission Network Assessment for All-Island Grid Study (WS3), TNEI. All Island TSO Facilitation of Renewables Studies, Ecofys and DIgSILENT GmbH.
Northern Europe	Risoe National Laboratory (SINTEF)	2005-11	Wind Power Integration in a Liberalised Electricity Market (WILMAR): System Stability Analysis (WP5), SINTEF.
Europe	ENTSO-E and European Commission (ENTSO-E)	2010-03	European Wind Integration Study (EWIS): Towards a Successful Integration of Large Scale Wind Power into European Electricity Grids
SPP (USA)	Southwest Power Pool (Charles River Associates)	2010-01	South West Power Pool Wind Integration Study
ACADEMIC STUDIES			
IEA25 (Global)	International Energy Agency (VTT)	2009	IEA Wind Task 25 Phase I 2006-2008, H. Holttinen, et al., 2009.
Reserves (Global)	NREL	2010-10	Operating Reserves and Wind Power Integration: An International Comparison, M. Milligan, et al., National Renewable Energy Laboratory.
SC current (General)	NREL	2010-10	Wind Power Plant Short-Circuit Current Contribution for Different Fault and Wind Turbine Topologies, V. Gevorgian, et al., National Renewable Energy Laboratory.

Table 3: Overview of selected wind integration studies. Source: energynautics

As seen from the Organisation (and consultant) column, most of the system-wide studies are financed by the governments or transmission system operators (TSOs). This reflects the fact that wind power development is mainly driven by political initiative while the responsibility for ensuring a secure supply to customers lies on the shoulders of the system operator. Therefore it makes sense that many studies are co-financed by these two bodies. Either TSOs in cooperation (in the case of EWIS) or independent consultants (in the case of ERCOT) are contracted to actually perform the studies so as to promote information sharing under confidentiality agreements and to have an unbiased view.

29 Some European studies are not published in the public domain due to confidentiality issues. Information regarding the methodology and results has been obtained as best as possible by energynautics based on summary reports and through dialog with relevant European TSOs.

The second step (Figure 4) was to review the selected studies in detail. Focus was placed on extracting information about the types of issues investigated in each study, the methodologies used, assumptions made, and the main conclusions drawn from the results. Figure 5 shows a list of issues commonly considered in wind integration studies. The dots marked in the figure correspond to the issues considered by the studies for the regions which are considered most relevant to the NEM. It shows the technical issues that are investigated in local or system-wide studies, as well as the timeframe for corresponding simulations.

Step 2

It can be seen that the most studied aspects are the impacts of wind power on balancing and reserve requirements, as well as voltage stability. The former is because it is recognised that an increase in reserve requirements can have large financial implications, while the latter is concerned with system security. In actual fact, voltage stability studies have lead to much of the recent developments in Grid Codes regarding fault ride-through requirements. Also of high concern are long-term planning issues, such as generation and grid adequacy.

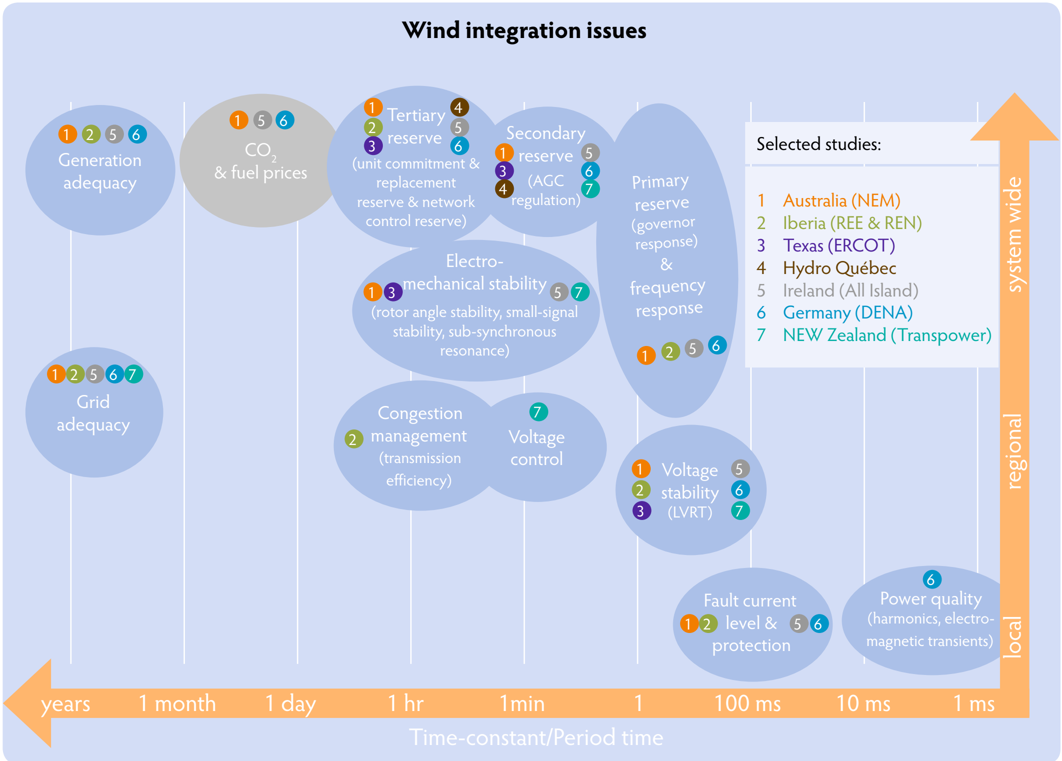

Figure 5: Overview of technical issues considered by wind integration studies. Source: energynautics

This information was synthesised with the findings from WP1 and WP2, as well as detailed summaries of wind integration studies already conducted in the NEM region, to draw out the key issues related to system-wide wind integration studies as well as the common approaches used to investigate each of the technical issues identified.

Table 4 below gives a summary of the six NEM studies reviewed.

Study area	Organisation (and consultant)	Date published	Name
South Australia	ElectraNet	2008-12	Internal ElectraNet Report
Victoria	VENCORP [now AEMO]	2007-12	Capacity of the Victorian Electricity Transmission Network to Integrate Wind Power
Tasmania	Transend	2009-05	Future wind generation in Tasmania study
South Australia	NEMMCO [now AEMO] (DIgSILENT)	2005-06	Assessment of Potential Security Risks due to High Levels of Wind Generation in South Australia - Stage 1.1
NEM	Clean Energy Council (ROAM Consulting)	2010-04	Transmission Congestion and Renewable Generation
South Australia	Electricity Supply Industry Planning Council	2003-03	South Australia Wind Power Study

Table 4: Overview of wind integration studies in the NEM. Source: AEMO

As with other wind integration studies around the world, the studies within the NEM are often commissioned by the TSOs. However, the studies focus on issues within a single state only and there are no prominent studies that cover NEM-wide issues. A more detailed list can be viewed in Appendix 8.2.

Step 3

Step three involved detailed discussions with AEMO staff in a workshop to put the intermediate findings in the perspective of the NEM. The workshop discussed key issues and conclusions from the investigation and sought to identify the aspects that are relevant for the NEM, which of these have not yet been adequately investigated, whether the study approaches can be adopted for the NEM and what assumptions can be made for each specific investigation.

Final step

Having put the analysis in the context of the NEM, the final step involved presenting the consolidated information in a report for the public domain, as well as an internal report. The report presents issues most relevant to wind integration in the NEM, and recommends approaches that could be adopted by AEMO to investigate them.

3

KEY TECHNICAL ISSUES

3. KEY TECHNICAL ISSUES

The following sections form the main body of analysis, describing each issue listed in Figure 5 in detail. Common methodologies adopted and the findings of wind impact studies are reported in order to draw conclusions on whether they are applicable to the NEM context. These conclusions should allow a set of recommendations to be developed for how AEMO can undertake a NEM-wide wind integration study in the future.

3.1. GENERATION ADEQUACY

The issue: Power systems must have adequate capacity to supply and deliver power required by customers at any time. The capacity of supply is dictated by the availability of the source. For conventional power plants this can be assumed to be constant at the level it is designed to operate, however, for wind power plants it is inevitably variable, as with other intermittent renewable energy generation such as hydro and solar power. Further to this, all power plants are subject to scheduled maintenance, therefore cannot be available all of the time. Therefore, for a system to be adequate there must be sufficient generation to cover demand during periods of low generation availability, while at the same time cover for critical contingencies such as the sudden loss of the largest power group delivering to the system[30]. With the peak demand projected to grow in the NEM (as with many other countries in the world), generation capacity must be expanded.

Possible impact of increasing wind penetration: The uncertainty resulting from wind intermittency and long-term wind forecasting makes it challenging to determine how much wind power will actually be available and can be considered as 'firm' generation capacity. This can become an issue when wind power replaces conventional power generation, because an underestimation of firm wind capacity will cause an over-supply in the system, implying redundant investment, while an overestimation could lead to power shortages. In addition, with wind power expected to replace retiring conventional power plants, the largest power group for assessment of contingency reserve may become a group of wind power plants, and, there may be fewer units that can provide contingency reserve.

Typical methods used for studying the issue: To estimate generation adequacy, each power plant is assigned a capacity credit, which indicates the likelihood of the generator being available when it is needed. According to the NERC 2009 report[31], the capacity credit of a wind power plant can be determined in two ways:

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- **Reliability-based method:** Estimation of the Effective Load Carrying Capacity (ELCC) of wind generation based on calculation of reliability metrics; and
- **Approximation method:** Calculation of the capacity factor of wind generation during specified time periods that represent high-risk reliability periods (typically peak hours).

The most recommended method, both by the IEA Task 25 report[32] and the NREL report[33], is the reliability-based method.

Reliability-based method

Assessment of generation adequacy is often based on reliability metrics such as Loss of Load Expectation (LOLE), Loss of Load Probability (LOLP) or Loss of Energy Expectation (LOEE), which indicate the likelihood that system load will not be met by the available generation at a given time. The level of reliability required is often expressed in terms of a percentage or maximum hours per year that generation cannot meet load, and is typically determined by the power system operator.

Using these metrics, the capacity value of wind can be estimated by calculating the Effective Load Carrying Capacity (ELCC), which is the amount of additional load that can be served at the target reliability level with the addition of the generator being considered. This may also be compared relative to a perfectly-reliable generating unit or a benchmark conventional unit (5).

Significant data and rigorous analysis is required to determine the capacity value of wind power generation using this method. For example, for a chronological method as described in the IEA Task 25 report (2), hourly or sub-hourly load and wind generation data covering a period of 10-30 years would be required to accurately estimate the capacity credit. In the case where extensive data is not available, wind data from numerical weather prediction models can be used to produce wind speed estimates to the required level of detail. This can then be converted to realistic representations of large scale wind power production. An alternative approach, to use sequential Monte Carlo to simulate wind generation retaining diurnal and seasonal characteristics has been used in Iberia[34] and the All Island Grid study[35], however, this method is not recommended[36] unless the process is benchmarked against several years of actual wind data.

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33 (7) Page 26
34 (47) Page 77
35 (121) Pages 53-55
36 (7) Page 10

Another approach in the reliability-based method is to use frequency distribution or duration curves. This approach immediately converts wind power time series into probability density of power levels, to be combined with the probabilities of conventional power stations' availabilities (2). The DENA study uses this approach (6), which uses probability distributions of wind and conventional power to calculate how much conventional power can be replaced with wind without compromising the level of reliability.

Capacity value is sensitive to the timing of wind energy delivery relative to peak load periods. Correlation of wind generation and load is difficult to calculate, therefore, it is important to use wind and load profiles that come from a common weather driver to calculate capacity value, such as historical data. In addition, data from several years is preferred to a single year because there is often significant variability in wind ELCC from year to year (7).

<u>Approximation method</u>

The approximation method calculates the wind capacity value as the capacity factor achieved by wind generation in peak periods. This method is not as accurate as the reliability-based method, but is used in several studies because it requires less intensive calculations and not as much data. This method is predominantly used in the USA (2). The study performed by NYSERDA on New York ISO (5) demonstrates this method by calculating the wind capacity factor during peak periods between 2 to 6 pm from June through to August, and 4 to 8 pm from December through to February (2). The capacity credit calculated with this approximation method is compared with a number of other methods including a reliability method based on three years of data.

A summary of the data requirements for each method is shown in the following Figure 6.

	Cronological	Frequency distribution	Approximate
Load	Time series data • hourly, etc. • 10 - 30 years	Load duration curve	Peak load
Wind	Time series data coupled with load	Probability density, varying by month or season	Capacity factor at peak load
Conventional generation	• Usable capacity • Forced outage	Probability distribution	N/A

Figure 6: Data requirements for typical methods to calculate wind power capacity credit. Source: energynautics

International experience: Many wind integration studies investigate wind impact on generation adequacy. Of the studies reviewed, these include the DENA study, the studies in NYISO, the All Island Grid study, studies in the Iberian Peninsula, IMO in Western Australia, as well as other prominent studies such as the Western Wind and Solar Integration Study (3) and Eastern Wind Integration and Transmission Study (4) (not reviewed).

Table 5 gives a summary of the level of capacity credits calculated by each of the studies.

Study	Capacity credit (method)
IEA25[37]	5-40%
Spain[38]	10% (Monte Carlo)
All Island[39]	20% (ELCC/Monte Carlo)
DENA	5-6% (Duration curve)
New York ISO[40]	10% (Peak Period)
ESIPC[41]	8% (Peak Period)

Table 5: Capacity credit calculated in each study reviewed. Source: Various

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38 According to article by Red Eléctrica Spain due to be published in Wind Power in Power Systems, Ed. 2, Editor Thomas Ackermann

39 (121) Page 21 and 25

40 (2) Page 89

41 (10) Page 4

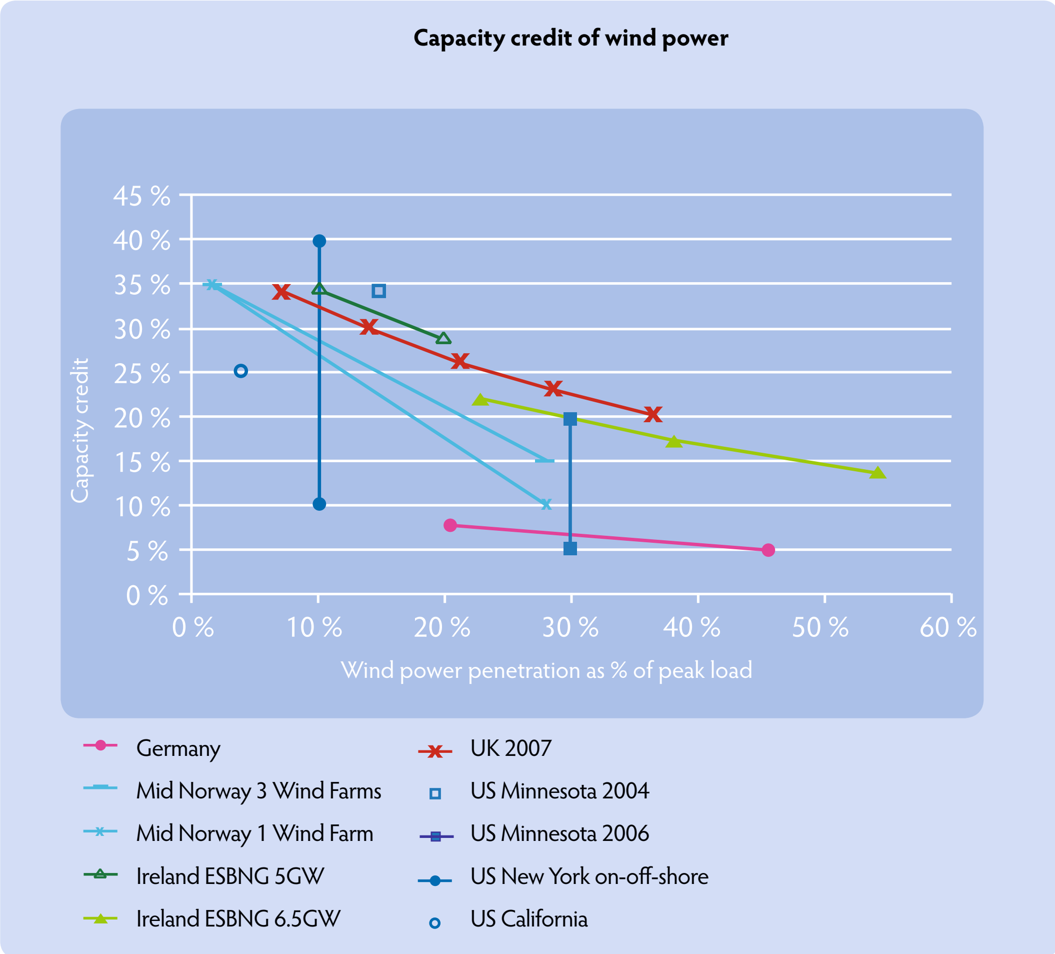

Figure 7: Capacity credit of wind power. Source: Reproduced with permission from (2) Page 185

It can be seen from Figure 7 that capacity credit reduces with higher penetration levels. However, this does not necessarily mean that less conventional capacity can be replaced by wind power, but rather that a new wind plant added to a system with high wind power penetration levels will substitute less than the first wind plants in the system (9).

Conclusions: Capacity credit calculations for wind power can be adapted to reliability calculation methods used by the system operator. However, to accurately assess the impact of the forecast error of wind generation on reliability requires data that demonstrates wind production characteristics coupled with system demand. Monte Carlo methods are often used to regenerate wind power data in cases where real measurement-based data is lacking, however, this is at a compromise of accuracy since there will be a weaker correlation with load.

Although it is easy to demonstrate how wind power contributes to energy adequacy, it is more difficult to ascertain the contribution to power demand adequacy because wind (and weather) is uncertain and variable. This can be mitigated to some level by aggregation across wider geographic areas (e.g. covering different balancing areas) and coupling with storage options or demand-side management, however, inevitably results indicate that the higher the penetration level of wind power the lower the capacity credit[42].

In addition, with variable forms of generation like wind and solar PV expected to replace conventional forms of generation, rather than be built in addition to it, the generation that contributes to contingency reserve may be reduced.

Relevance for NEM system: The 2003 South Australian Study by ESIPC (10), makes a comparison of the capacity factor resulting from calculations based on peak load periods, an all hour analysis, and a summer peak hours analysis. It was found that while the average output from wind power is higher during the summer peak hours, it does not necessarily provide more power during the periods of peak load. It concludes that the contribution from wind generation during the peak hours of the summer months is not sufficiently reliable to be considered 'firm' supply.

In the context of the NEM, the capacity factor for wind power in each State is calculated by comparing the average historical wind generation output with its rated capacity. The ability to meet seasonal maximum demand is calculated from the minimum level of output available at least 85% of the time during the top 10% of the seasonal demands in a region[43].

Based on international experiences, this conclusion should be revised as most international studies consider a capacity credit for wind power. It is particularly important to consider the whole NEM area for capacity credit calculation of wind power.

Recommendations: The calculations used to determine the contribution of wind generation in reliability studies should be based on a reliability calculation method rather than a simplified method as it gives a more accurate indication of the firm contribution of wind power generation to generation adequacy. However, extensive data is required that demonstrates wind production characteristics coupled with system demand. Therefore, AEMO should select the most appropriate methodology based on:

- the mandated level of reliability,
- type of data available, and
- the amount of wind penetration expected.

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43 (122) Page 12

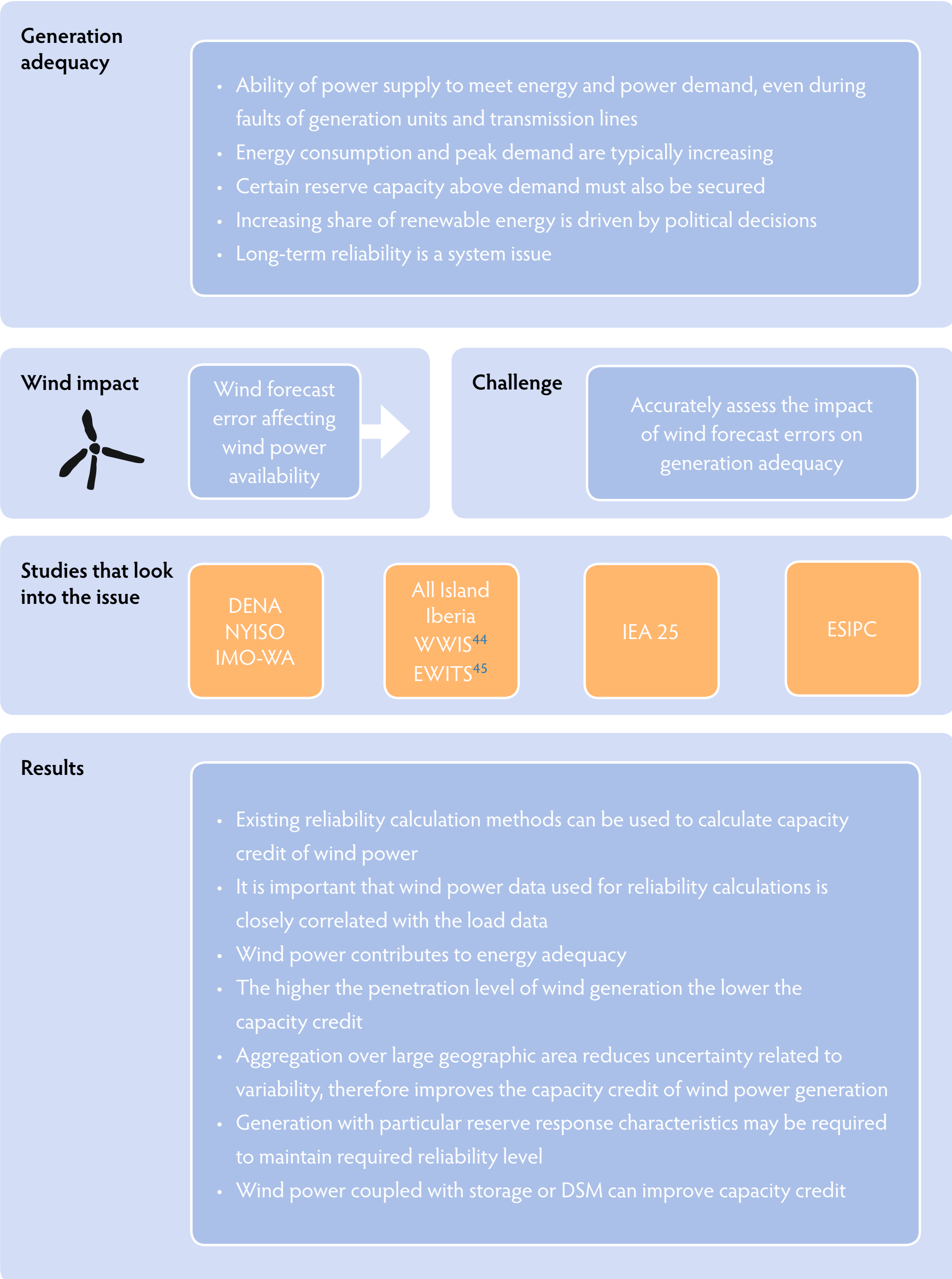


Figure 8: Summary of issues involving generation adequacy. Source: energynautics

44 Western Wind and Solar Integration Study

45 Eastern Wind Integration and Transmission Study

3.2. GRID PLANNING

The issue: Even if there is sufficient generation capacity, if it cannot be delivered to the consumers, the system is still not adequate. Therefore, ensuring sufficient delivery capacity is also part of power system adequacy. Power flow in a system can be limited due to thermal and voltage equipment ratings, reactive power reserve requirements and the dynamic characteristics of the network. The grid must be designed so that supply can be delivered to consumers without violating any of these limits. It is also important to build in a certain level of redundancy to cover for contingency situations such as when there is a fault on a transmission line (N-1 situation).

Possible impact of increasing wind penetration: These impacts are not unique to wind power; they are part of standard grid planning practices. However, wind power is often available in remote locations requiring grid extensions or they are connected to the distribution rather the transmission network, which is more susceptible to voltage issues. Due to the short construction lead-time of wind power compared to conventional power plants and transmission equipment, it is important to understand potential problems and prepare mitigation for high wind penetration even if it is anticipated in some years' time.

Typical methods used for studying the issue: Transmission planning studies are typically based on steady-state load flow and voltage analysis for future generation scenarios. In some cases (typically in Europe), focus is placed on the available transfer capability between balancing areas, while investigations into the dynamic stability limits would be required for detailed planning studies.

International experience: Most studies assess the impact of wind power generation on the transmission grid in order to identify reinforcement efforts that will be required to support the future integration of wind power. Of the studies reviewed, these include the DENA study (6), the Transpower wind integration study (11), All Island Grid study (12), studies of the Iberian power system[46], EWIS (13), as well as Southwest Power Pool (14) and New York ISO (15) in the USA.

There is a general tendency in Europe (with the exception of the Iberian Peninsula and offshore projects) for wind power plants to be connected at the distribution level, while in the USA the power plants are larger in size (and often remote in location) hence connected to a higher voltage network. This explains why distribution codes and voltage support requirements for wind power plants have been developed and adopted rapidly in European countries, whereas large transmission projects have been seen predominantly in the USA.

46 Summaries of the Study of Wind Energy Stability in the Iberian Peninsula by Red Eléctrica España, Spain and Rede Eléctrica Nacional, Portugal available on:
http://www.ewec2006proceedings.info/allfiles2/743_Ewec2006fullpaper.pdf
http://onlinelibrary.wiley.com/doi/10.1002/we.253/pdf

In Texas (16) for example, it was recognised that there was a severe lack of incentive for building transmission lines to cater for wind power, which is generally available in remote parts of the network. To overcome this problem, competitive renewable energy zones (CREZ) have been created and strategic transmission planning has been underway to cater for these regions to connect to the ERCOT network.

Developing transmission alternatives based on studies of the best wind resource availability has also been carried out in a study for the Southwest Power Pool, in Midwest USA and in California.

In Europe, an extensive study was performed by the TSOs in the Iberian Peninsula, and the German DENA study also identified the need for large transmission projects to help integrate the North Sea Offshore grid to the land-based grid. Since in Europe however, the lead time for transmission projects can be more than a decade, some studies, such as EWIS identified the need to implement short-term intermediary measures.

Conclusions: Given the unique characteristics of location and short lead time for wind power expansion, the Transmission System Operator (TSO) must anticipate and prepare to address potential issues before they arise. Solutions range from implementing voltage control requirements for wind power plants, upgrading the distribution and transmission grid to accommodate larger power flows in the long-term, and to optimise the use of currently-installed equipment in the short-term.

Many power system operators are now realising that, compared to traditional transmission planning where the main concern was designing supply systems which can most efficiently supply demand centres, major changes are required to the planning process to effectively integrate wind power and other renewable energies. When large transmission projects such as grid extensions to remote areas are required, politically-backed schemes such as the CREZ project appear to be most effective (16).

NEM

Relevance for NEM system: Most wind resources in the NEM are located at a significant distance from the main demand centres, implying that grid extension and reinforcements may be required for effective integration of wind power. However, grid augmentations in the NEM are market-driven, therefore only take place if there is seen to be a market benefit. This has the potential to create an obstacle to wind integration as wind power. Effectively, plant developers require a connection option to build, while the grid will not be extended until the plant is generating and creating market benefits.

Furthermore, wind power plants in the NEM tend to be larger than those in Europe, and Australia's widespread adoption of the latest turbine technologies is expected to be slower than Europe or North America since there is no manufacturing base onshore. Technical performance requirements in the NEM will therefore need to be sufficient to manage voltage issues.

Recommendations: For efficient integration of wind power, it is recommended that the grid planning approach is reviewed to identify strategies to better accommodate the particularities of wind power.

In the short term however, wind power may increase congestion on grid, and therefore face curtailment without adequate grid reinforcements. To avoid this, there are short-term measures to manage the expected power flows that can be investigated.

3.3. STEADY-STATE ANALYSIS

The issue: With the connection of new wind power plants, active and reactive power is injected in different parts of the power system, altering the power flow characteristics in such a way that thermal and voltage limits may be violated.

Possible impact of increasing wind penetration: The addition of new generating capacity may:

- change the power flow, so N-1 criteria might be violated in certain cases;
- change the voltage profile, requiring additional reactive power support measures, or
- displace conventional generation, changing the amount and location of available reactive power supply.

Typical methods used for studying the issues: Most wind integration studies observe this impact through power flow simulations based on a set of conditions which emulate the "worst case" scenario. The worst case scenario is a situation which results in high power transfers across the grid. This may occur in a high demand situation when the load centre is a long way from generation, such as is the case in Australia, where all the available power has to be transferred to the load centres in the cities. High power transfers are also possible in a low demand situation combined with high wind power output, as it occurs in Spain, where wind power generation can displace other generation that may be closer to the load centre, but more expensive.

International experience: In the study of the Iberian Peninsula system (17), assessment was done using winter peak and summer off-peak demand scenarios combined with three different levels of wind power integration. The country was divided in four zones to study the influence of wind power in the transmission system. Wind power generation is set up to 80% of the installed capacity in the studied zone, while the wind power generation in the other three zones is fixed according to studies of statistical production data. Solar generation was also considered in the study. Load flow analysis was conducted to study network contingency situations (N, N-1 and N-2), and short-circuit scenarios were also simulated to study the power system recovery after a disturbance. Transient stability simulations were solved to validate wind power production scenarios that have been admissible in the steady-state studies. The planned wind and solar power generation must be capable of providing mainly dynamic voltage control, given the massive penetration of these new technologies. Simulations were carried out during 20 seconds from the beginning of the three-phase faults, studying in particular the voltage recovery and how wind power penetration affects the power system. Dynamic voltage control implementation was emphasised, since without it, voltage dips would be deeper and more extensive, resulting in an unacceptable situation from the point of view of transient stability.

Even if long-term studies can identify network augmentation requirements, the actual construction of transmission infrastructure can take a long time and short-term solutions are required. The European Wind Integration Study (EWIS) (13) performed year-round market analysis coupled with detailed representations of the networks to assess use of interconnectors. This study identified that Europe would encounter significant problems related to loop flows, and recommended ways to deal with the situation using the resources available until major grid reinforcements could be put in place.

The Irish All Island (12) grid study used security-constrained optimised power flow (OPF) to assess how much the new renewable electricity sources were going to contribute to load flow in the system. This approach identified how what portion of future power system upgrades are instigated by wind integration, separate to those upgrades required for conventional generation or change in demand. This approach can also help account for costs.

Most of the wind integration studies look at a specified amount of wind power and use steady-state analysis to determine grid upgrades necessary to integrate it. However, the final priorities for upgrades are typically based on economic and market integration studies.

The Minnesota study (18) is unique in that it aims to determine the maximum capacity of wind power that can be installed at 42 potential connection points. At any single connection point a maximum of 40 MW can be connected. Therefore power flow studies are performed starting with 40 MW of wind power capacity. If this results in a violation, the connected capacity in the model is reduced by 5 MW and the resulting power flow is checked again. This process is continued until no more violations occur, and for all 42 sites.

NEM

Relevance for NEM system: Wind power already has significant influence on the power flow in certain areas of the network and its relevance will increase as more wind power is introduced. For example, a study by Vencorp (19), identified that the increased injection of wind power at certain points of the network may result in thermal overloads and low voltages requiring reinforcement and support measures to be implemented. The impact on reactive power requirements appear to be critical in the networks of Victoria, South Australia and Tasmania for dealing with large quantities of wind power integration (19), (20), (21). Furthermore, for the relatively isolated systems of South Australia, a minimum level of conventional generation remaining online near the major load centre, to provide voltage support, was found to be critical (20).

Recommendations: Based on the characteristics of the transmission network and wind resource availability, it is recommended that a number of future renewable energy development scenarios are used to study the possible augmentation requirements and associated costs. In this way a system which is prepared for a variety of possible future directions can be developed at least cost. In addition to assessments based on the worst case scenarios, which are typcially summer-peak scenarios, off-peak scenarios coupled with high wind power output, as well as situations subject to extreme weather can also assist in the design of a robust system.

Grid adequacy

- Ability to deliver available generation to demand even during faults of generation units and transmission lines (N-1)
- Energy consumption and peak demand are typically increasing
- Increasing share of renewable energy is driven by political decisions
- Retirement of nuclear and coal power plants
- Long-term reliability is a system issue

Wind impact

Location and capacity

- Remote location
- Distribution or transmission connected
- Short lead time for construction

Challenge

Adapt transmission planning procedures to ease the integration of renewable energy sources.

Studies that look into the issue

DENA Minnesota	Iberia All Island EWIS SPP	IEA 25	ElectraNet Vencorp Tansend NEMMCO-SA

Results

- Impacts on grid adequacy are not unique to wind power.
- Wind integration on large scale requires major grid augmentations because:
  - wind power is often available in remote locations requiring grid extension
  - wind power is often connected at distribution level rather than transmission level, which is more susceptible to voltage issues
- Transmission planning methods need to be modified to support renewable energy integration, particularly location and lead-time.
- In the short-term, wind power may increase congestion on grid, requiring temporary measures such as FACTS, DSM or storage.
- Wind power may need to be curtailed if there is insufficient grid adequacy.

Figure 9: Summary of issues involving grid adequacy. Source: energynautics

3.4. POWER SYSTEM SECURITY

Power system security is concerned with the ability of the system to withstand contingencies, set requirements for generation reserve and limits to transmission loading, as well as to avoid cascading outages leading to a blackout. Overall security is managed by protection schemes, set to operate at the operating limits for voltage, frequency and current.

Figure 10 depicts the different issues that affect system security. It should be noted that these aspects are not unique to wind power integration; rather they must be tested for addition of all types of new generation as well as any system augmentations. These issues are explained in more detail in the following sections.

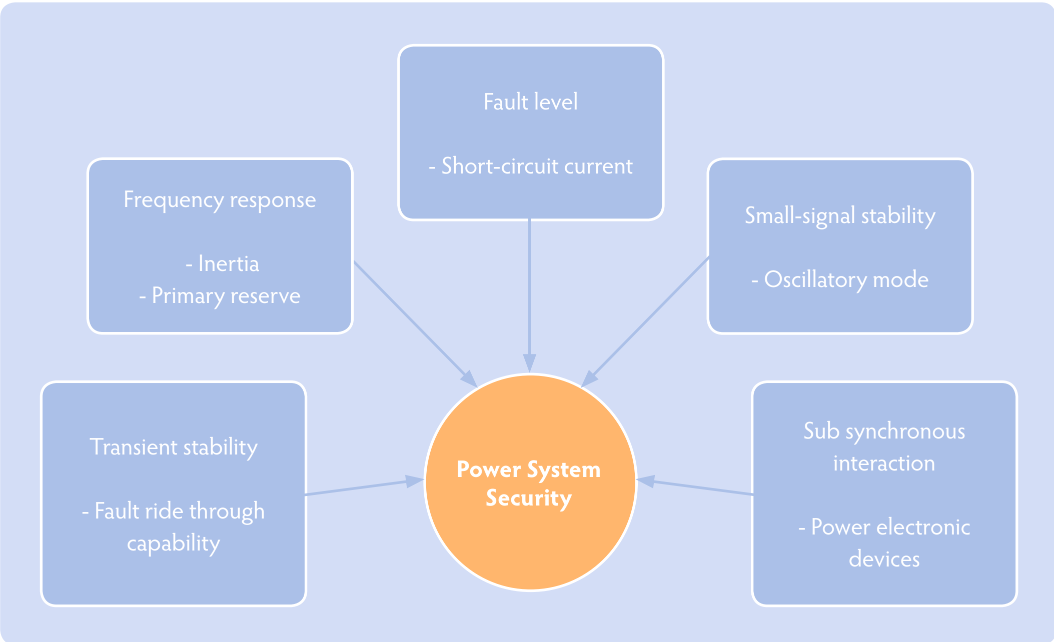
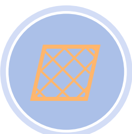


Figure 10: Issues affecting power system security. Source: energynautics

3.4.1. TRANSIENT ANALYSIS



The issue: The goal of transient analysis is to assess the ability of the power system to maintain synchronism when subject to a severe transient disturbance such as a fault on transmission lines, loss of generation, or loss of a large load. Generating units may lose synchronism and be disconnected by their own protection systems if a fault persists on the power system beyond a critical period.

Possible impact of increasing wind penetration: The addition of new generating capacity may:

- change the system stability characteristic by displacing synchronous generation, and
- make post-fault recovery more challenging if wind power plants (WPPs) are tripped during the fault.

For the second point in particular, the capability of the WPP to remain connected during and following a fault (fault ride-through) is important.

If the wind turbine is an old model, and the grid code does not require the wind power plants to ride through faults, protection devices may disconnect them when a transient event occurs, affecting the ability of the system to return to a stable operating point after the contingency event.

The degree to which the wind power plant contributes to fault ride-through and post contingency recovery of the system can therefore have an impact (worsening or improving) on the recovery of the system after the fault, which is the 'transient response.'

Typical methods used for studying the issues: Loss of synchronism due to transient instability will be evident within 2 to 3 seconds of the initial disturbance. Therefore, transient stability is assessed using dynamic simulations, where parameters such as the generator rotor angles, machine speeds, and bus voltages are observed while a fault is applied for a fixed amount of time, cleared, and the behaviour is observed for some 20-30 seconds after the fault, until the system becomes stable or a generating unit becomes unstable.

Lightly loaded cases and high wind penetration cases are more susceptible to transient instability because there are less synchronous generators online which normally provide reactive power support during and after a fault.

International experience: The study by Transpower New Zealand[47] investigated the impact of wind power integration on stability-related constraints. The constraints limit power flows between areas to levels where power system transient stability can be maintained. The constraint may be increased or decreased depending on the new generation's capability to support system stability. This is not unique to new wind power generation. However, wind power's ability to support system stability varies greatly with the type of technology employed. The analysis in this study showed that old Fixed Speed Induction Generation (FSIG) absorbs reactive power during and after a fault, worsening the transient stability performance. These kinds of units will eventually trip off when there is a disturbance on the power system unless additional dynamic reactive support (e.g. static compensators) is built.

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Other types of turbines such as Doubly Fed Induction Generators (DFIG) and Full Scale Frequency Converters (FSFC) have improved fault ride-through capability, and have the potential to improve transient performance. However, this is largely reliant on the requirements stipulated by the Grid Code.

In systems where the wind turbines are not equipped with fault ride-through (FRT) capabilities, the main objective of the study is to determine the amount of wind generation that would be disconnected due to the disturbance.

For example in Spain and Portugal, many of the already installed wind turbines are not equipped with FRT capability and studies[48] have shown that large quantities of wind power would be switched off during a voltage dip. Based on this finding, a new FRT requirement was introduced, as well as coordinated operation and control schemes, improved forecasting and aggregation techniques. On the other side in Germany, FRT requirements for the wind turbines to remain connected but not provide reactive power support has been in place for over a decade. Therefore, many of the old wind power plants are available for generation following a fault. All new wind power plants as well as re-powered plants must comply with an updated requirement for the wind turbine to contribute reactive current during a fault in the same manner as a synchronous generator. To get the requirements right, it is important to have accurate modelling of the dynamic characteristics and fault ride-through capability of different turbine technologies that are in the system. In this context, the German DENA grid study was performed with a variety of wind power plant capabilities incorporated.

Most systems these days have FRT requirements in their grid codes. Therefore, future wind power plants are expected to have low voltage ride-through (LVRT) capabilities as well as a certain level of voltage control. Most studies performed in Europe and the USA consider these aspects when assessing the impact on transient stability.

Relevance for NEM system: In the NEM, transient stability was investigated in the studies carried out for South Australia (20) (23), Tasmania (21) and Victoria (19), where the most wind power growth is expected. Introduction of wind generation was not found to significantly degrade transient stability. However, WPP models were not available for the transient studies.

In some of the studies, reactive power support and fault ride-through requirements were met with static compensators, therefore these are included in the analysis. However, depending on the expectation of the future technology employed, it would be beneficial to include modern wind generation technology with inbuilt FRT capabilities in the models.

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3.4.2. FREQUENCY RESPONSE ANALYSIS

The issue: Frequency response refers to a number of aspects, namely the inertial response of the power system, which acts in a few seconds, the governor response, which is the primary response reacting in 1s to 10s of seconds, and the AGC response, which is the secondary response acting in a time frame of tens of seconds to minutes (explained in section 3.5). The key to maintaining frequency stability when there is a disturbance such as a loss of a generator is to have high rotating inertia in the power system. For large interconnected systems like the UCTE system in Continental Europe, the aggregate inertia is high enough that frequency problems are rarely seen. However, for smaller systems, particularly island systems like the Irish All Island system, or systems with a slow primary frequency response such as those with large amount of hydropower, like the Hydro Québec system, frequency stability may be difficult to maintain when large amounts of wind power are introduced to the system.

Possible impact of increasing wind penetration: The addition of new generating capacity may:

- change the maximum fault level with the single connection of a large WPP, and
- reduce inertia in the system if conventional generation is switched off during high times of wind generation.

Typical methods used for studying the issues: The system's frequency nadir following a transient event such as the loss of a generator can be observed, to ensure that it remains within a controlable range. Loss of synchronism due to lack of inertia will be evident within 2 to 3 seconds of the initial disturbance. The amount of primary reserve required to bring back the frequency can then be evaluated on a longer time scale. Therefore, frequency response is assessed using dynamic simulations, where the system frequency is monitored for some 20-30 seconds after the loss of a generator, until the system becomes stable. Lightly loaded cases are more susceptible to instability because there is less rotational inertia to absorb the disturbance. The same can be said for situations where wind power penetration is high, as inertia-less wind power plants displace conventional synchronous generators.

International experience: A number of studies have been performed in various regions, particularly for systems which are frequency islands or weakly coupled such as Ireland, UK, Hydro Québec and ERCOT. Although none of these studies indicate critical security issues, some recommended operating limits have been found. The most prominent of these is the All Island Renewables Facilitation study (24), where a 60-80% limit was identified for inertia less penetration.

This implies that the maximum amount of generation which does not contribute to system inertia (such as wind generation and import via HVDC) should not exceed 60-80% of the total system generation to maintain adequate system frequency response.

Two potential mitigation measures have been suggested, one being to run conventional power plants in synchronous compensation mode, providing inertia without generating active power. The other is for wind turbines to emulate inertia, utilising kinetic energy stored in the rotor to provide a boost in power over a short time frame of a few seconds.

For larger systems such as the European UCTE system and the eastern and western interconnected systems in the USA, the lack of inertia from wind turbines is not likely to bring about security issues. However, if significant amounts of conventional generators providing primary reserve are displaced, the financial implications in securing further reserve may become of concern.

The following table 6 gives a summary of inertia response requirements for wind power plants in selected power systems.

Region	Requirement
Red Electrica, Spain	REE encourages development of a virtual inertia requirement but does not foresee a need for it for the Iberian Peninsula for a long time.
Hydro Québec, Canada	Wind Power Plants are required to contribute to reducing large (> 0.5 Hz), short-term (< 10 s) frequency deviations in the power system, an equivalent response as provided by a synchronous machine with a inertia constant, H=3.5 s.
ERCOT, USA	No formal requirement exists although it has been under discussion for a number of years.
UK	No formal requirement exists although National Grid has been studying this for the last 2-3 years. A current draft suggests a primary control with +10 % over 5 s, and 1 s max delay time.
Ireland	No formal requirement exists. The issue has been studied and so far been concluded not critical.
Denmark	Similar to Hydro-Québec
ENTSO-E Draft EU Grid code	The TSO shall have the right to require an equivalent delivery related to the rate of change of frequency.

Table 6: Frequency and inertia response requirements for wind power plants in selected systems. Source: energynautics

Relevance for NEM system: The Transend report (21) found that the displacement of conventional generation by wind generation leads to a reduction in system inertia which in turn increases the requirement of fast FCAS and increases the rate of change of frequency following disturbances. Displacement of conventional generators also reduces of the amount of online plants available to deliver FCAS.

It is recommended that a more thorough study be conducted for the systems of Tasmania and South Australia (in island mode), as increasing wind power penetration levels may lead to a requirement for a minimum "must run" synchronous generation.

3.4.3. FAULT LEVEL ANALYSIS

The issue: Short-circuit fault may draw large amounts of fault currents which then trips the current protection to isolate the fault. But to function correctly, the protection must be designed to withstand the expected fault currents. Also the fault current must be sufficiently large enough for it to be detected by protection. Therefore, it is important to calculate the expected level of fault currents.

Possible impact of increasing wind penetration: The addition of any new generating capacity may affect fault levels and require a change in protection settings.

Wind power can change the fault currents in both directions. Adding generation capacity may increase the local short-circuit level in the electricity system. However, short-circuit capability of wind turbines are significantly lower than that of synchronous generators, and depend on the wind turbine technology (26). As a consequence, short-circuit levels of the system may also decrease if conventional generation is replaced by wind power (24).

Typically methods used for studying the issues: Steady-state analysis can be performed for different wind penetration scenarios to gain an insight into the general impact on fault levels. However, to properly design the system, electromagnatic time domain transient simulations for short-circutis at particular points in the network, such as the connection point of the wind power plant or at the terminals of a HVDC device, are needed to ensure that the short-circuit ratio of the wind turbine is adequate for correct operation of equipment at that point.

International experience: A comprehensive investigation was conducted for the New Zealand system by Transpower (27) and for the Irish All Island grid in the Facilitation of Renewables report (24).

In the Transpower report, steady-state analysis was used to analyse the changes in fault levels. A scenario with light system load was considered as this is when the most conventional generation is displaced by power (equating to an instantaneous maximum penetration of 75%). The displacement of conventional power changes the dispatch pattern and alters the distribution of system fault levels. It was found that introducing wind generation in load centres where local generation is sparse, increases short-circuit levels locally, whereas the regions with significant conventional generation may experience a reduction in fault level by more than 50%. In addition it was found that Full Scale Frequency Converter (FSFC) wind turbines more significantly impact fault levels than Full Scale Induction Generators (FSIG) and Double Fed Induction Generators (DFIG). This is because FSFC fault current contribution is limited by the power converter rating. This is a problem because reducing the fault level makes it more difficult for the power system to maintain voltage during short-circuit faults.

In the Irish All Island Facilitation of Renewables study, short-circuit calculations were carried out in a similar fashion. In this study it was found that in general, fault levels decreased with increasing wind power. None of the fault levels fell low enough to compromise the correct operation of the protection system, however. It was found that, at buses close to large wind power plants, but far from conventional generation, fault levels increased with higher wind generation. Furthermore, in areas where the fault levels were already quite high, additional contribution from the wind power plants could push the system beyond allowable limits.

As a sensitivity check, the Irish study varied the share of wind capacity connected to the distribution and transmission systems, respectively, (80%/20% versus 65%/35%). It also varied the share of FSFC turbines in the total wind capacity (15%/85% versus 50%/50%). However in both cases, the results did not change significantly.

In the Iberian system and German DENA (6) studies, similar approaches were used to determine the impact on fault levels for the high voltage system and offshore system respectively. In both cases, no values low enough to compromise the correct operation of the protection system were found.

NEM

Relevance to NEM system: In the Vencorp study[49] it was mentioned that connecting wind power generation to the Victorian transmission network increases overall transmission network fault levels. Several factors affect the amount of the fault current contribution from a wind power plant however, such as the type of the wind turbine, the installed capacity of the wind power plant, and the impedances of the wind turbine, the step-up transformers, and the collector cable network and transmission connection. This is assumed to be because the wind power generation is in addition to existing generation and does not actually displace it.

However, it is also possible to have very low fault levels when wind generation displaces a significant portion of conventional generation. The Transend report[50] stresses the importance of maintaining system fault levels above a certain level in the Tasmania region, since if the fault level falls too low then Basslink operation will be curtailed. If the total system fault level is too low then problems involving high dynamic over-voltages, voltage instability, harmonic resonance and objectionable voltage flicker may also arise[51].

Given the characteristic of the NEM that wind power plants are likely to be connected at higher voltage levels and in weakly connected areas of the network, it is recommended that fault level analysis is conducted in detail for each connection to ensure the correct operation of the system.

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50 (21) Page 16
51 (120) Page 528

3.4.4. SMALL-SIGNAL STABILITY ANALYSIS

The issue: Small-signal stability refers to the ability of a power system to remain in synchronism when subjected to small disturbances. These disturbances can be variations in load and/or generation which occur in normal operation. Synchronous machines respond to these variations by varying their rotor angle, which need to be sufficiently damped, otherwise can result in a group of machines swinging output against another group of machines, leading to a loss of synchronism. The natural frequency of these oscillations is typically in the range of 0.1 to 1 Hz (28).

Possible impact of increasing wind penetration: Wind power plants generally do not induce new oscillatory modes since they are not synchronously connected to the grid. However, depending on the wind turbine concept (constant or variable speed), and penetration level, it may be possible that the damping performance of the system is indirectly changed by:

- wind power generation displacing synchronous generation,
- significantly altering the power flows in the transmission network, and
- wind power interacting with synchronous machines to change the damping torques induced on their shafts[52].

Typical methods used for studying the issue: Modal analysis by eigenvalue calculation is the most common method used to investigate small-signal stability.

International experience: Of the studies reviewed, only a few investigate the impact of wind power on small-signal stability. For example the Transpower study (29) assesses the impact of four wind power scenarios on the damping performance of the existing North Island and South Island power systems. This study compares the damping performance of a base case scenario which has no wind generation to a scenario where wind generation is introduced to the system by displacing an equivalent amount of synchronous generation.

The investigation also considers the sensitivity of the damping performance to the following factors:

- Type of wind turbine technology employed (includes Doubly-Fed Induction Generators (DFIG), Full Scale Frequency Converter (FSFC) generators and conventional induction generators driven by an active-stall or passive-stall turbine);
- Whether or not selected wind power plants are equipped with continuously acting voltage controllers (i.e. STATCOMs);

52 (29) Page 6

- Level of system loading; and,
- Variation in the power output from a WPP.

The results of the sensitivity studies indicated that such voltage control facilities are unlikely to significantly affect the damping performance of the system.

It was found that the damping performance of the system with DFIG and FSFC type turbines were practically identical, and that large-scale wind generation did not appear to significantly affect small-signal stability on the New Zealand power system.

The Irish All Island study (24) also investigated small-signal stability. Its analysis focused on dispatch cases with zero export because HVDC interconnectors and wind power were assumed not to introduce any electromechanical oscillation modes but basically change the number of online synchronous generators with their corresponding controllers and modes.

The general finding was that an increase of wind power tends to improve the damping of oscillations in the system. This is because the system coupling is strengthened by synchronous generation being replaced by wind power generation.

The WILMAR study (28) and EWIS (13) also reported results of small-signal analysis however in these studies the models used for analysis were not very detailed and only general conclusions could be drawn. In either case major impacts were not caused by the integration of wind power generation, and the oscillation modes already known to exist in the respective systems continued to exist in the system with wind power integrated.

Relevance to NEM system: Of the studies reviewed, the study by ElectraNet (20) and NEMMCO in the South Australian region (23) mentioned results from small-signal analysis. In either case no major impacts were reported, however, the NEMMCO study reported a slight tendency for small-signal damping to decrease under high load, high wind conditions.

In both the NEMMCO and ElectraNet studies WPPs were modelled as negative loads as appropriate small-signal models were not available. Thus the impact of wind generation on small-signal stability of the NEM has not been studied in detail.

3.4.5. SUB-SYNCHRONOUS STABILITY ANALYSIS

The issue: A number of studies reviewed (30) (31) (32) indicated that wind power plants with power electronic converters and controls operating near series-compensated transmission lines can experience sub synchronous stability issues.

Possible impact of increasing wind penetration: If the connection of a new wind power plant in a remote location requires HVDC or series-compensated lines, particularly in a radial configuration, this may result in sub synchronous interactions between the wind and the transmission system. Such resonant conditions can lead to severe system overvoltages, undamped oscillations and instability, risking system outages and equipment damage.

Typically methods used for studying the issues: A variety of sub synchronous interactions (SSI) exist (Figure 11), and can be investigated by electromagnetic time domain transient simulations, however, the main concern for wind integration studies (if any) is the sub synchronous control interactions (SSCI). This was demonstrated in a real life example in Texas, where a line fault left a large wind farm connected radially with a series-compensated line and caused a fast build-up of sub synchronous oscillations, which caused damages both to the series capacitor and the wind turbines (30).

Sub Synchronous Resonance (SSR)

- Interaction between generators and the electrical resonance formed by series capacitors and the system effective impedance.
- Often seen when series capacitors are installed near gas turbines or thermal generators.
- Frequencies of oscillation are fixed and determined by the known mechanical torsional modes of oscillation in the generator shaft system.

Sub Synchronous Torsional Interaction (SSTI)

- Interaction between power electronic controller (such as an HVDC link or SVC) and generators.
- Can cause undamped or growing oscillations in known mechanical torsional modes of oscillation in the generator shaft system, including WTGs, although the torsional modes are generally at low frequencies and do not pose a problem.

Sub Synchronous Control Interaction (SSCI)

- Interaction between a power electronic device (such as an HVDC link, SVC, wind turbine, etc) and a series-compensated system.
- There is no mechanical shaft system that is part of the oscillations, so the frequency of the electrical resonance formed by a series capacitor and the system effective impedance will change under different load or system conditions.
- These oscillations can build up quickly (as it is purely control/electrical), and depend highly on the power electronic controller algorithm.

Figure 11: Explanation of sub synchronous interactions. Adapted from (30)

International experience: The issue of sub synchronous interaction has been investigated in association with the transmission plans for the competitive renewable energy zones (CREZ) development in the ERCOT system, which are mostly series-compensated HVAC lines. According to the CREZ Reactive Power Compensation Study, Squirrel Cage Induction Generators and Wound-Rotor Induction Generator with Variable External Rotor Resistance wind turbines generally do not have sub-synchronous interaction (SSI) if they are close to synchronous frequency. However, DFIG-type turbines are more sensitive to SSI, due to the controls responding to the sub synchronous series resonance. Furthermore Full-Converter turbines did not show any sensitivity to SSI.

A report published by Elforsk (32), Sweden, also investigates SSI of wind turbines, in this instance for the impact of variable-speed wind turbines. Using an aggregated model of a power plant, frequency scanning analysis was performed to estimate the harmonic impedance of the network to screen for conditions that can give rise to potential resonance in the power network. The Elforsk study findings agree with the ERCOT study that full-power converter turbines have minimal effect due to the decoupling between the generator and transmission line, while DFIG generators were more susceptible to resonant conditions at low frequencies.

The main findings from these studies are summarised below:

- Fixed-speed wind turbines might be affected by SSR if radially connected to a series-compensated line, while variable-speed full-power converter turbines do not seem to be affected.

- If a frequency matching the resonant frequency of the DFIG wind turbine exists in the transmission network due to the presence of the series capacitors, the system might become unstable and sub synchronous oscillations can grow.

- The resonant frequency of the DFIG is highly dependent on the converters' (both the rotor-side and the grid-side converter) controller parameters as well as on the operating conditions. This dependency leads to a fairly wide range of frequencies, meaning that resonance can occur for a wide range of series compensation levels.

- It is important to represent the DFIG and full-converter type wind turbine impedance characteristics to accurately assess SSR and induction generator effects. These characteristics should cover a frequency range of 0Hz to 120Hz in 1Hz or smaller increments for normal SSR screening studies. Higher frequencies may be needed for other types of harmonic impedance calculation studies and should also be provided up to approximately 1kHz.

Relevance to the NEM system: Since wind power potential in the NEM is mainly in remote areas, it is likely that series-compensated HVAC lines or HVDC lines will be used more in the future to bring the wind power to the demand centres. In addition, integration of wind farms into systems where the short circuit ratio (SCR) is low (<5) should be identified as potential locations for SSR. Therefore, if specific projects are foreseen, it is recommended that studies are performed to investigate the possible sub synchronous interactions.

System security

- Ability of the system to withstand contingencies, such as short-circuit faults and the sudden loss of generation.
- The system must be able to return to safe operation following large transient events, as well as damp out small-signal disturbances.
- Primary generation reserve and operating limits may need to be set.
- System security may be a local or system issues.

Wind impact

Wind power generation displaces synchronous generation with certain grid support capabilities.

Challenge

Identifying the limits where the system may become unstable based on an uncertain mix of wind power penetration rates and technical capabilities.

Studies that look into the issue

ERCOT DENA Québec NYSERDA IMO-WA	All Island Iberia EWIS SPP Transpower	IEA25 SC Current	ESIPC Transend Vencorp NEMMCO Electranet

Results

- Fault ride-through and voltage support requirements in Grid Codes are important to recover from transient faults.
- Displacing large amounts of synchronous generation with wind power generation reduces system inertia and may lead to a minimum "must run" synchronous generation requirement for island and weakly interconnected systems.
- Wind power generally lowers fault levels. It is more critical for wind power plants connected in weak parts of the network and for HVDC devices.
- If the connection of a new wind power plant in a remote location requires HVDC or series-compensated lines, particularly in a radial configuration, this may result in sub synchronous interactions between the wind system and the transmission system.

Figure 12: Summary of issues involving system security. Source: energynautics

3.5. BALANCING (FREQUENCY REGULATION, DISPATCH, AND SHORT-TERM CAPACITY RESERVE)

Operation of a power system is largely concerned with balancing supply and demand at any time. Given the few options to store electricity available in a modern power system, it is important that the same amount of generation is produced at the instant that it is consumed. To do this efficiently, the system operator optimises the use of available resources (often through markets), given a set of transmission constraints, to cover the amount of electricity consumption forecasted at a certain point ahead of time. The degree of time lag between the forecast schedules and delivery in this process can be broken down into a broad categorisation of 5-15 minutes (regulation), 15-30 minutes (dispatch or load following) and 30 minutes to some hours (short-term capacity). These are highlighted in orange in Figure 13 below.

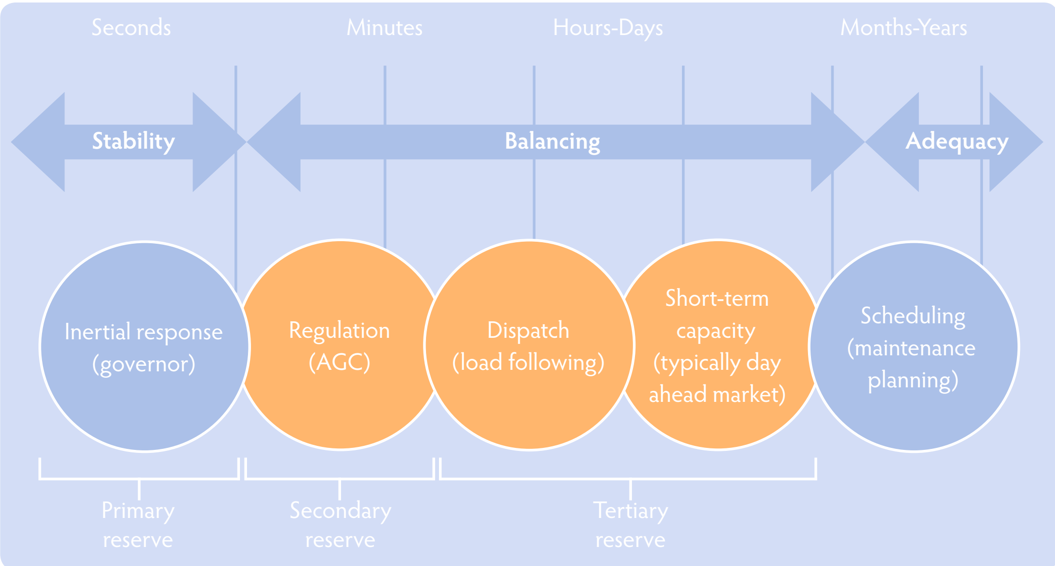

Figure 13: Time scale for different balancing categories. Source: energynautics

The terminology for reserves varies between countries. In this report, primary reserve is reserve that acts on a second's basis, through Governor response, and corresponds to fast and slow contingency FCAS in the NEM. Secondary reserve corresponds to regulation reserve, defined as reserves made available in 5-15 minutes. Tertiary reserve corresponds to dispatch or 'load-following reserve', available in 15-30 minutes and short-term capacity reserve, available in 30 minutes to some hours (and up to a day).

The issue: Power system operation is concerned with ensuring that enough generation capacity with the right characteristics is available to respond to the variable nature of demand and supply (i.e. wind and solar PV) as well as forecast errors.

Possible impact of increasing wind penetration: As with system load, there are seasonal, diurnal, hour-to-hour, minute-to-minute, and second-to-second variations to wind power output. Figure 14 below, adapted from the NYSERDA report (5), shows that wind generation variability has less correlation between wind generating resources as the time frame decreases.

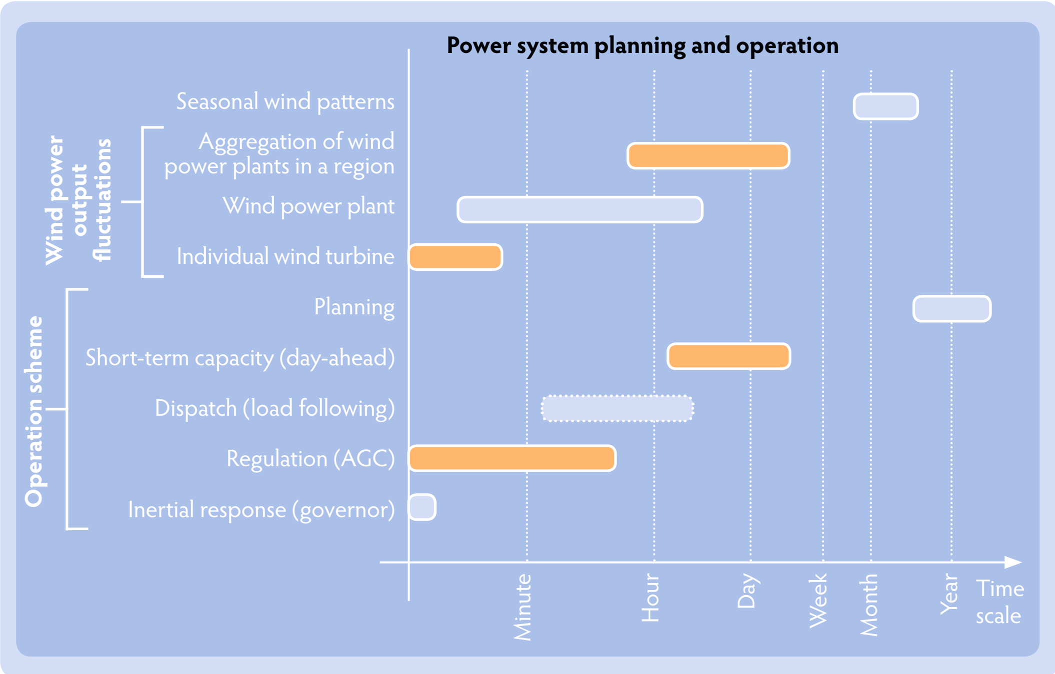

Figure 14: Power fluctuation and operation time scales. Adapted from (5) Page 16

While individual wind turbine generators can experience power output variations over time frames of seconds to minutes, when many of them are aggregated as a wind power plant, the short-term variations are smoothed out and the power output variations will be in the range of minutes to hours. This variation is typically covered by market dispatch (e.g., 1 hour in Germany, 5 minutes in the NEM), and regulation ancillary services after that. Similarly, in systems with multiple wind power plants, regional wind fluctuations will be in the hour to day range, which is covered by a short-term capacity planning process (e.g. unit-commitment in USA). Seasonal wind patterns, of course, fall into the several-month timeframe[53] and should be captured in long-term planning.

Wind generation forecast errors can also impact the balancing processes, particularly when the actual generation dispatch differs from what was forecasted during generation scheduling. The risk in this case is that the power system cannot adjust quickly enough to accommodate for the discrepancy between the scheduled generation and actual required output[54]. This is more of a problem for markets with 1 hour dispatch like that of Germany, with slow conventional generation. For the NEM, this is less of a concern as it has a 5-minute market, where the generators can adjust their scheduled output closer to the actual time of dispatch.

53 (5) Page 16
54 (115) Page10

1 2 3

Typical methods used for studying the issue: According to the NREL report on Operating Reserves and Wind Integration (33), most wind integration studies measure wind energy's impact on balancing by evaluating the incremental need for additional operating reserves. This is done through simulation of operation, where available generation is matched to the forecast demand on a rolling basis. The time lapse between the forecast schedule and actual delivery can vary from days ahead to minutes, which are normally administered through a number of markets.

This process varies significantly between power systems. A comparison of the balancing time frames in selected areas is shown in Table 7.

Power system	Frequency response reserves (seconds)	Regulating reserve (5-15 minutes)	Ramping reserve (30 minutes-hours)	Load following reserve (available in 15-30 minutes)	Supplemental reserve
NEM	X (Contingency services)	X (Regulating services and network loading control)		X (Short-term capacity reserve)	
ENTSO-E (Europe)	X (Primary reserves)	X (Secondary reserves)		X (Tertiary reserves)	X (Tertiary reserves)
Spain	X (Primary reserve)	X (Secondary reserve)	X (Deviation reserve)	X (Tertiary reserve)	
Ireland	X (Operating reserves, primary, secondary and tertiary reserves)	X (Regulating reserves)		X (Replace-ment/ substitute)	X (Contingency/ substitute)
Hydro Québec	X (Stability reserves, spinning reserves)	X (Frequency regulation reserves, AGC)		X (Load following reserves)	X (Energy balancing reserves)
New Zealand	X Instan-taneous reserves)	X (Frequency regulating reserve)			
ERCOT [55]	X (Responsive reserve)	X (Regulation reserve)	X (Non-spinning reserve)	X (Load-following, 15 minute dispatch)	X (Replacement reserve)

55 Reference: http://www.uwig.org/FortWorth/workshop/Dumas.pdf

Power system	Frequency response reserves (seconds)	Regulating reserve (5-15 minutes)	Ramping reserve (30 minutes-hours)	Load following reserve (available in 15-30 minutes)	Supplemental reserve
NYISO		X (Frequency and tie-line regulation)	X (Unit com-mitment and day-ahead scheduling)	X (Load following, 5 minute dispatch)	
Germany	X (Primary regulation reserve)	X (Secundary regulation reserve)		X (Minute reserve)	
Western Australia	X (Spinning reserve)			X (Load following)	

Table 7: Summary of reserve types used in operations today. Adapted from (33) and (25)

In the NEM, pre-dispatch is one day ahead and actual market dispatch is 5 minutes ahead of delivery. For the variations within this final 5 minutes, ancillary service is employed to correct for discrepancies between final dispatch and actual demand.

According to the IEA Task 25 report (2), the method to evaluate the impact of wind power on balancing involves the determination of reserve requirements based on statistical evaluation of variability in load and wind power, or the net load (i.e. load minus wind power). The results of this evaluation however are not likely to be universally applicable, as the characteristics are highly dependent on the location and size of the power system, as well as the distribution of wind power within the system.

The only study out of the ones that have been reviewed where the market arrangement is close to the NEM is the New York Independent System Operator (NYISO). The NYISO system has a 5 minute real-time market that complements its day-ahead market, as well as an AGC with 6 second operation.

New York ISO

The study by NYSERDA (5) evaluated 3,300 MW of wind power on the 33,000 MW peak load NYISO system. Based on Milligan's method (35), the confidence level for how much of the variations (wind and load) should be covered by reserves is calculated to be three times the standard deviation of the variability. Therefore, to determine the impact on regulating reserve requirements, the standard deviation of 6-second variability due to net load was compared with that of load only. The finding was that approximately 14% more regulating reserves would be required compared to the current level. Furthermore, the study concluded that no incremental contingency reserves would be needed since the largest single severe contingency would remain the same.

Table 8 below summarises the impacts on balancing found by different studies.

Power system security studies	Balancing
ERCOT	Impact of integrating 15,000 MW wind power in 65-GW peak load system with 15 minute dispatch period. 54 MW increase in up-regulation and 48 MW in down-regulation required.
Québec	Impact of integrating 3,000 MW wind power calculated using statistical method used by BPA, an additional 2% of AGC and 22% of load following reserves are required. However, significant seasonal discrepancies are found to exist. A simulation based approach for determining the impact on balancing is currently being developed.
DENA	Impact of integrating 20% of renewable energy generation (majority wind) with day-ahead dispatch. The calculation of an average day-ahead regulating and reserve power capacity is discussed. It was found that: • An additional maximum 7,064 MW of positive regulating and reserve power capacity is needed, of which on average 3,227 MW has to be contracted day-ahead (9 % of wind power capacity). In 2003, the corresponding values were 2,077 MW maximum and 1,178 MW on average. • Additional maximum 5,480 MW of negative regulating and reserve power capacity is needed, of which on average 2,822 MW has to be contracted day ahead (8 % of wind power capacity). In 2003, the corresponding values were 1,871 MW maximum and 753 MW on average.
NYSERDA	Impact of integrating 3,300 MW wind power in 33-GW peak load system with 5 minute dispatch period. 36 MW increase in regulation required. No additional spinning reserve is needed.
IMO-WA	It was found that the load following requirement increases substantially, from the current value of 60 MW to around 200-300 MW by 2030. This corresponds to an average increase of 14% of the new installed wind power capacity. It was also found that placing ramping limits on wind power generator would not be effective at reducing variability.
Western Power	Load following requirements would increase around 320 MW in 2019/20 for a scenario with 20% of wind power installation penetration.
Iberia	Studies by REE and REN concluded that deterministic methods and classical probability methodologies were insufficient for evaluating reserve requirements. A time-stepping Monte Carlo simulation as a method is now being studied to determine operational reserve strategies. It has been identified that operational reserve, defined as reserve mobilised in less than one hour, should be sufficient to absorb changes in net load within that time frame. However, unit commitment has to be redefined and this is still being investigated.
All Island	The maximum amount of wind power that could be integrated without compromising system reliability was evaluated. The scheduling and dispatch study found that it was feasible to operate the All Island power system reliably with up to 42 % energy from renewable resources, mainly wind.

Power system security studies	Balancing
Wilmar	Impact of 10% and 20% wind power penetration on balancing costs were evaluated. The general findings were that: • Integration costs are highest in Denmark and Germany which are dominated by thermal production, whereas they are lowest in Norway where hydro-based generation dominates. • Norway with high amounts of flexible hydro power generation is extremely suitable for integrating wind power. The integration costs for Norway decreases from 10% to 20% wind power integration scenarios. • Integration costs increase in a country when its neighbouring country gets more wind power.
SPP	The study found that even if all needed transmission upgrades are in place, integrating 10-20% of wind power will increase operational complexity and lead to economic challenges. Specifically the following impacts were reported: • The need for flexible resources increases as forecast errors increase. Therefore, consolidating SPP into a single balancing area (as planned) will reduce the overall needs for reserves and flexible resources. • Ancillary service requirements depend on the wind power penetration level. Regulation-up and regulation-down requirements are not symmetrical. Wind power plants may be able to provide regulation-down during high wind periods. • Forecast errors increase start-ups of flexible units and reduce generation of less flexible units. • The impacts of forecast errors are different depending on whether the deviation from the forecast is positive or negative. Wind under-forecasts tend to exacerbate wind curtailments while over-forecasts have a much smaller impact on curtailment but could lead to reliability issues if not enough non-wind resources are committed.
ESIPC [56]	ESIPC used the PLEXOS model to make a half hourly chronological analysis. It was found that the volumes of installed wind power used in the study were able to be accommodated without significant operational impact.
Transend	A total installed capacity of 1043 MW of wind generation in the state, as well as a potential further 700 MW has been considered. This is against the current off-peak demand of around 780 MW. It was found that generation scheduling and regulation reserve requirements will be manageable even for very high wind penetrations. A modest increase in regulation FCAS requirements is likely to be required.

Table 8: Summary of balancing in the wind integration studies selected for review. Source: energynautics

Conclusions: In general, wind variability and forecast errors increase the required level of reserve. If the wind penetration level is low, significant changes are not usually required because the existing operating method is designed to deal with a certain level of uncertainty. As the wind penetration level increases, however, challenges arise due to the displacement of conventional power plants (which provide spinning reserve) and the introduction of potentially higher ramp rates.

56 This was not a detailed study of operational impacts.

Relevance for NEM system: In a market such as the NEM, where bidding is relatively short, at 5 minutes before dispatch, the real balancing concern is on the very short-term basis, particularly regulation reserves. It has been found, however, that wind forecast errors are the main factors affecting reserve, and they are larger with increasing time frame away from dispatch. The closer to real-time dispatch the better the forecast accuracy. Therefore, it is envisioned that impact on balancing in the NEM will be less burdensome than for some other power systems with day-ahead markets. However, it would be pertinent to conduct a study of the variability of the wind power based on measurement data in the NEM, particularly regarding weather-based changes in output, for example to assess the event of a storm front coming through the coast line of South Australia, and whether changes to the existing regulating reserve requirements are necessary.

Similarly, integration of solar power should be considered, as forecast error and weather-related variability issues (max ramp rates) could also impact balancing depending on the expected penetration level.

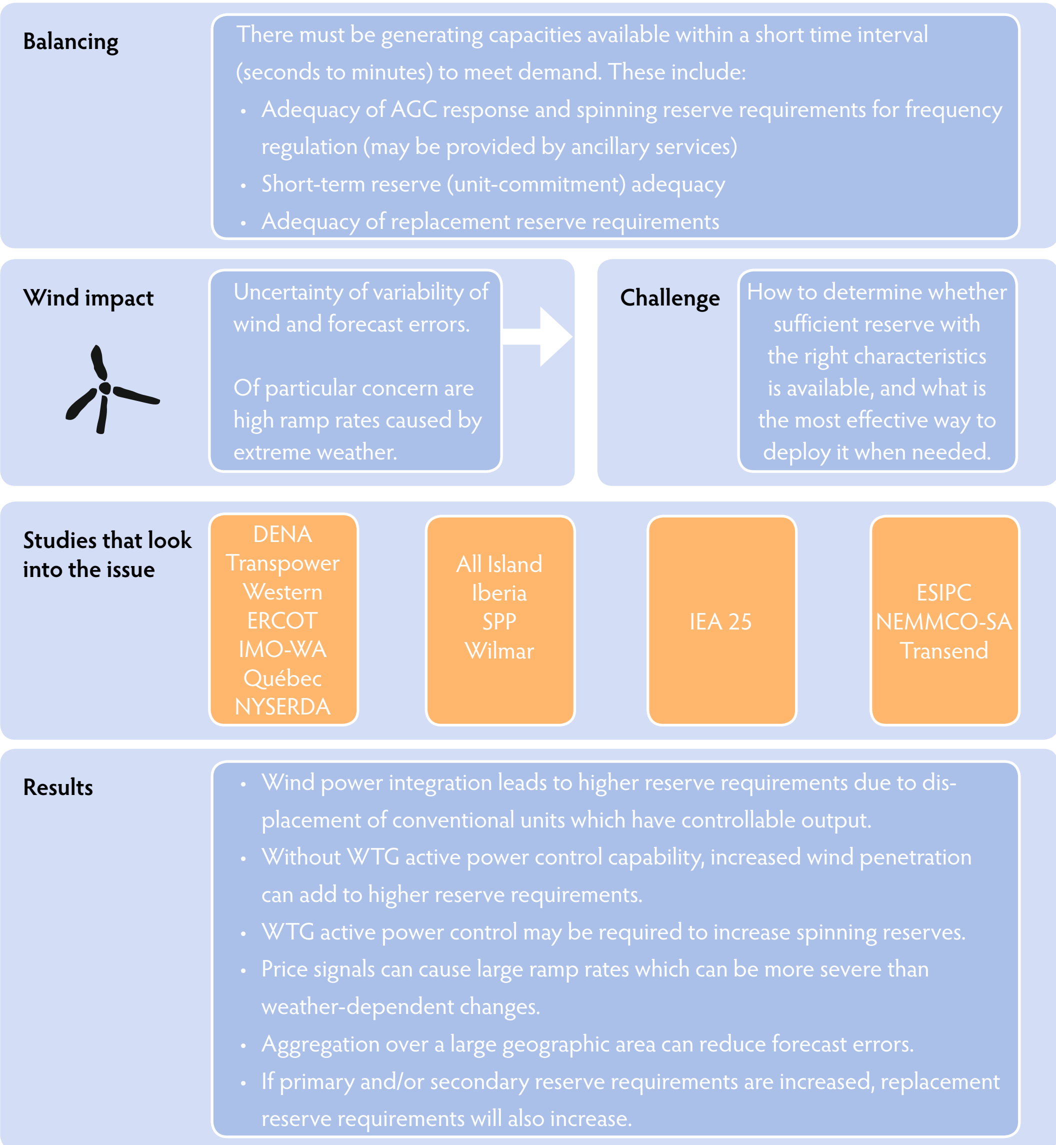

Figure 15: Summary of issues involving balancing. Source: energynautics

3.6. VOLTAGE CONTROL

The issue: The main challenge for voltage control is to maintain acceptable steady-state voltage levels and voltage profiles in all operating conditions, ranging from minimum load and maximum wind power production to maximum load and zero wind power[57]. Constantly changing supply and demand implies a constantly changing power flow and voltage profile all over the network. Therefore operation is also concerned with keeping these parameters within operating limits.

Possible impact of increasing wind penetration: Since adding wind power to the system changes the steady-state and dynamic stability characteristics of the power system, new voltage support systems may be required. Furthermore, if wind power plants with inferior voltage support capabilities replace conventional generators, more support measures may be required.

Typical methods used for studying the issues: Reactive power demand must be provided locally, since it cannot be transported over long distances. This is generally managed by obtaining reactive power support from generation, loads, or external voltage support devices. Power Voltage (PV) and Reactive Power Voltage (QV) analyses are typically used to determine the stability limit for a particular area. These analyses calculate the relationship between voltages and load as the load is increased. The load is increased until the load flow cannot be solved, indicating the point of collapse and the limit for load in the region.

International experience: The Irish All Island Renewables Facilitation study[58] performed steady-state analysis of voltage stability limits by calculating the PV and QV curves for dispatches with zero exchange over the interconnector to Great Britain. The worst case scenario was emulated by assuming that tap changers of all transmission to distribution transformers were locked and that reactive power capability of wind power plants was limited to unity power factor. Analysis of this case identified that a high amount of distribution-connected wind power decreases voltage stability. This is because distribution-connected wind power plants (35% in this case) cannot participate in voltage control unless they are equipped with additional reactive power compensation. In addition, providing reactive power at distribution level would not effectively solve reactive power issues at transmission level. Since reactive power capability of wind power plants are generally lower than that of synchronous generators, when they displace conventional generators, it was found that significant amounts of reactive power sources were needed at strategic locations in the transmission system. Based on the findings, a number of mitigation measures were suggested:

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58 (24) Pages 32-35

- Specify a continuously variable and continuously acting voltage regulation system (e.g. power factor for different operation points) in the Grid Code for transmission-connected wind power plants.

- Place additional reactive power sources, e.g. static VAR compensators (SVCs) or similar equipment, at strategically chosen locations where necessary.

- Define a minimum requirement for conventional generation units that should never be put offline ("must run units") in certain regions.

- Sensitivity analysis suggested that it makes little difference whether additional reactive power is provided by static VAR compensators, similar equipment or large wind power plants connected to the transmission system because wind power plants are dispersed throughout the All Island Power System. But if wind power plants provided reactive power in a region where wind speeds suddenly fell, they would have to continue feeding reactive power into the transmission grid (even at zero active power) until conventional power plants with synchronous generators are started up.

Transpower New Zealand[59] also performed PV analysis to assess the impact on voltage stability limits when wind generation with limited ability to control voltage displaces other forms of regional generation. The worst case scenario was used as a preliminary study to identify areas which may require detailed investigations at a later date. It was found that the addition of wind generation (or any other generation) within most regions has a positive effect on voltage stability limits because the real power output of the new generation reduces the amount of power transferred into the region (reducing reactive losses and voltage drop). However, it was also found that the displacement of other forms of regional generation by wind generation reduces voltage stability limits by about 10-34% of the amount of regional generation displaced by wind generation.

The IEA Task 25 report (2) suggests some common mitigation measures. Firstly, modern wind turbines equipped with power electronics to control reactive power output and terminal voltage should be employed. This can be enforced by a Grid Code, particularly for transmission-connected wind power plants.

After the generators themselves, capacitor banks and transformer tap changers represent the most common means to control voltage profiles. Static VAR Compensators (SVC) and STATCOMs placed in the grid or at wind power plants open up possibilities to serve both the grid and wind power plants and benefit both. It is also possible for synchronous generators to operate as reactors, or voltage support services to be sought from network ancillary services.

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Relevance for NEM system: As noted in section 3.3, studies of the NEM indicate that the addition of wind power can have significant impacts on the availability and location of reactive power sources. In the NEM, most reactive power is provided through performance standard requirements placed on generators. A relatively small amount of voltage control services is provided by Network Control Ancillary Service (NCAS). Additional NCAS may be sourced if there is a lack of reactive power. Under these ancillary services, generators absorb or generate reactive power from or onto the electricity grid and control the local voltage accordingly.

It is recommended that voltage stability studies are performed for specific connections and regions, appropriately considering the voltage support capabilities of the wind power plants, to assess whether the performance standard requirements in place are sufficient.

3.7. POWER QUALITY

The issue: Power quality is observed at the connection point, and includes aspects such as harmonics, flicker, and voltage and current distortion due to unbalanced faults. It is affected by WTG converters and reactive compensation equipment such as STATCOM, series capacitors and switched capacitors.

It is important that the power delivered to consumers has an adequate quality according its usage. Without this, an electrical load may malfunction, fail prematurely or not operate at all. In this respect, the following items are often observed:

Transient overvoltage is a brief, high frequency increase in voltage on the AC mains. Low frequency transients in the 100 Hz range are typically caused by capacitor switching which resonate with the inductance of the distribution system. High frequency transients in the 1 kHz range are caused by lightning and inductive loads, and can be absorbed using surge suppressors.

Harmonic distortion occurs when there are loads that draw current only at the peak of the voltage waveform, causing distortion in the sinusoidal voltage and current. Total Harmonic Distortion (THD) and Total Demand Distortion (TDD) can be used to measure the level of distortion. It is an important aspect for efficient and accurate power system operation, as it can affect transformer and meter operation and interfere with protection circuit breaker operation.

Flicker is a specific problem related to incandescent light and a human's sensitivity to it. The sensitivity is a function of the fluctuation frequency as well as the voltage level of the lighting.

The voltages and currents on each phase of the three-phase system can be unbalanced if there is a problem such as a fault that affects the phases differently.

Possible impact of increasing wind penetration: The operation of wind turbines can affect power quality of the local grid. Depending on the grid configuration and the type of wind turbine used, different power quality problems may arise. Fluctuating power production from wind generation using old turbines (fixed speed induction generator type) may cause flicker disturbances. In the case of variable speed turbines, one drawback might be the injection of harmonic current into the grid. Depending on the type of inverter used, different orders of harmonics might be produced.

Typical methods used for studying the issues: Investigation of impact on power quality resulting from wind integration is not the subject of system-wide studies; it is more relevant for small island studies. Therefore it is relevant for studies on the installation of certain types of equipment, but should not be the focus of large system-wide studies.

International experience and relevance for NEM system: Of the studies reviewed, the only one that investigates power quality is the DENA study, and even in that, it is specifically for the offshore wind power plant. This is most likely because power quality is a problem (if any) observed on a local level, and the study must be performed for each and every specific setup of the wind power plant and connection. Therefore it makes little sense to investigate this issue in detail for a system-wide wind integration study. Rather, it is recommended that this issue be investigated when specific connection studies are required.

4

KEY TECHNICAL SOLUTIONS: MEASURES THAT SUPPORT WIND INTEGRATION

4. KEY TECHNICAL SOLUTIONS: MEASURES THAT SUPPORT WIND INTEGRATION

A number of technical solutions are introduced in the wind integration studies to counterbalance the negative impacts of wind power and to support their integration into power systems. Mostly, solutions relate to modifying the output of the wind power plant to provide network services similar to those of conventional power plants. Another objective is to increase the flexibility of the power system to be able to adapt to variable generation.

4.1. WIND TURBINE TECHNICAL REQUIREMENTS

Modern wind turbines can offer sophisticated controllers which can provide a variety of network support and production services. These are described below.

4.1.1. Low voltage ride-through

Voltage ride-through mechanisms can be integrated into all modern wind turbine generators (Type 3 and 4[60]), mainly through modifications of the turbine generator controls and adding additional equipment such as an uninterruptible power supply (UPS) to the wind turbine. This allows the wind turbine to remain connected during voltage dips, rather than disconnect, and contribute to post-contingency recovery. Older Type 1 or 2 wind turbine-generators typically need additional equipment such as DVARs (subject to detailed studies)[61] to achieve low voltage ride-through.

4.1.2. Dynamic reactive power support

Reactive power support and power factor control can be provided through built-in capability (available for wind turbine generators Types 3 and 4), however, some manufacturers still choose to use farm level reactive compensation through a combination of switched capacitor banks and/or power electronic transmission technologies such as SVC/STATCOM, reserving more converter capability for real power production.

4.1.3. Frequency regulation

Sudden changes in wind power output may cause fast frequency changes. When demand is low and wind production is high, there may not be enough conventional units online to adjust to these changes and maintain frequency stability. Since wind turbine outputs are controllable

60 Type 1: Squirrel Cage Induction Generators (SCIG), Type 2: Wound-Rotor Induction Generators with Variable External Rotor Resistance, Type 3: Doubly Fed Induction Generator (DFIG), Type 4: Full Converter Wind Turbine Generator

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with very fast response times, in a high frequency situation the outputs can be reduced and contribute to frequency control. Figure 16 depicts different ways in which the wind turbine output may be controlled. In addition, a concept called "delta control" is being demonstrated in Denmark. This is where the wind power plant's output is normally operated at a compromised level so it has room to either boost or reduce its output as a conventional spinning reserve unit would. The wind power output from such a control mechanism can be seen in Figure 16 below (far right). In this way, wind power plants can also provide ancillary services. However, for this concept to work, it would have to be financially compensated for constantly curtailing production (for example through the FCAS market in the case of the NEM).

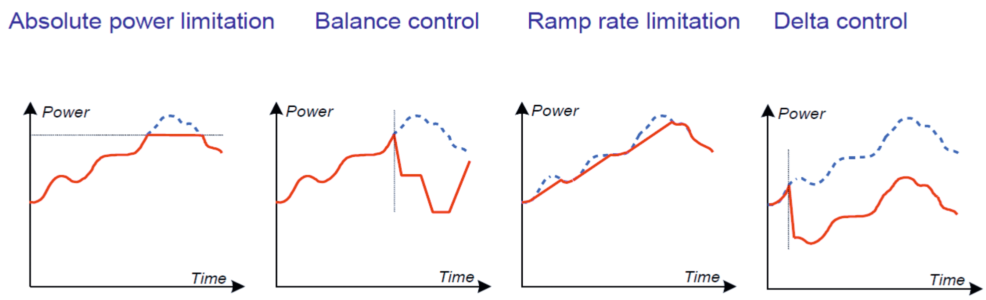

Figure 16: Power control options. Source: (36) Page 6

4.1.4. Virtual inertia capability

Wind turbines can provide inertia in the case of a frequency excursion, by taking out all the energy stored in the rotating mass of the rotor in a short time frame, effectively mimicking inertia response from a synchronous generator for a few seconds. This service can be solicited by the grid operator and would only be used when there is a significant frequency deviation. Providing virtual inertia can be useful during low demand periods when high wind penetration displaces conventional synchronous generation which would normally provide system inertia in contingency situations.

4.1.5. Power system stabiliser

Currently under academic discussion and development by some wind turbine manufacturers is to offer power system stabiliser (PSS) features which can add to system damping. In the case of a Type 3 wind turbine, the contribution to damping can be made by including an auxiliary PSS loop in the control scheme that, under oscillatory network conditions, injects power variation into the network that stimulates additional damping power in the network synchronous generators[62].

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4.2. USE OF FLEXIBILITY MECHANISMS TO SUPPORT WIND POWER INTEGRATION

In addition to advanced turbine capabilities, there are a number of measures that are commonly used to accommodate wind power variability. The term "flexibility options" is often used to refer to these measures because they make the system more flexible and adaptable to wind power characteristics.

4.2.1. Grid optimisation

Operating limits of the grid are often designed against the worst case scenario, which rarely occurs in reality. Incorporating a monitoring scheme for critical parameters may allow a flexible operating limit to be applied, and opmise the use of the existing system.

The EWIS (13) for example, examines the use of power flow control to optimise the use of the existing grid. Particularly on a medium term, while wind power capacity is increasing much faster than transmission capacity, dynamic rating and flow control with phase shift transformers are suggested as measures to reduce the bottlenecks. Dynamic rating adapts the allowable line loading according to the line temperature, while flow control permits power flow sharing between parallel circuits to be controlled in order to maximise available capacity.

The DENA study (6) also investigates the potential of a temporary loading and dynamic rating of overhead lines to increase their transmission capacity.

In Portugal, phase shift transformers are already operating in selected substations and dynamic rating is being used for main transmission lines to support the integration of wind energy[63].

Although these measures can help to relieve network congestions, they are only effective as temporary solutions, until actual grid reinforcements are implemented.

For voltage support, stability can be improved by installing FACTS devices (dynamically modifying the impedance of the power system seen from the generating unit terminals[64]), switchable reactors or static VAR compensators/static synchronous compensators (SVC/STATCOMs).

4.2.2. Demand-side management and storage

Rather than having generation follow demand for balancing all the time, it may be possible to control some parts of demand. With more and more smart appliances being installed and smart grid initiatives being considered, it is anticipated that in the future demand-side management (DSM) could be used to counterbalance the variation in renewable energy

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64 (32) Page 10

sources and support its integration. There are very few studies that assess the impact of DSM coupled with wind integration; however it may be a valid topic for investigation. Similarly, storage devices such as Electric Hybrid Vehicles (EHVs) are seen to play a major role in DSM strategies. Emerging storage devices like EHVs, traditional forms of storage like pumped hydro schemes, as well as newer forms of storage like hydrogen can be coupled with wind power to reduce curtailment and also to assist with balancing.

4.2.3. Grid upgrades/widening balancing areas

It has been shown in a variety of studies[65] that the aggregation of wind power plants over a wide geographic area reduces output variability and forecast errors. In addition, by widening balancing areas through strengthening tie-lines and coordinated markets, balancing resources and reserves can be shared, alleviating the burden on conventional resources within a region. Therefore it makes sense to reinforce the grid so that wind power can be delivered to the demand centres without causing congestions which may impede the supply of required reserves.

4.2.4. Monitor and real-time network management

Although most of operation is automated, it is constantly monitored from a control centre by system operators. The system operators ensure that operating limits are not violated, and take actions to prevent or deal with violations if they occur. The system operator may also produce system performance reports using the data that is monitored and recorded.

With increasing amounts of wind generation and other renewable energies, the system is becoming more complex. Even if there are automatic adjustment measures, the system may run into situations where human judgement and manual adjustment are required.

In Spain and Portugal, a special control centre for renewable energies (CECRE) has been set up to monitor and collect information about production from renewable energy resources. In this control centre almost real-time calculations can be made to analyse the interaction of the power system with wind power and to avoid contingency situations. Due to the fact that not many systems actually have high penetration of renewable energy, or the facilities to collect and analyse such large amount of data, experiences from this control centre is expected to produce interesting results and valuable insights as to what factors are important in wind integration studies. For example it has already been demonstrated that there is value in treating wind production in an aggregated manner to improve forecasts, and even across different types of renewable technologies.

65 (115) Page 3, (2) Page 12, (77)

Furthermore in Germany, it has been observed that treating renewable energy other than wind simply as embedded generation may cause complications. With close to 18 GW of installed solar PV capacity in Germany, at this size it cannot be treated as embedded generation without grid support requirements. In order to properly assess the type of risks involved, it is important that this technology is appropriately modelled and included in system-wide integration studies to prepare for future scenarios where large penetration of wind and solar PV is expected. (The solar PV forecast for NTNDP of the NEM is vulnerable in this sense because it is treated as embedded generation (i.e. reduced demand) and does not consider the potential impact at all.)

5

EVALUATION OF TECHNICAL IMPACTS WITH SYSTEM PERFORMANCE

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To ensure that all the measures are implemented in the most efficient manner possible (i.e. lowest cost), certain parameters can be monitored. These include economic evaluation of grid reinforcements versus curtailing energy production to relieve bottlenecks, the cost of changing merit order versus benefits from avoided CO_2 emissions, and an evaluation of transmission and distribution losses.

5.1. WIND ENERGY CURTAILMENT

Traditionally, base load is covered by large conventional power stations (e.g. coal/nuclear) and variable load by sources that can adapt to fast changes such as gas and hydro. Intermittent renewable power in small quantities can be considered as negative load, displacing the conventional units responding to variable load. With only small amounts of intermittent generation the overall dispatch process is relatively unchanged.

However, with larger penetration levels, conventional power generation is displaced, while increasing CO_2 prices and fuel prices raise production costs for conventional power. Furthermore, base-load units such as nuclear and coal power plants may be phased out. These factors mean that that the characteristics expected from traditional base load units are changing. For example, despite the fact that they were not designed to operate in a flexible manner, they may be required to shut down or operate at part of their load levels more often. This kind of operation may place stress on the components of the units and could lead to increased outages and plant depreciation (38).

Particularly in the case of nuclear and coal power plants, a certain minimal generation level may be required, both for operational and economic reasons. Furthermore, generation units with certain characteristics may also be needed online, in order to meet minimum reserve and/or inertia requirements. If this is coupled with a low demand and/or a high wind period, there may be too much generation available in the system even with the export capability. In this case the only option is to curtail the wind energy (in the absence of storage options). Figure 17 on the next page gives an overview of the situation.

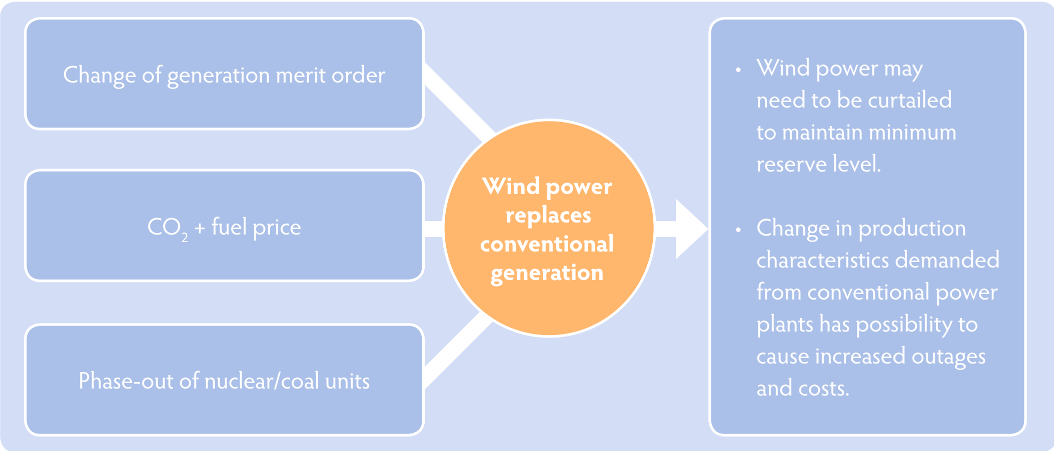

Figure 17: Impact of wind power on generation pattern. Source: energynautics

A commonly raised issue is what to do if there is a surplus of renewable energy generation during low demand. It would be logical to reduce the output of wind to match demand, however, this results in financial loss and wasted energy, because wind energy must be harnessed instantaneously and cannot be stored (sometimes referred to as "volatile energy"). The decision is usually made based on which option is more economic, however in a regulated market where renewable energy may be mandated to produce a certain amount of energy, this could result in unnecessarily high prices (likely in the case of NEM, where wind is competing with cheap coal and gas units). Also the question remains about the spinning reserve required to cover for wind volatility, when there is sufficient wind generation to cover for more than the minimum demand. (37)

While in most countries in Europe, TSOs can curtail wind energy in order to preserve system security, in some countries, the ability to curtail is extended to other specific situations (for example, if significant congestion occurs or if wind production exceeds consumption levels). Financial compensation for wind power curtailments is provided in some countries and not in others. For example, in Spain, weak interconnection with France constrains dispatching, especially in low load hours where wind power cannot substitute conventional generation that would be required only some hours later[66]. This power cannot be exported, neither can reserve be imported. Therefore, the need for a certain amount of conventional generation in low load moments makes wind curtailment unavoidable.

The study by NYSERDA (5) found that no operating conditions justified the need for wind power curtailment at a state-wide level (i.e. backing down all wind generators at the same time). Rather, curtailment may be required to maintain system reliability, to handle temporary local transmission limitations (e.g. line out of service) or in anticipation of severe weather (e.g. intentionally curtail wind generation in advance of a severe storm affecting a large portion of the state). This may be done by sending maximum power orders to wind power operators or via SCADA in the case of unmanned generation facilities. In light of this investigation it was recommended that market mechanisms should include incentives to reward the accuracy of wind generation forecasts.

66 (13) Page 48

One solution is to add an interconnection with a neighbouring power system and export the wind generation and share ancillary services. However, these problems must be foreseen well ahead of time because building additional capacity between states in the NEM is an arduous and time consuming process at best. This is why a system-wide study is recommended, at least considering wind and ancillary service import/export capabilities.

5.2. CO_2 EMISSION

CO_2 emission resulting from generation dispatch is likely to be reduced with higher penetration of wind power generation because conventional power such as coal-fired power generation will be displaced. However, if gas units are operated more frequently to compensate for the variable wind power output, the reduction in CO_2 emission from coal power plants may be offset somewhat by emissions from gas power plants.

The DENA study, NYSERDA, All Island and EWIS study make brief investigations into the effect of resulting CO_2 emissions. Despite the stated concern, in all cases the general trend was that CO_2 emissions are reduced with increasing wind penetration.

If the cost of CO_2 emission is included in the analysis, this may also affect the resulting dispatch pattern. Therefore an investigation including market interaction is recommended.

5.3. CHANGE IN POWER FLOW CHARACTERISTICS ON SYSTEM LOSSES

Transmission loss increases if high power transfer is required from one location to another. Whether wind power has positive or negative effect depends on the installed capacity and location. If large wind power plants are installed at remote locations from the load centres and contribute to power flows on the transmission network when it is already congested, losses will increase. However, if wind generation is mostly distributed generation and installed locally in and around load centres, it will reduce losses.

This was demonstrated by the study in Minnesota (18), which evaluated the change in system-wide electrical losses caused by integration of wind power. PSS/E load flow program was used to evaluate summer peak and summer off-peak scenarios for a base case which has no additional wind installation and a distributed renewable generation case with 600 MW of predominantly wind generation. In this model, losses decreased in the summer peak scenario compared the base case, whereas the losses increased in the summer off-peak scenario. The reason for the increase in losses for the off-peak scenario was that local generation may not be used to supply the load centres, in favour of a more economical dispatch.

Because system loss is highly dependent on the distribution of power sources, it is unlikely that integration of wind power will decrease system losses in the NEM, since wind resource is available at the margins of the system in South Australia and Tasmania where there is very small load.

6

CONCLUSIONS

6. CONCLUSIONS

The review of various wind integration studies has identified the type of issues commonly investigated and the approaches used. A summary of these findings is presented in Table 9. The common findings and conclusions for the studies are explained below, with their relevance to the NEM highlighted.

The impact of generation capacity build-up on system adequacy and security is a concern for power systems, regardless of the energy source. Adding new generation can change the expected power flows and stability characteristics. For wind power however, new challenges and concerns are introduced because its output is weather dependent, the resources are typically available in remote areas of the network, and time from planning to construction is much shorter than for conventional power plants or system components.

Generation adequacy: For long-term reliability, it is important to provide adequate generation capacity to cover the projected peak demand. The capacity credit of wind power becomes an important aspect in this assessment, especially if retirement of conventional power plants is envisioned, so that wind power could partly replace the current base load generation. Since in most cases generation adequacy is assessed using reliability metrics, calculation of wind power capacity credit using a reliability method is most intuitive, and recommended, as it is the most accurate calculation method. However, if the wind penetration level is distinctly low, and the purpose for calculating the capacity credit is for an analysis which does not require a high level of confidence, an approximation method may be sufficient.

Accurate estimation of wind power capacity credit

6

Grid planning: Wind power plants often require grid extensions and reinforcements to be able to efficiently deliver their energy because they are located further from loads. Combining this with the short lead time for construction of wind power plants, it becomes vital that grid adequacy and integrity is assessed well ahead of time. In many countries and regions, grid planning is driven by political will to increase the penetration of renewable energies, rather than economic efficiency of transmission investment. In order to build a robust network which can adapt to a range of future wind development scenarios, the current grid planning process in the NEM may require revision.

Priority for renewable energy integration

System security (electromechanical impact): Although direct impact on rotor angle stability, small-signal stability and sub synchronous interaction is not warranted for wind turbines which are generally decoupled from the grid, indirect impact may be visible when: 1) large amounts of synchronous generation is displaced by non-synchronous generation and changes the oscillatory characteristics of the system; or 2) HVDC or series-compensated HVAC lines are used to connect remote wind power plants.

Displacement of synchronous generation may impact system stability

System security (low voltage ride-through): The main concern for wind power integration is the impact following a short-circuit fault or a voltage dip. Older turbine types, and in some cases wind power plants treated as negative load, do not provide fault ride-through capability. In these cases the wind power plants are disconnected when a voltage dip is observed, leaving the system more prone to instability. In response to this issue modern turbines can provide fault ride-through capability and Grid Codes can mandate that wind turbines remain connected during voltage dips, and provide reactive power support post-contingency. If this feature is not offered by the generator technology, it can be provided with external equipment like DVARs.

FRT and voltage support capability requirements in Grid Code

System security (frequency response): When wind power generation reaches high penetration rates, there may be times when demand is supplied completely by wind power (e.g. during off-peak periods). In these situations, it may be necessary to have a minimum inertia requirement, to maintain the ability to control frequency excursions, particularly for weakly interconnected systems. The Irish system operator for instance currently limits the non-synchronous generation (mainly wind and PV) to 60-80% of system generation. With a peak penetration of over 80%, which is one of the highest instantaneous penetration levels for weakly interconnected power systems observed in the world, South Australia may need to impose a similar limit.

Frequency response requirements more important for weakly interconnected systems

System security: It is important that the ability of the wind power plant to support voltage and frequency is modelled appropriately when assessing steady-state, transient, small-signal stability and frequency response. It was found that until now, some studies performed in the NEM assume the "worst case" scenario, that wind power generation is expanded using old turbine types without voltage support capabilities. This is an unrealistic assumption, as future wind generation technologies are developing in the direction to provide more and more support capability options. Therefore, it is recommended that a system-wide study is performed with a variety of wind technology capabilities, and to test if the current Grid Code is sufficient for mixed turbines scenarios.

Assess system security reflecting actual technical capabilitiy of wind power plants

Frequency regulation (balancing): One of the major aspects of wind power integration frequently investigated is that it is weather dependent and intermittent. Although its output can be forecasted with a good level of accuracy, the increased degree of uncertainty in the balancing process often results in higher requirements for operating reserves. Power systems are already designed to operate with variability and uncertainty of load, and the process to incorporate wind power does not require reinventing the wheel. Nonetheless it is important to check the adequacy of existing reserves and make sure that the existing procedures are sufficient for handling the additional level of uncertainty.

Ability of balancing system to accommodate uncertainty and ramp rates caused by wind power

Variability and ramp rates: One of the major concerns of wind power integration is that it is weather dependent and intermittent. For example, in the case of a storm front hitting the coastline of South Australia, there might be the risk that almost all wind power plants in the state are shut down consecutively over a short to medium time frame (details have not been studied yet for SA) due to extremely high wind speeds. Furthermore, some studies have shown that the impact from ramp rates created by price volatility can be larger than weather-based variability. For the NEM which trades on a 5-minute dispatch market, this could also be a problem as it is subject to highly volatile prices.

Solar PV power: Although the focus of this report is on wind power integration, discussions with various transmission systems operators indicated that solar PV growth cannot be dismissed as an insignificant issue for renewable integration studies. For example in Germany and Italy, the growth of solar PV has rapidly reached some giga-watts, and considerable problems that affect stability and balancing have been observed. Although in the NEM solar PV penetration may be considered to be at insignificant levels, the potential growth and impact should not be underestimated. Therefore, it is recommended that how solar PV is treated is revised and included in any future renewables integration studies.

Development of future renewable energy scenarios including solar PV

System-wide study: Compared to many other power system which settle the market bidding in a day-ahead market and manage the balancing with ancillary services, balancing issues in the NEM will be easier to deal with since it has a 5-minute dispatch market. However, it is recommended that generation adequacy, balancing, and dynamic stability impacts by wind power, are evaluated on a NEM-wide basis rather than a state-by-state basis. It has been shown in many studies that aggregation of wind power over a larger geographic area reduces variability, improves forecast accuracy, and balancing resources can be shared between interconnected regions. Although interconnections between states are currently limited, there are benefits that system-wide studies can bring in certain situations.

Consider the benefits of system-wide studies

Power quality: The effect of wind power variability and technology employed for the installation of wind power plants on power quality issues such as harmonics and flicker, as well as the response to unbalanced faults may be investigated. These effects are likely to be observed locally however, therefore it is recommended that power quality is studied for each particular connection when specific sites are considered.

Measures that support wind integration: To deal with the potential issues identified through technical analysis, several solutions have been suggested in the wind integration studies. Some of the common measures, that have been identified as being important for smooth wind integration and with merit for further investigation, are the following:

- Aggregation of wind power plants over a larger area, coupling with storage devices, implementing demand-side management to reduce variability of wind power output.
- Aggregated control of wind power plants and other renewable energy generation such as solar power plants.
- Augmentation of the grid to increase access to wind power resources as well as to share balancing resources over a wider area.
- Optimisation of the use of existing infrastructure using FACTS devices and phase shifting transformers are suggested as an intermediate measure.

- Application of operation constraints to secure minimum contingency and balancing reserves, system inertia, voltage support, fault current level and dynamic stability.

- Implementation of generation performance requirements in Grid Codes.

- Implementation of real-time network management based on wind power output.

Evaluation of system performance: To evaluate the financial consequences of technical impacts of wind power and to assess system efficiency, the performance of the power system including wind power is often evaluated. Market simulations are used to determine the likely impact on market performance (costs and price volatility), as well as the resulting system wide CO_2 emissions, while operation efficiency is measured by network losses and the amount of unused (or curtailed) wind energy. It is recommended that AEMO consider carefully the objectives of the studies, and use an appropriate performance indicator to assess the effectiveness of the implemented solution.

Technical issue	Method	Data requirements			Studies that look into it	Relevant NEM area
		Demand	Wind power generation	Non-wind generation		
Generation adequacy	Estimate the capacity credit of wind power by: a) Calculation of reliability metrics such as LOLP, and compare reference case with wind power integration case b) Calculation of average capacity factor corresponding to high demand periods Type a) is the preferred methodology	Historical demand (+10 years) a) Hourly/15 minutely historical demand profiles b) Defined high demand period based on analysis of historical demand	High/medium/low wind development scenarios (different distribution of wind power plants may be considered) a) Hourly/15 minutely historical wind power generation may be developed from wind speed measurements (time-synchronised with demand) b) Wind power generation corresponding to high demand periods	a) Available generation capacity considering scheduled and forced outages b) Not considered	IEA Task 25 a) Iberia, All Island, IMO-WA, DENA b) NYSERDA, NYISO, ESIPC	Currently using a process that looks at average capacity factor corresponding to high demand periods on a region (type b)) by region basis. It may be pertinent to review the calculation methodology and also consider capacity factor on a whole of NEM basis.
Grid planning	a) Steady-state power flow simulations for (N) and (N-1) situations b) Time-synchronised dispatch (market) simulation (analysis of inter-area flows, often compromised grid model)	a) Peak demand b) Forecast demand (historical demand scaled to future)	High & low wind output P&Q output based on fixed wind speed corresponding to the point in time analysed Aggregated wind power plant model with fixed wind speed corresponding to the point in time analysed	a) P&Q output model with full availability corresponding to the point in time analysed b) Available generation capacity considering scheduled and forced outages	a) DENA, Minnesota, Iberia, All Island, SPP, IEA 25, NYISO, ERCOT a) EWIS, NEM, ESIPC	NEM: Grid planning approach should be more top-down

Technical issue	Method	Data requirements			Studies that look into it	Relevant NEM area
		Demand	Wind power generation	Non-wind generation		
Stability (steady-state, transient, oscillatory)	a) Dynamic power flow simulations following a 3-phase fault or sudden loss of a generating unit b) Modal analysis by eigenvalue calculation of small-signal stability with and without wind power c) Electromagnetic time domain transient simulations to evaluate the sub synchronous control interaction (SCCI) between the wind turbine converter or solar PV inverter and the HVDC link or series-compensated system	a) Off-peak demand b/c) Appropriate static and dynamic load modelling	a) High wind power output for aggregated WPP model, P&Q output based on fixed wind speed. Model must include corresponding LVRT and reactive power support capability of WPP. b) Detailed WPP models, or assume constant mechanical torque c) Detailed models of WTGs and external devices providing reactive power support	a) Dynamic models of generators, external reactive power devices and protection equipment b/c/d) Dynamic models of generators, excitation, speed governors and power stabilisers	Voltage: DENA, Transpower, Minnesota, IMO-WA, Iberia, All Island, SPP, EWIS, Wilmar, IEA 25, ElectraNet, NEMMCO-SA, Transend, Vencorp Rotor angle: All Island, EWIS, ElectraNet Oscillatory: Transpower, All Island, Wilmar (limited), EWIS, ElectraNet, NEMMCO-SA Sub synchronous: ERCOT, Forsk, Elforsk	NEM: In support of grid planning studies SA, TAS, VIC: Regions with high wind power penetration
Fault level	Short-circuit calculations (steady-state) (Electromagnetic transient simulations for detailed connection studies)	Off-peak demand	P&Q output based on fixed wind speed	P&Q output model with full availability corresponding to the point in time analysed	General: NREL report on SC current Thorough: Transpower, All Island Brief: Iberia, DENA (offshore only)	Basslink: Low fault levels may impact Basslink operation SA, TAS, VIC: Weakly connected WPPs

Technical issue	Method	Data requirements			Studies that look into it	Relevant NEM area
		Demand	Wind power generation	Non-wind generation		
Inertia and frequency response	Dynamic frequency simulations following the sudden loss of generation	Off-peak demand	P&Q output based on fixed wind speed (high output level) Wind power plant features such as low voltage ride-through, reactive power support, low/high frequency ride-through, and virtual inertia may be considered if expected to be implemented.	Dynamic models of generators, excitation, speed governors and power stabilisers	Minimum inertia: All Island Primary reserve: Hydro Québec, Transpower, IMO-WA, IEA 25, Wilmar, ElectraNet, Transend	SA and TAS: frequency island
Balancing (regulation, dispatch, scheduling)	Estimate reserve requirements resulting from time-synchronised simulation of the dispatch process The performance can also be evaluated in terms of the resulting CO_2 emissions, utilization rate of major interconnectors (if modelled), and curtailed amount of wind energy.	Historical demand (x years) scaled to future	Hourly/minutely historical wind power generation and forecast profiles (time-synchronised with demand) Wind power output and forecast values may be estimated based on historical wind speed measurements Statistical analysis of wind power output (or net load) variability to find highest ramp rates (typically experienced during extreme weather conditions)	Available generation capacity considering scheduled and forced outages Conventional reserve availability characteristics (ramp rates, unit start/shut down times, etc)	General: NREL report on operating reserves, IEA 25 Regulation: ERCOT, NYISO, SPP, Hydro Québec, Wilmar, DENA, IMO-WA, Iberia, Transend Dispatch: Transpower, Western, DENA, NYISO, SPP, All Island, Iberia Scheduling: Transpower, All Island	NEM

Technical issue	Method	Data requirements			Studies that look into it	Relevant NEM area
		Demand	Wind power generation	Non-wind generation		
Voltage control	Steady-state PV and QV analysis	Peak demand	Model the behaviour of the wind power plant at the point of connection considered. (For example in the case of New Zealand, WTGs must meet minimum power factor correction requirements, therefore, WTGs were modelled as PQ loads with unity power factor).	Various generation and dispatch scenarios	Transpower, All Island, NEMMCO-SA	Weakly connected WPPs

Table 9: Technical issues and approaches commonly used to investigate them in wind integration studies. Source: energynautics

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102. Experience from Wind Integration in Some High Penetration Areas. **Söder, Lennart, et al., et al.** 1, s.l. : IEEE, March 2007, IEEE Transactions on Energy Conversion, Vol. 22.

103. On Limits for Wind Power Generation. **Söder, Lennart.** 3, 2004, International Journal Global Energy Issues, Vol. 21, pp. 243-254.

104. On Methodology for Modelling Wind Power Impact on Power Systems. **Söder, Lennart and Holttinen, Hannele.** 1/2, 2008, International Journal Global Energy Issues, Vol. 29, pp. 181-198.

105. A Review of Different Methodologies used for Calculation of Wind Power Capacity Credit. **Söder, Lennart and Amelin, Mikael.** s.l. : IEEE, 12 August 2008, Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, pp. 1-5. ISSN : 1932-551.

106. The Impact of Large Scale Wind Power Generation on Power System Oscillations. **Slootweg, J. G. and Kling, W. L.** s.l. : Elsevier, February 2003, Electric Power Systems Research, Vol. 57, pp. 9-20. doi:10.1016/S0378-7796(03)00089.

107. CanWEA Pan-Canadian Wind Integration Study Paper. **Tremblay, Martin, et al., et al.** [ed.] Uta Betancourt and Thomas Ackermann. Québec City : Energynautics, 2010. 9th International Workshop on Large-Scale Integration of Windpower into Power Systems/Transmission Networks for Offshore Wind Power Plants. pp. 11-17.

108. Frequency Control in Power Systems with High Wind Power Penetration. **Tarnowski, German Claudio, et al., et al.** [ed.] Uta Betancourt and Thomas Ackermann. Québec City : Energynautics, 2010. 9th International Workshop on Large-Scale Integration of Windpower into Power Systems/Transmission Networks for Offshore Wind Power Plants. pp. 329-336.

109. Operational Experience of Extreme Wind Penetrations. **Estanqueiro, Ana, Mateus, Carlos B. and Pestana, Rui.** [ed.] Uta Betancourt and Thomas Ackermann. Québec City : Energynautics, 2010. 9th International Workshop on Large-Scale Integration of Windpower into Power Systems/Transmission Networks for Offshore Wind Power Plants. pp. 34-40.

110. Frequency Control in Quebec with DFIG Wind Turbines. **Dernbach, M., Bagusche, D. and Schrader, S.** [ed.] Uta Betancourt and Thomas Ackermann. Québec City : Energynautics, 2010. 9th International Workshop on Large-Scale Integration of Windpower into Power Systems/Transmission Networks for Offshore Wind Power Plants. pp. 342-347.

111. Fast Simulation of Wind Generation for Frequency Stability Analysis in Island Power Systems. **Conroy, James.** [ed.] Uta Betancourt and Thomas Ackermann. Québec City : Energynautics, 2010. 9th International Workshop on Large-Scale Integration of Windpower into Power Systems/Transmission Networks for Offshore Wind Power Plants. pp. 337-341.

112. Large Scale Wind Power Integration from a European Point of View. Spanish TSO - REE- Studies in the Context of EWIS Project. **Diaz, Agustin, Mertinez, Sergio and Prieto, Eduardo.** [ed.] Uta Betancourt and Thomas Ackermann. Quebec City : Energynautics, 2010. 9th International Workshop on Large-Scale Integration of Windpower into Power Systems/Transmission Networks for Offshore Wind Power Plants. pp. 27-33.

113. **de Montigny, M, et al., et al.** A New Simuation Appraoch for the Assessment of Wind Integration Impacts on System Operations. s.l. : energynautics, 2010. pp. 460-467.

114. **Kamwa, I, Heniche, A and de Montigny, M.** Assessment of AGC and Load-Following Definitions for Wind Integration Studies in Quebec. s.l. : energynautics, 2009.

115. The Spanish experience in the integration of the electricity from wind power plants into the electrical system. **Ceña Lázaro, A and Gimeno Sarciada, J.** Madrid : Energynautics, 2008. 7th International Workshop on Large Scale Integration of Wind Power and on Transmission Networks for Offshore Wind Farms. Vol. I.

116. **Transpower New Zealand.** Wind Generation Investigation Project 1B: Effect of Unpredictability of Wind Generation Output on Scheduling. Planning and Investigations. s.l. : Transpower New Zealand, 2007.

117. **Transpower New Zealand.** Wind Generation Investigation Project 6: Effect of Wind Generation on Small Disturbance Voltage Stability. Planning and Investigations. s.l. : Transpower New Zealand, 2007.

118. **GE Energy Applications and Systems Engineering, EnerNex Corporation, AWS Truewind.** Technical Requirements for Wind Generation Interconnection and Integration. s.l. : GE Energy, 2009.

119. **Anaya-Lara, Olimpio, et al., et al.** Wind Energy Generation: Modelling and Control. Chichester : Wiley, 2009.

120. **Kundur, Prabha.** Power System Stability and Control. New York : McGraw-Hill, 1994.

121. **Doherty, Ronan.** All Island Grid Study WS2A: High Level Assessment of Suitable Generation Protfolios for hte All Island System in 2020. Dublin : The Department of Enterprise, Trade and Investment and The Department of Communications, Energy and Natural Resources, 2008.

122. **AEMO.** Electricity Statement of Opportunities: Executive Briefing. s.l. : AEMO, 2011.

8

APPENDICES

8. APPENDICES

8.1. APPENDIX 1: SUMMARY OF SELECTED WIND INTEGRATION STUDIES REVIEWED (NON-NEM STUDIES)

Study area	Study name, date, organisation (and consultant), link (where available)	Purpose, scope and impact of study
NATIONAL/SINGLE AREA STUDIES		
ERCOT (Texas, USA)	1. Analysis of Wind Generation Impact on ERCOT Ancillary Services Requirements, March 2008, Electricity Reliability Council of Texas (GE Energy). http://www.uwig.org/AttchB-ERCOT_A-S_Study_Final_Report.pdf	1. To assess the impact of integration up to 15 GW of wind power capacity (57% penetration) on the requirements for ancillary services procurement. The findings will aid the Electricity Reliability Council of Texas (ERCOT) and the Public Utility Commission of Texas (PUCT) to evaluate the reliability implications of wind generation penetration and to develop procedures and protocols for ancillary services procurement needed to keep a balance between system reliability and economic operation of the system.
	2. ERCOT CREZ Reactive Power Compensation Study, ABB, 3 December 2010, Electricity Reliability Council of Texas (ABB). http://www.uwig.org/CREZ_Reactive_Power_Compensation_Study.pdf	2. As part of the CREZ Transmission Plan, the reactive power support requirements had to be defined for nine circuits designated with approximately 50% series capacity compensation. • The size, type and location of reactive power support required were determined based on steady-state, dynamic and chronological analyses. • The potential for sub synchronous interactions between the proposed reactive compensation devices and nearby generators were also assessed.
Hydro Québec (Canada)		Much focus is placed on frequency control in the Hydro Québec system because it is mainly interconnected with neighbouring systems through DC links, making it a dominantly electrically isolated region.
	1. Assessment of AGC and Load-Following Definitions for Wind Integration Studies in Québec, October 2009, Hydro Québec.	1. Three methods for calculating AGC and load-following requirements are compared in this report. The approaches are based on statistical analysis of year-long minute/minute time series of load, wind and their forecasts, and are compared with actual AGC measurements.

Study area	Study name, date, organisation (and consultant), link (where available)	Purpose, scope and impact of study
Hydro Québec (Canada)	2. A New Simulation Approach for the Assessment of Wind Integration Impacts on System Operations, October 2010, Hydro Québec.	2. The impacts of wind integration on AGC and load-following is assessed through simulation, and compared with two other statistical methods. The impact on the number of additional alternators start-ups and shut-downs, as well as the number of interrupted exports/imports are also evaluated.
	3. Frequency Control in Québec with DFIG Wind Turbines, October 2010, Hydro Québec (RE Power). Note: All papers are published in the proceedings to the International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants for the corresponding year.	3. Wind power contribution to frequency response is evaluated. The use of DFIG wind turbines running under a controls scheme to support grid frequency through additional active power contribution is assessed.
Germany	DENA Grid Study I: Energy Management Planning for the Integration of Wind Energy into the Grid in Germany, Onshore and Offshore by 2020, February 2005, Deutsche Energie-Agentur GmbH (DEWI, E-ON Netz, EWI, RWE, Vattenfall) http://www.uwig.org/Dena-2005_English.pdf The Project Steering Group includes: • Bundesverband Windenergie e.V. • ENOVA GmbH • E.ON Netz GmbH • EWE AG, Offshore-Bürger-Windpark Butendiek GmbH & Co. KG • Offshore Forum Windenergie • Plambeck Neue Energien AG • Projekt GmbH • RWE Transportnetz Strom GmbH • Vattenfall Europe Transmission GmbH • VDMA Fachverband Power Systems e.V. • Verband der Elektrizitätswirtschaft e.V. • Verband der Netzbetreiber e.V. • VGB PowerTech e.V. • WINKRA-ENERGIE GmbH • Wirtschaftsverband Windkraftwerke e.V. • Zentralverband Elektrotechnik und Elektronikindustrie e.V. • Federal Ministry of Economy and Labor • Federal Ministry of Environment • Nature Protection and Nuclear Safety (guest)	The German Energy Agency (DENA) commissioned this study to: • Identify grid augmentations required to accommodate the projected amount of on- and off-shore wind power development • Identify critical grid conditions on the short-term • Assess long-term generation adequacy • Assess adequacy of balancing scheme The study was supported by associations and firms in the sectors of wind energy, grid and conventional power plants. **This study was a milestone in the public and political awareness of the challenges of grid integration of wind power in Germany. The results of the study were accepted by the wind industry as well as the grid operators. Some of the conclusions of the Dena grid study were integrated into the new German Renewable Energy Act, which came into effect 1. January 2009 (2).**

Study area	Study name, date, organisation (and consultant), link (where available)	Purpose, scope and impact of study
Transpower (New Zealand)	Wind Generation Investigation Project (WGIP), March 2007 – June 2008, New Zealand Electricity Commission (Transpower System Operator). http://www.systemoperator.co.nz/wind-generation	**The Electricity Commission initiated the Wind Generation Investigation Project (WGIP) to determine what changes to the Electricity Governance Rules and Regulations (EGRs) and industry arrangements will be necessary to accommodate the connection of large scale wind generation (11).** **Nine areas where the variability of wind generation output or the technical capability of wind generation may adversely impact on the operation of the New Zealand power system and electricity market were investigated, for a specified set of wind generation development scenarios.** • Investigation 1: Effect of unpredictability of wind generation output on pre-dispatch processes • Investigation 2: Effect of variability of wind generation output on dispatch of generation • Investigation 3: Effect of variability of wind generation output on asset loading • Investigation 4: Effect of wind generation capability on steady-state voltage management • Investigation 5: Effect of wind generation capability on management of frequency excursions • Investigation 6: Effect of wind generation capability on voltage stability • Investigation 7: Effect of wind generation capability on power system transient stability • Investigation 8: Effect of wind generation capability on oscillatory stability • Investigation 9: Effect of wind generation capability on dynamic voltage stability Based on the findings of these studies, a number of options for addressing each of the identified issues was developed. These were then reviewed and recommendations were made to the Commission Board regarding allocation of each of the identified tasks to Commission work streams. The recommendations include both additions to existing tasks and new tasks, and include a priority level for each task.[67]

67 Source: http://www.ea.govt.nz/our-work/programmes/pso-cq/wgip/

Study area	Study name, date, organisation (and consultant), link (where available)	Purpose, scope and impact of study
NYISO (New York, USA)	1. The Effect of Integrating Wind Power on Transmission System Planning, Reliability and Operations, March 2005, The New York State Energy Research and Development Authority (NYSERDA) and New York Independent System Operator (GE Energy). http://www.nyserda.org/publications/wind_integration_report.pdf	1. Integration of 3,300 MW of wind generation (10% of NY State peak load), considering impacts on: • Reliability and generation capacity • Forecast accuracy • Operation of day-ahead and hour-ahead markets • Economic dispatch and load following • Regulation • Stability performance following major disturbances to the grid. Following the completion of this study, a number of the recommendations was adopted. They include the adoption of a low voltage ride-through standard, a voltage performance standard and the implementation of a centralised forecasting service for wind plants.
	2. Growing Wind: Final Report of the NYISO 2010 Wind Generation Study, September 2010, New York Independent System Operator (NYISO). http://www.uwig.org/GROWING_WIND_-_Final_Report_of_the_NYISO_2010_Wind_Generation_Study.pdf	2. Integration of 8,000 MW of wind-generation: • Study the potential impact on regulation requirements and the overall impact on ramping. • Evaluate the impact on system planning by identifying specific transmission constraints. • Evaluate the impact on the overall system energy production by fuel types, locational-based marginal prices (LBMP), congestion cost, operating reserves, regulation requirements, and load following requirements. • Identify the impact of transmission constraints on wind energy that is not deliverable (i.e. "bottled") and identify possible upgrades for the limiting elements/transmission facilities. • Loss-of-load-expectation (LOLE) analysis to determine the impact of installed wind on system load carrying capability or reserve margin requirements.

Study area	Study name, date, organisation (and consultant), link (where available)	Purpose, scope and impact of study
Minnesota (USA)	Minnesota Dispersed Renewable Generation Transmission Study Vol. I, II and III, June 2008, Minnesota Department of Commerce Office of Energy Security (The Minnesota Transmission Owners) http://www.uwig.org/DRG_Transmission_Study_Vol_I_061608045236_DRGTransmissionStudyVolI.pdf	To assess the possibility to accommodate 600 MW of dispersed renewable generation in the state. The maximum admissible wind power in each of 42 sites in five zones of the state was determined, so that it would not cause any network violations.
IMO (Western Australia)	Various studies by the Renewable Energy Generation Working Group, August-November 2010, Independent Market Operator (ROAM Consulting, McLennan Magasanik Associates, Sinclair Knight Merz) http://www.imowa.com.au/n3086.html	The Renewable Energy Generation Working Group (REGWG) was established in 2008 by the Market Advisory Committee of the Independent Market Operator (IMO) of Western Australia. The scope of the group was to consider and assess system and market issues arising from the increase in the national Mandatory Renewable Energy Target (MRET) to 45,000 GWh by 2020. In particular, the Working Group focuses on issues related to: • intermittent renewable energy generation; • capacity credits allocated to intermittent generators through the reserve capacity mechanism; and • the impact on demand for ancillary services and system security at times of low load. Four Work Packages were established to address these issues. WP 1: Scenarios for Modelling Renewable Generation in the SWIS, ROAM Consulting WP 2: Reserve Capacity and Reliability Impacts, McLennan Magasanik Associates WP 3: Assessment of FCS and Technical Rules, ROAM Consulting WP 4: Intermittent Generation Penetration within the Wholesale Electricity Market, Sinclair Knight Merz

Study area	Study name, date, organisation (and consultant), link (where available)	Purpose, scope and impact of study
Western Power (Western Australia)	Effects of increased penetration of intermittent generation in the SWIS, January 2010, Western Power (ROAM Consulting) http://www.imowa.com.au/f3086,1258360/SM_report_Effects_of_increased_penetration_of_IG_in_the_SWIS.pdf	Analysis by System Management of Western Power is reported to inform participants as well as to endorse further work packages of the IMO's Reenwable Energy Working Group to examine in more detail impacts of higher penetrations of wind power in the SWIS. In this study the amount of wind power and other must-run generation curtailment that may result between 2009 and 2020 was determined. The main issues studied were the changing requirement for load following and degree of curtailment during low levels of demand expected from the increasing penetration of intermittent generation.
REGIONAL STUDIES		
All Island (Ireland and North Ireland)	1. All Island Grid Study: Transmission Network Assessment for All Island Grid Study (WS3), January 2008, Governments of Ireland and North Ireland (TNEI Services Limited). http://www.dcenr.gov.ie/Energy/North-South+Co-operation+in+the+Energy+Sector/All+Island+Electricity+Grid+Study.htm	The All Island Grid study is the first comprehensive assessment of the ability of the grid on the island of Ireland to absorb large amounts of electricity from renewable energy sources (RES-E). A working group was established to specify and oversee the undertaking of studies that would provide more detailed information on wind integration issues, and four work streams were defined. WS1: Resource assessment study WS2: Assess the extent to which RES-E can be accommodated on the grid system with regards to variability and predictability WS3: Engineering implications for the grid, reinforcements to accommodate the specified RES-E WS4: Relative economic impact and benefits of various RES-E levels for society as a whole, as well as various stakeholder groups.
	2. All Island TSO Facilitation of Renewables Studies, June 2010, EirGrid (DIgSILENT). http://www.uwig.org/Faciltiation_of_Renwables_WP3_Final_Report.pdf	To investigate in more detail than the All Island Grid study the technical and operational implications associated with high shares of wind power. Consequently, building blocks for an operational strategy of the 2020 All Island Power System had to be developed allowing secure, safe and reliable power system operation. The study is very thorough assessing all manners of power system security issues for 63 dispatch cases.

Study area	Study name, date, organisation (and consultant), link (where available)	Purpose, scope and impact of study
Iberian Peninsula (Spain and Portugal)	Study of Wind Energy Stability in the Iberian Peninsula (Confidential68), May 2005, Red Eléctrica España, Spain and Rede Eléctrica Nacional, Portugal. Summaries available on: http://www.ewec2006proceedings.info/allfiles2/743_Ewec2006fullpaper.pdf http://onlinelibrary.wiley.com/doi/10.1002/we.253/pdf	Spanish and Portuguese TSOs (REE and REN) collaborated with the Wind Business Association and ABB performed stability analysis of the grids to determine the maximum wind capacity that the Iberian grid could withstand and to revise regulatory issues regarding the performance requirements of WPPs. Specifically the following have been assessed: • Identify grid augmentations required to accommodate wind • Assess long-term generation adequacy • Assess adequacy of WPP performance requirements • Develop monitoring and control schemes for RES-E
Northern Europe	Wind Power Integration in a Liberalised Electricity Market (WILMAR): System Stability Analysis (WP5), November 2005, Risoe National Laboratory (SINTEF) http://www.wilmar.risoe.dk/	Identify any system barriers to integration of wind power that will oppose initiatives by the overall EU policy. The project objectives were to develop strategic planning tools and to give recommendations to the European Commission regarding the possibilities of handling the problems in a policy context. This is done through the following: • To analyse the technical impacts (system stability under 10 minutes, hourly balancing) of introducing win power in northern Europe covering Nordic countries and Germany. • To analyse the performance of different integration measures • To quantify the costs associated with integration of large amounts of wind power.
Europe	European Wind Integration Study (EWIS): Towards a Successful Integration of Large Scale Wind Power into European Electricity Grids, March 2010, ENTSO-E and European Commission (ENTSO-E). http://www.wind-integration.eu/downloads/	The EWIS was initiated by Transmission System Operators (TSOs) in Europe with the objective of ensuring the most effective integration of large-scale wind generation into Europe's transmission networks and electricity system. It builds on preceding work such as the TradeWind study[69] which highlighted the benefits of a pan-European transmission network of sufficient capacity such that diversity between wind output in different geographic areas can be exploited and the facilities needed to provide backup and other balancing services can be shared. EWIS has sought to identify what needs to happen in the short-term for such benefits to be achieved in practice.

68 Some European studies are not published in the public domain due to confidentiality issues. Information regarding the methodology and results has been obtained as best as possible by energynautics based on summary reports and through dialog with relevant European TSOs.

69 F. Van Hulle, et al., Integrating Wind: Developing Europe's power market for the large-scale integration of wind power, EWEA, May 2009 Belgium.

Study area	Study name, date, organisation (and consultant), link (where available)	Purpose, scope and impact of study
SPP [70] (USA)	South West Power Pool Wind Integration Study, January 2010, Southwest Power Pool (Charles River Associates). http://www.uwig.org/CRA_SPP_WITF_Wind_Integration_Study_Final_Report.pdf	The Southwest Power Pool (SPP) is a regional entity of the Federal Energy Regulatory Commission (FERC) which ensures reliable supplies of power, adequate transmission infrastructure and competitive wholesale prices of electricity in the nine member states covering the southwest part of the Eastern Interconnected System in the USA. Although wind power only made up 2% of the total installed generation capacity in the SPP in 2008, significant growth is expected, with approximately 48 GW of wind generation in the SPP Generator Interconnector (GI) queue as of December 2009. Even in the Eastern Wind Integration and Transmission Study, 60-95 GW of wind development is projected for the SPP. In early 2009, SPP designated Charles River Associates (CRA) to conduct a study to determine the operational and reliability impacts of integrating wind generation into the SPP transmission system and energy markets. The study investigates wind power penetration levels at 10%, 20% and 40% by annual energy, assuming that SPP operates as a single balancing authority with a co-optimised energy and ancillary service market. The following issues are considered: • Grid augmentations required to accommodate the studied levels of wind power generation • Impacts on ancillary services and reserve requirements • Wind power generation impact on congestion patterns, unit commitment and dispatch • Methods to address forecast errors • Market impacts and policy recommendations

70 The Southwest Power Pool covers the states Kansas, Oklahoma, most of Nebraska, and parts of New Mexico, Texas, Louisiana, Missouri, Mississippi and Arkansas.

Study area	Study name, date, organisation (and consultant), link (where available)	Purpose, scope and impact of study
ACADEMIC STUDIES		
IEA25 (Global)	IEA Wind Task 25: Final Report for Phase One 2006-2008, 2009, International Energy Agency (VTT). http://www.vtt.fi/inf/pdf/tiedotteet/2009/T2493.pdf	The "IEA Implementing Agreement on the Co-operation in the Research, Development and Deployment of Wind Turbine Systems" formed Task 25: Design and Operation of Power Systems with Large Amounts of Wind Power in 2006. This R&D task collects and shares information on the experience gained and the studies made on power system impacts of wind power, and reviews methodologies, tools and data used. The results of the first 3-year period was reported in this report. The work is planned to continue with a second 3-year period. The following countries and institutes have been involved in the collaboration (TSO is Transmission System Operator): • Denmark: Risø-DTU; TSO Energinet.dk • EWEA (European Wind Energy Association) • Finland: VTT Technical Research Centre of Finland (Operating Agent) • Germany: ISET; TSOs RWE and E.ON Netz • Ireland: SEI; UCD; ECAR; TSO Eirgrid • Norway: SINTEF; Statkraft • Netherlands: ECN; TUDelft • Portugal: INETI; TSO REN; INESC-Porto; IST • Spain: University Castilla La Mancha • Sweden: KTH • UK: Centre for Distributed Generation & Sustainable Electrical Energy • USA: NREL; UWIG. The Task has also started the work of developing guidelines on the recommended methodologies when estimating the system impacts and the costs of wind power integration.

Study area	Study name, date, organisation (and consultant), link (where available)	Purpose, scope and impact of study
Reserves (Global)	Operating Reserves and Wind Power Integration: An International Comparison, October 2010, National Renewable Energy Laboratory (NREL). http://www.nrel.gov/docs/fy11osti/49019.pdf	This paper provides a high-level international comparison of methods and key results from both operating practice and integration analysis, based on the work in International Energy Agency IEA WIND Task 25 on Large-scale Wind Integration. The paper concludes with an assessment of the common themes and important differences, along with recent emerging trends.
SC current (General)	Wind Power Plant Short-Circuit Current Contribution for Different Fault and Wind Turbine Topologies, October 2010, National Renewable Energy Laboratory (NREL). http://www.nrel.gov/docs/fy11osti/49113.pdf	This is an academic paper published by NREL in the USA on evaluating short-circuit current contribution of wind power plants. Simulations are carried out for different configurations and it is shown that the response of the WPP to faults vary with the type of installed WTGs.

Table 10: Summary of selected wind integration studies. Source: Energynautics

8.2. APPENDIX 2: SUMMARY OF SELECTED WIND INTEGRATION STUDIES IN THE NEM

Study area	Organisation (and consultant)	Purpose of study
Victoria	Capacity of the Victorian Electricity Transmission Network to Integrate Wind Power, December 2007, VENCORP [now AEMO].	The objectives of the report are to: • Review international and national experiences of integrating wind power generation with the electricity network • Investigate the technical impact of wind power generation developments on the Victorian shared transmission network • Determine the amount of wind power generation that the Victorian shared transmission network can accommodate
NEM	Transmission Congestion and Renewable Generation, November 2010, Clean Energy Council (ROAM Consulting).	The report seeks to answer the following questions with relation to the Renewable Energy Target (RET): • Existing congestion - Where in the grid are there transmission congestion problems already? What are they caused by, and at what times do they typically occur? • Congestion in 2020 - Where will there be significant transmission congestion problems in 2020, with the full RET implemented? What will it be caused by? • Location decisions of renewables - How may the build decisions of renewable generators be changed or impacted by transmission congestion? Is transmission congestion likely to be a significant driver of location decisions for renewable generators? • Operational impacts - How could the operation of renewable generators be changed or impacted by transmission congestion? • Transmission augmentation - What significant transmission augmentations may be justified to facilitate the entry of renewable generation on a least cost basis? How often and in what manner would these augmentations be utilised?

Study area	Organisation (and consultant)	Purpose of study
Tasmania	Future Wind Generation in Tasmania Study, May 2009, Transend.	One aim of the study was to investigate the effects of wind generation on the operation of the Tasmanian power system that are not affected by the location of the developments (so called system wide issues). Another study was done on local issues using as an example the potential Robins Island and Jims Plain developments. System wide issues studied in this report were: generation scheduling and reserve requirements, system inertia, Frequency Control Ancillary Services (FCAS), Basslink constraints, wind generator fault ride-through and system fault levels. The other aim of the report was to study local issues caused by increased wind generation. Local issues are the focus of connection studies performed once a development reaches the connection application stage and as such are not normally of concern from a strategic point of view. The local issues studied were: • Transmission network thermal limitations, including the relationship between wind generation and transmission line thermal ratings • Reactive support requirements • Transient stability for faults on the Sheffield to Palmerston circuit • Power quality
South Australia	Assessment of Potential Security Risks due to High Levels of Wind Generation in South Australia, June 2005, NEMMCO [now AEMO] (DIgSILENT).	The work was aimed at determining: • What are the critical stability mechanisms that could significantly impact operation of the South Australian power system with increasing levels of wind generation; • Whether the existing stability mechanisms change fundamentally or new stability mechanisms emerge with increased levels of wind generation; • What is the trend for system stability for increased levels of wind generation, in order to understand what level of wind generation may cause changes to network limits or other operational impacts, and whether there is a limit to installed wind capacity in South Australia, beyond which stable operation of the network is not possible.

Study area	Organisation (and consultant)	Purpose of study
South Australia	South Australian Wind Power Study, March 2003, Electricity Supply Industry Planning Council.	The project begins the assessment of the market implications of the emerging wind power sector in South Australia and indicates directions for future, more detailed analysis. Specifically, the Planning Council has investigated the impact of WPPs on the following aspects of the operation of the South Australian electricity market and the NEM: • The contribution of wind to "firm" generating capacity; • the predictability of WPP output and any correlation between wind and temperature. • the State's load shape and load factor; • the operation of existing generators; • the viability of other forms of new generation in the State and the technology mix of new conventional generation; • the operation of the Heywood interconnector and the requirement for additional interconnector capacity; • the operation of the fuel supplies in the State; and • reductions in greenhouse gas emissions in the NEM.
South Australia	ElectraNet.	Internal report.

Table 11: Summary of selected wind integration studies in the NEM. Source: AEMO

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solutions for a sustainable development