WIND FARMS IN EASTERN AUSTRALIA – RECENT LESSONS

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ABSTRACT

Academic discussion continues as to whether a fleet of grid-connected wind farms, widely dispersed across a single grid network, can provide a reliable electricity supply. One opinion is that wide geographical dispersion of wind farms provides sufficient smoothing of the intermittent and highly variable output of individual wind farms enabling the wind farm fleet to provide for base load demand. In an examination of the 5-minute time-averaged wind farm operational data for 21 large wind farms connected to the eastern Australian grid - geographically the largest, most widely dispersed, single interconnected grid in the world (AER, [1]) - this paper challenges that opinion. The findings also suggest that the connection of such a wind farm fleet, even one that is widely dispersed, poses significant security and reliability concerns to the eastern Australian grid. These findings have similar implications for the impact of wind farms on the security of electricity grids worldwide.

Keywords: Wind, Electricity, Intermittency, Geographic Dispersion, Smoothing, Grid Security

1. INTRODUCTION

Oswald *et al* [2], performing an analysis of the 10-metre wind data available from the UK meteorological office, demonstrated that there is evidence to doubt the view that wide geographic dispersion of wind farms across the United Kingdom National Grid would be sufficient to smooth the collective outputs of that wind farm fleet. (It is now generally accepted that the output of any single wind farm is inherently highly variable and intermittent (Diesendorf, [3]).) In particular, Oswald *et al* (*ibid.*) demonstrated that the occurrence of mid-winter blocking high pressure systems might result in prolonged periods where the entire wind farm fleet in the UK region generated little or no electricity. This concern has since been confirmed by operational experience in the UK during the months of January 2009, 2010, and as reported for the period November 2008 – December 2010 by Young [4]. In Australia, Miskelly and Quirk[5], analysing wind farm operational data from the much more widely dispersed eastern Australian grid for the month of June 2009, expressed similar concerns. These authors also expressed concern at wind's increasing contribution to grid instability. This paper presents the findings of an analysis of the performance of the AEMO-listed[1], and now significantly larger, wind farm fleet, for the later period of 1 January – 31 December 2010 inclusive.

PROPERTIES OF ELECTRICITY GRIDS

On an electricity grid supply and demand must be maintained in balance on a second-by-second basis (AEMO, [6]). Kirby *et al* [7], for example, in discussing these fundamental concepts, state:

> *"Small mismatches between generation and load result in small frequency deviations. Small shifts in frequency do not degrade reliability or markets efficiency although large shifts can damage equipment, degrade load performance, and interfere with system protection schemes which may ultimately lead to system collapse."*

Bevrani *et al* [8] discuss control parameters and strategies in detail and stress that any degradation of electricity grid control system safety margins will result in frequent, unscheduled, widespread blackouts ("system collapse"). A recent German government report[2] highlights the likely catastrophic consequences resulting from any such event.

RELEVANT CONTROL SYSTEM THEORY

To perform an analysis of system transient response, the system under study must be analysed at timescales that are at least comparable to it's natural frequency response. The requirement for second-by-second control of the grid determines that any analysis be conducted at sub-second timesteps . The strategy required to balance an upended broom on a person's open hand is a useful analogy: the hand has to be moved constantly, at sub-second intervals, to correct the constantly changing error from the true balance position of the broom. A similar sub-second error measurement and correction control strategy is required for the grid. Futher, for control systems using digitally-sampled data, as occurs on a grid control system, the Nyquist-Shannon sampling rule applies (Shannon C E [9]). The applicability of this rule in systems engineering is discussed in texts on transient analysis in sampled-data control systems, for example Chapter 9 of Elgerd [10]. In brief, in a sampled-data control system, to obtain perfect reconstruction of a given signal, the sampling frequency has to be at least twice the highest frequency expected to be encountered in that measured signal[3]. For effective control of the behaviour of an electricity grid, continuous sampling of such "signals" as generator power, demand, etc, is required at sub-second rates. The second-by-second balancing requirement means that the grid may not be regarded as a large lake into which electricity is merely dumped.

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[1] The AEMO, the Australian Energy Market Operator, is the responsible operator of the eastern Australian electricity grid. Refer to http://www.aemo.com.au for a statement of the AEMO's role and responsibilities.

[2] What happens during a blackout?, Office of Technology Assessment by the German Bundestag, 7 Apr 2011,translated from: "Was bei einem Blackout geschieht". Available at: http://www.tab-beim-bundestag.de/en/pdf/publications/books/petermann-etal-2011-141.pdf . Last accessed 6 June 2012.

[3] Audio CD technology uses this principle. An audio frequency range to 20,000 Hz is required for best fidelity. A sampling frequency of 44,100 Hz, somewhat more than twice this maximum frequency, is used in the production of the digital data on the CD and the reconstruction of the sound as heard by the listener.

Performance measures for generator output of plant that is both highly variable and highly intermittent, as wind generation is, that are expressed as daily, or even longer, term averages, are rendered irrelevant by the second-by-second grid control requirement. In particular, the oft-used measure, Capacity Factor[4], or long-term average output, used for controllable generation, is not particularly useful for intermittent sources. A more useful performance measure would take into account both the variance and the rate of change that are inherent properties of wind farm output.

CLAIMS BY WIND ENERGY PROPONENTS

Variations on the following claims are stated by the wind industry, wind's proponents, and more importantly, by policymakers worldwide:

1. Electricity demand variation is normal. Electricity supply can drop by 1000 MW or more in a fraction of a second when a large conventional plant experiences a forced outage, going offline unexpectedly. By contrast, "*wind output changes slowly and often predictably*." (Italics added for emphasis.) (Goggin, 2010 [11], Footnote 2.)
2. The fluctuations in the total output from a number of wind farms, *where they are geographically distributed in different wind regimes*, are much smaller and partially predictable than that of the individual wind farm. Therefore, geographic dispersion of the wind farms provides sufficient smoothing, so that, where this fleet is coupled with a few peak load plants (gas turbines) that are required to be operated infrequently, the reliability of the output of the whole wind fleet is brought, relatively inexpensively, to a level that is equivalent to that of a coal-fired powerstation. Thus coal-fired powerstations may be replaced by wind generation. See Diesendorf, (*ibid*.).

RECENT WIND INTEGRATION STUDIES

Two important, detailed studies by the (U.S.) National Renewable Energy Laboratory (NREL) studies are relevant. These are, the Eastern Wind Integration Study and, the Western Wind Integration Study. "Eastern" and "Western" refer to the two major portions of the United States electricity grid. These are very detailed, complex, simulation studies, examining both the feasibility and the costs of incorporating massive amounts of wind generation into the US grid. In the Western Wind Study an installed capacity of 920 GW of wind generation was considered. In the Eastern Wind Study two scenarios of installed capacity: 225 GW (20% penetration) and 330 GW (30% penetration) of wind generation were modelled. The methodology used in each Study was similar. That of the Eastern Wind Integration Study is described in Corbus *et al* [12]. From a generated atmospheric circulation model, 10-minute data of windspeeds at 100 metres altitude at the various chosen wind farm sites in the region was extracted and from this, and, using the Vestas 3 MW wind turbine as the

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[4] At: http://www.aemo.com.au/planning/ESOO2011_CD/documents/glossary.pdf , *the AEMO defines Capacity Factor as: "The output of generating units or systems, averaged over time, expressed as a percentage of rated or maximum output." At*: http://bravenewclimate.com/2010/05/22/tcase10/ , *there is a discussion as to why the Capacity Factor for wind farms is not equivalent to that for controllable plant.*

benchmark, simulated electricity performance data was generated. The Western Wind Integration Study similarly used a detailed atmospheric circulation model to generate the required atmospheric circulation data, coupled to a technique called SCORE-lite to generate the wind farm operational data. Potter *et al* [13] provide some detail as to how the shortcomings of the modeling technique in generating realistic electricity preformance data were minimised. The electricity performance data used in both studies is generated entirely by their respective computer models. It would seem that no actual wind farm operational data was used to validate the output of this important subset of the simulation data.

These NREL models identified the need for the largest possible geographical spread of wind farms on the respective grids, and the need for extensive transmission system augmentation (see Milligan [14] for an extensive overview)[5].

EASTERN AUSTRALIAN WIND FARM DATA AVAILABILITY

As the operator of the eastern Australian electricity grid, the AEMO is the primary source of reliable operational data. (For access to the statement of the AEMO's role and responsibilities see footnote 1, and for greater detail of the electricity grid responsibilities, see Swift [15, 16].) For transient analysis purposes, the most useful AEMO publicly accessible data is that in the form of 5-minute average power outputs for each registered generator connected to the grid. Other market data is also supplied, but at half-hourly, hourly, and daily, averages. Although the analysis above would indicate that the 5-minute data is inadequate for a full transient analysis, because it fails to present generator transients at shorter timescales, it still provides useful information. The data is available at the AEMO's website, under "MMS datasets". There is a wealth of generator data information available there at:
http://www.nemweb.com.au/ . The two relevant subdirectories containing the actual operational data are:
http://www.nemweb.com.au/REPORTS/CURRENT/Next_Day_Actual_Gen/
http://www.nemweb.com.au/REPORTS/CURRENT/Daily_Reports/

These repositories provide a collection of compressed files, each file containing the data for one 24-hour day. Data for all generators of the given category, one generator per line, is listed at each time point in each daily file. Each line contains - among other details in the "Daily_Reports" data - the average output for the 5-minute period (in megawatts – MW) for the generator named on that line. The "Daily_Reports" category shows the outputs of all the major generators on the eastern Australian grid. It also includes the wind farms more recently categorised as "semi-scheduled" by the AEMO. The "Next_Day_Actual_Gen" category includes all small generators (less than 30 MW installed capacity) such as small hydro, sugar cane bagasse, and the early-commissioned wind farms.[6] The AEMO updates the file collection daily. The previous day's data (the 24 hours commencing from 4:05 am) is uploaded each morning.

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[5] Given the models' shortcomings, (as identified by their authors), it is interesting to note that these conclusions are not all that different from those of the recent AEMO report discussing future supply/demand scenarios for the South Australian (SA) portion of the eastern Australian grid (AEMO, [6]), (further discussed in the present analysis).

[6] The latter, interestingly, are not subject to the 30 MW installed capacity limit. For example, the Capital and Canunda wind farms, of 140 MW and 46 MW, respectively, are included in this category.

The wind farm operational data, extracted from the above AEMO datasets, is available, downloadable in .csv format, at: http://windfarmperformance.info/. (Miskelly, [17]).[7] Additionally, this data is also provided there in graphical format, with concurrent synoptic meteorological data, wind farm installed capacities and location data, and other relevant material.

ANALYSIS OF WIND FARM OPERATIONAL DATA

An examination of the actual wind farm operational performance data for wind farms connected to the eastern Australian grid during the calendar year 2010 shows:

a) the output of any individual wind farm can vary enormously. It may do so very rapidly, and very often. It often varies across the full operational range of the individual wind farm in a very short time. Output can frequently fall from near full power to zero in a few minutes. The converse is also the case.

b) total wind output across the entire grid falls rapidly, to zero or near zero, on many occasions during the calendar year. Some of these occurrences are comprised of multiple falls and rises in quick succession.

An output value that is 2% or less of total installed wind capacity[8], termed here the Minimum Acceptable Level (MAL), is used in this analysis as the criterion of "near zero".

INDIVIDUAL WIND FARM PERFORMANCE

As a typical example, Figure 1 shows the output of the Capital wind farm for the 6 months of January 2010 to June 2010 inclusive. A 6-month period was chosen as giving a balance between the requirement to show data for a significant part of the year yet still obtain a legible data display. As well as the many large and frequent power excursions observed in the data, there are many periods where the output is zero.

An analysis of this data shows the following:

- There are 559 intervals of varying length where the output is zero,
- The longest interval is 803 x 5 minutes = 67 hours or 2.8 days,
- The total number of 5-minute intervals of zero output is 20,276 5-minute intervals, or 70.4 days. This is in a period of 52,129 intervals, or 181 days.

For 38.9% of this 6-month period, the output of the Capital Wind Farm was zero. This characteristic means that the generator has very limited usefulness. It cannot be used for load following. The extreme, and rapid, variation demonstrated in the individual wind farm output shows that wind generation may place an enormous strain locally on grid operation. Fast-acting plant (the inexpensive choice is open-cycle gas turbine (OCGT)), has to be permanently operationally ready to fill the gap caused by the drops in output.

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[7] This data is extracted automatically on a daily basis from the listed AEMO datasets. The data extraction process used is entirely separate from that used to perform the analysis described in this paper. Any errors in this paper therefore are entirely the author's own.

[8] The value of 2 percent of total installed capacity is an arbitrary choice. It was set sufficiently low to be recognized as a value below which output levels are clearly unacceptable. Operational reasons may determine that higher values are more appropriate. In that case, even more unacceptable performance findings than those reported here will result.

To better illustrate the rapidity and magnitude of the short term fluctuations of the output of an individual wind farm on a daily basis, Figure 2 shows the output of the Capital wind farm during the month of January 2010.

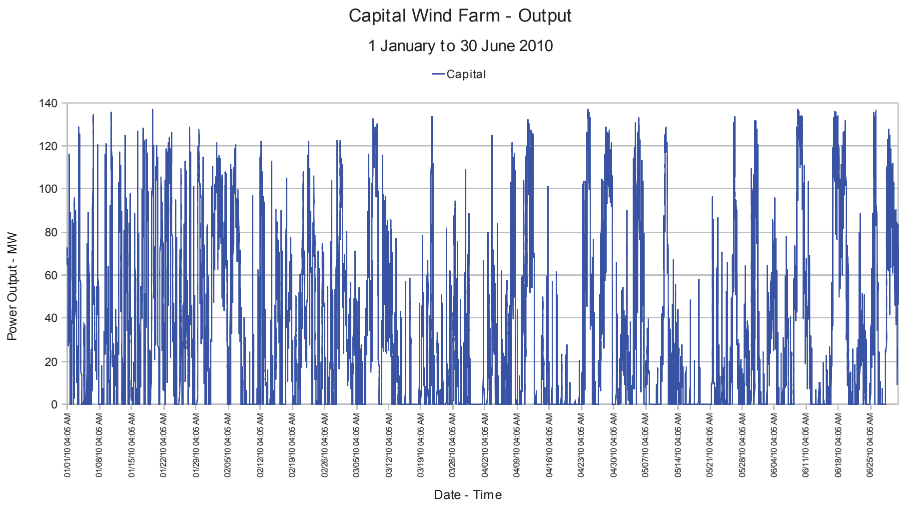

Figure 1. Capital wind farm (5-minute average data) output 1 January - 30 June 2010

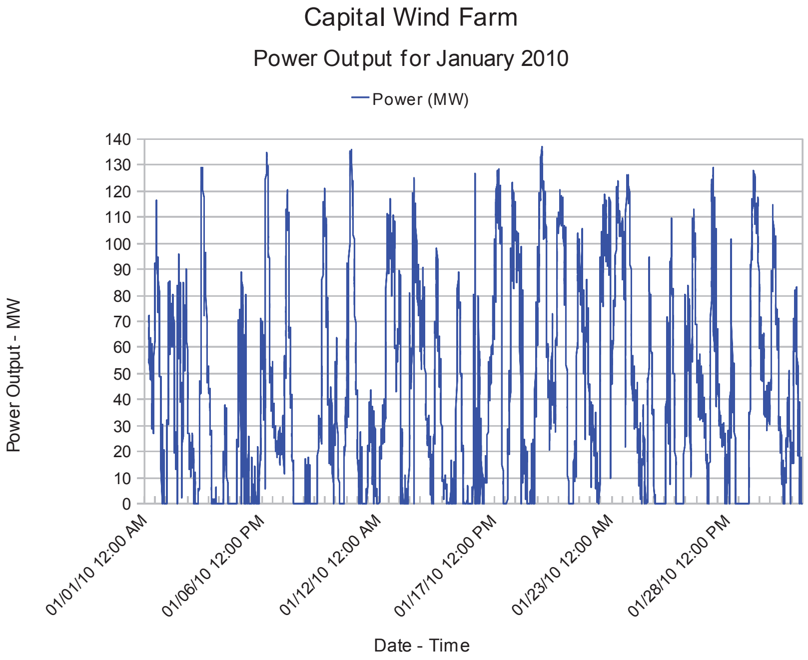

Figure 2. Output of the Capital Wind farm for January 2010.

TOTAL WIND FARM FLEET PERFORMANCE FOR CALENDAR YEAR 2010

Each of the four panels of Figure 3 shows three months of electricity output of the total reported wind farm fleet on the eastern Australian grid. The data displayed in the first two panels show the total wind farm output that occurred during the same 6-month period as that of the individual wind farm of Figure 1. While the variation in the individual wind farm output seen in Figures 1 and 2 is worrying, the clearly large variation in the total wind farm output on the eastern Australian grid is of far greater concern.

Again, the critical item to determine is the frequency of occurrence of dips to unacceptably low levels of output. As the MAL is defined in terms of total wind farm installed capacity, it is important to adjust this value through the year as required, because a number of newly-completed wind farms commenced operation for the first time during 2010. These, with their installed capacity and their date of commencement of operation, are shown in Table 1.

Table 1. installed capacity and commencement date of new wind farms during 2010.

Wind Farm	Installed Capacity (MW)	Start Date
Lake Bonny 3	39	2 July 2010 12:05 AM
North Brown Hill	132.3	19 July 2010 12:05 AM
Snowtown	99	1 July 2010 12:05 AM
Waterloo	129	20 August 2010 12:05 AM

As a result, from 20 August 2010 onwards there was an additional 300.3 MW of installed capacity above that available during the first half of 2010. The analysis allows for this addition to total installed capacity.

As the start dates for the newly-connected wind farms occur during the second half of the calendar year 2010, the analysis summary is usefully divided into two 6-month periods. During calendar year 2010, the number of intervals, and their characteristics, where the total output falls to below 2% of total installed capacity, are summarised in Table 2.

Table 2. Intervals when total wind farm output dropped below 2% installed capacity.

	No. of intervals	Longest interval(s)	Total No. of 5-minute intervals
Jan-June	58	229 x 1	1314
July-Dec	51	81 x 1	553
Year Total	109	229	1867

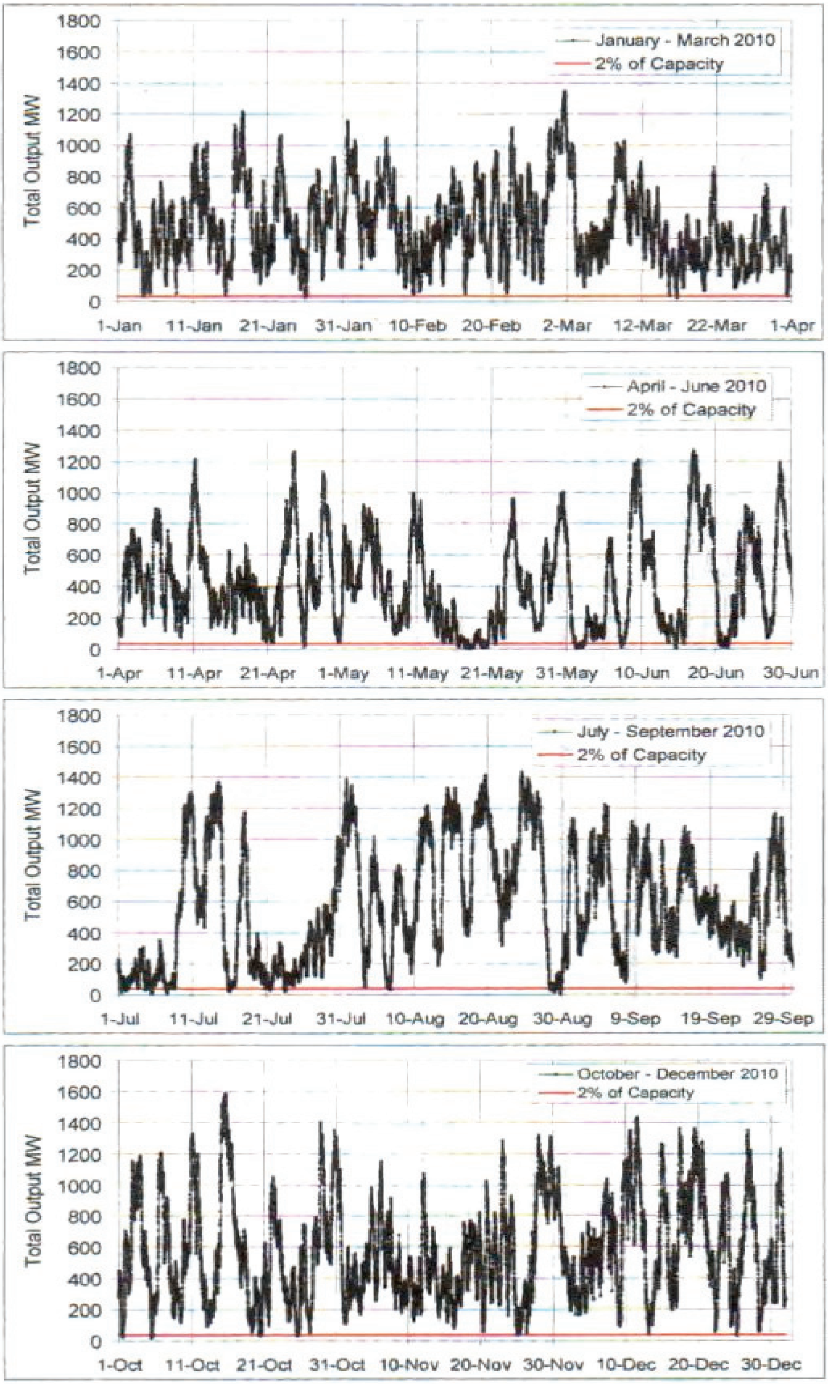

Figure 3. Total Wind Farm output to the eastern Australian grid 1 January – 30 December 2010

Table 2 shows the following:

- During the first 6 months of the year, there are 58 intervals where the output falls below the MAL. The longest such interval is 229 consecutive 5-minute time steps, or 19 hours approximately. This event occurred in May 2010.
- During one such event, on May 18, on two occasions, the total output actually dropped to slightly below zero, the first starting at 2.50 am and lasting 40 minutes, the second commencing at 4.35 am and lasting for 70 minutes.
- During the first 6 months of 2010, the total period where output is below the MAL, including non-consecutive events, expressed in 5-minute intervals, is 1314 intervals, or 109.5 hours.
- For the entire year, there are 109 such intervals of varying length, comprised of a total number of 1867 5-minute intervals, totalling 155.6 hours, or nearly 6.5 days.

Figures 4a and 4b show the date and length of each contiguous period (interval) through the full calendar year, where the total wind output dropped to less than the MAL. The figures show that a higher frequency of the forced outage events occurs during the months of May through July inclusive. However there are other such events outside this period, some of which are each of considerable length.

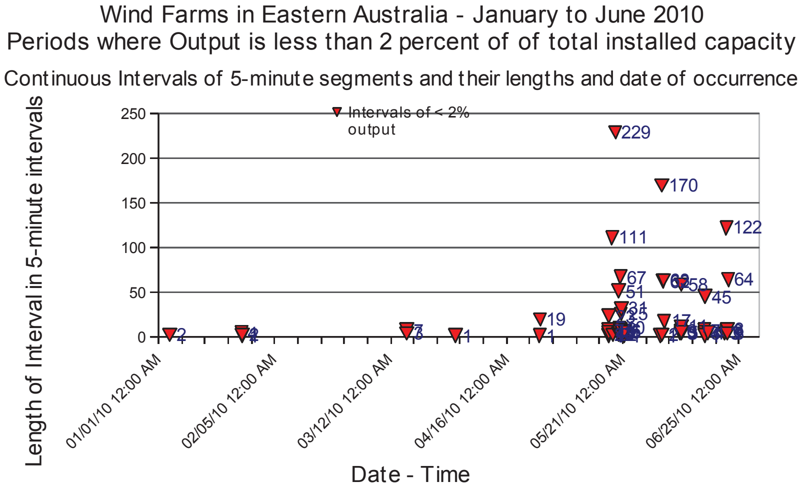

Figure 4a. Periods where Wind Farm Output Jan. – June 2010 falls below 2% installed capacity.

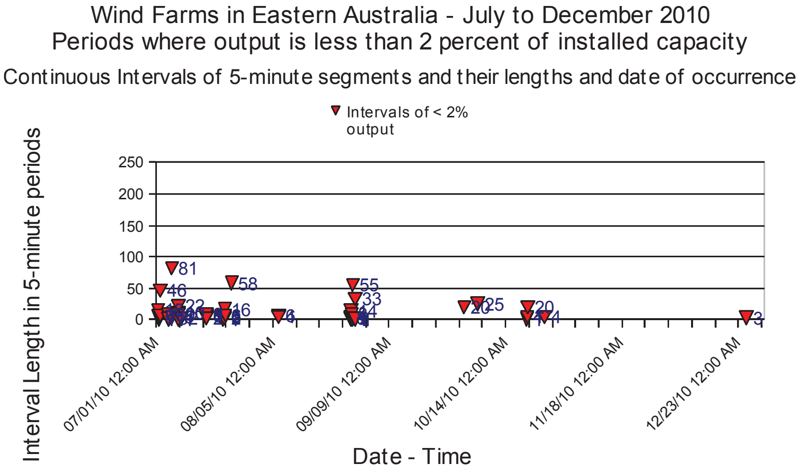

Figure 4b. Periods where Wind Farm Output July – Dec. 2010 falls below 2% installed capacity.

These Figures illustrate that, throughout the year, a common-mode, i.e., "forced outage" of the entire 1900 MW approx. installed capacity wind generation fleet occurs, and occurs frequently. Figure 5 charts the frequency of occurrence of the various interval lengths where output fell to below the MAL.

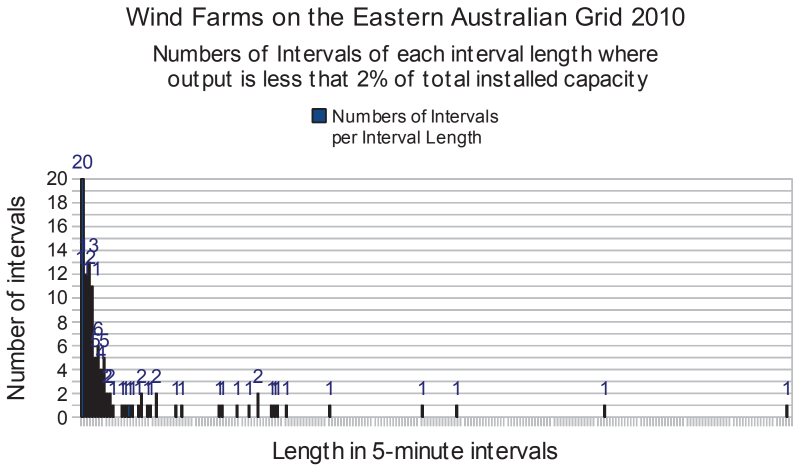

Figure 5. Histogram showing the frequency of each contiguous <2% output segment. The horizontal scale extends to a segment length of 230 5-minute intervals.

OUTAGES IN CONVENTIONAL GENERATION

The AEMO [18] provides information on the frequency of a number of different types of forced outage. Of interest here are the AEMO's "Loss of Transmission Element(s) and Generating Unit(s)" (TG), "Loss of Generating Unit and Load Interruption (GL)", and "Loss of Multiple Generating Units (GG)". This data is summarised in table 3[9].

Table 3. Frequency of "reviewable operating incidents" by incident per financial year for the period 2006 – 2011. Compiled from AEMO [18].

Year	TG	GL	GG
2006-2007	5	-	2
2007-2008	5	-	7
2008-2009	8	-	2
2009-2010	7	-	10
2010-2011	2	-	3

In the Introduction the AEMO (*ibid.*) reports these loss-of-generation incidents as "reviewable operating incidents". They are not considered to be major events, the latter being classified as "credible contingency events". The Reliability Panel of the Australian Energy Market Commission provides an Annual Market Performance Review Final Report in which a summary of these incidents and events and their impact on the eastern Australian Grid is discussed[10]. Goggin's [11] concerns notwithstanding, it would seem that the loss of a single generating unit or powerstation is not deemed a "credible contingency event" on the Eastern Australian grid by the AEMO (*ibid.*). The loss of a major trunk transmission line is deemed to be a far more serious event. A perusal of the Reliability Panel's recent Annual Reports (e.g., *ibid.*) found no mention of occurrences of common-mode failure of conventional generator units.

TOTAL WIND FARM OUTPUT YIELD CURVES

The wind performance operational data may also be plotted in the form of a power output yield curve (Figure 6). Here, the data has been plotted as two separate yield curves, one for each of the two 6-month periods of the year. These curves can address two questions:

- Is the 300 MW increment of new wind farm generation that came on line during the latter half of 2010 a cause of the difference between the curves?
- Is there evidence of additional smoothing?

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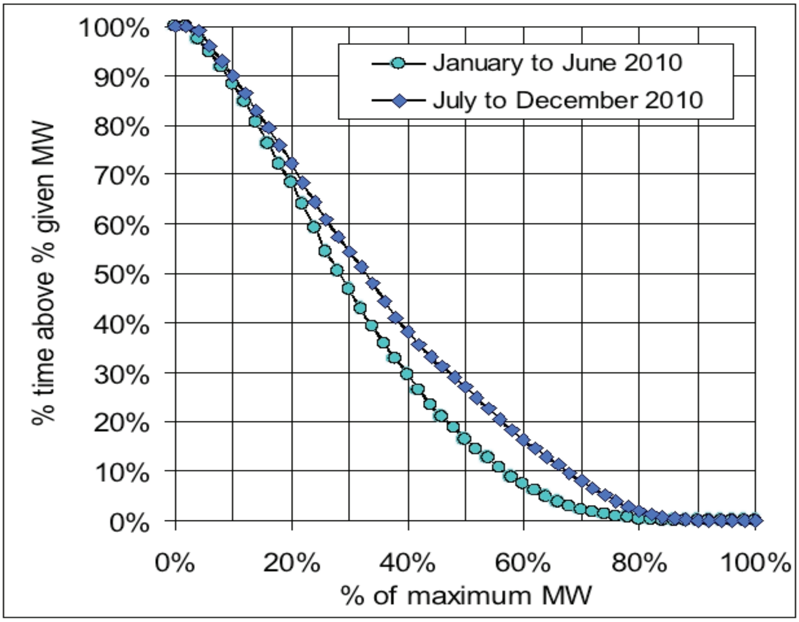
[9] The individual incident reports may be viewed by month at: http://www.aemo.com.au/reports/incident_reports.html.

[10] See, for example, The AEMC Reliability Panel 2012, Annual Market Performance Review, Final Report, AEMC Reliability Panel, 1 March 2012, Sydney, available at: http://www.aemc.gov.au/.../Final-Report-755a5cf0-450f-458c-8be8-43e92301528b-0.PDF .



grid for calendar year 2010.

Figure 6. Total Wind farm yield on the eastern Australian grid for calendar year 2010.

The shape of the yield curves provides valuable information. Unless regional transmission constraints are violated, wind farm output is accepted by the grid operator on a "must take" basis – that is, whatever is generated is accepted by the grid operator. Therefore, these curves show the maximum possible performance. Thus they show that this "generator" can never supply the base load. Commencing from the 100% value on the y-axis, to provide for base load generation, each curve would be required to pass through a point that is both at a high value, and to the right side, of the graph. The curve would have to be able to pass through, as an example of an acceptably high value, a point near [90% of maximum MW, 80% of the time above a given % of maximum MW]. That is, the generator would have to be able to provide an output that is above 90% of rated capacity for over 80% of the time. In graphical terms, the "skirt" of the curve would have to extend in a near-straight line from the 100% y-axis value across to the (80%, 80%) point before falling away to zero. It is clear from Figures 1 – 3 that wind can never remotely achieve this level of performance.

Both curves show that the output never (for the January-June curve) or rarely (for the June-December curve) exceeds 80% of the max MW (the installed capacity). This indicates that, as the total wind farm output could be anywhere along the respective curve at any given time, the installed capacity of the required backup has to be some 80% of the installed wind farm capacity. The slight shift to the right in the curve for the second half of the calendar year 2010 is likely to be a result of the significant increase in the Capacity Factor for the month of August. (See Figure 7).

A clear indicator that there is no significant improvement in smoothing is that there is no lowering of the "% of maximum MW" value in the July-December curve compared to the January-June curve. Indeed the value increases slighty. The value at which the skirt approaches the x-axis remains close to 80%. If there was increased smoothing, then there would be expected to be some shift to a lower value (towards the left, ie towards the average output value), on the x-axis, along with a larger increase in the height of the entire curve.

IMPACT OF VARIATION IN CAPACITY FACTOR

Figure 7 shows that the higher Capacity Factor (CF) for the latter part of the year is not reflected in a significant lowering of the number of intervals during the second half of the year (see Table 2), where the output fell to and remained below the MAL. However these intervals where output is below the MAL are significantly shorter, as reflected in the number of 5-minute intervals comprising each (Figure 4b). This may be a result of the increase in the CF. This suggests that even though there is an increase in average CF during the latter half of the year, the lack of significant difference in the total number of such dips to below the MAL between the two sets of 6-monthly data (58 vs 51), indicates that there is another, overriding, mechanism operating (presumably also meteorological), separate from any increase in average wind speeds, that continues to cause the frequent, if shorter, dips in total output.

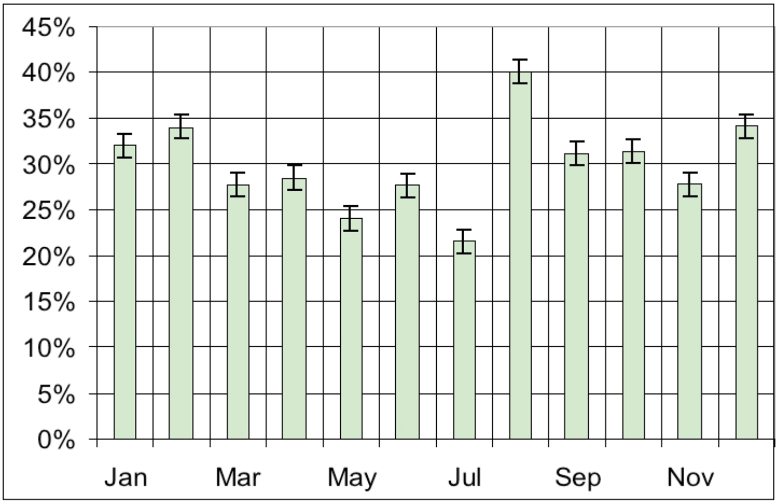


Figure 7. Total Wind Farm Capacity Factor by month for calendar year 2010

DISCUSSION

The outage frequency reported for this wind generation network is far greater than would be tolerated in any single large coal or nuclear power station, let alone, as is seen with wind, among all power stations of a given type simultaneously[11]. This is a "common-mode" forced outage. No level of common-mode forced outage would ever be tolerated in conventional generation.

The occurrence of frequent common-mode forced outages is a matter of very serious concern, particularly as the size of the, continually-increasing, wind farm fleet in eastern Australia is already very much larger than the largest single conventional generator. That a common-mode forced outage of the wind fleet might be predicted with any certainty up to some hours in advance is of little consequence, the net result is that a fleet of new-build fast-acting OCGT plant, of comparable capacity to that of the total installed wind capacity, constantly operational in standby mode, is required to balance wind's mercurial behaviour.

The graphs of wind farm total output in Figure 3 are of actual operational data – they are not a result of computer simulations. Putting these observations of so many common-mode outages by the wind farm fleet into context: if a "large coal or nuclear plant" (Goggin [11]), goes off-line unexpectedly, part of operational grid management is to ensure that there are reserves always available to deal with that contingency, for example spare capacity of similar, schedulable, plant, ready to replace any single plant. That is, there are other generators always available to cover that situation. The methodology for determining this spare capacity, called Minimum Reserve Levels (MRL's) by the AEMO, is explained in ROAM Consulting (for AEMO) [19]. Also, the probability of such single-generator occurrences is generally small, certainly they occur at an outage rate at a frequency very much less than the 109 times complete failure per year, identified above as that for the wind fleet in eastern Australia.

SERVICING THE BASE LOAD

In contrast to wind's demonstrably erratic behaviour, the routine output of the "large coal or nuclear plant" is very different. The AEMO-published data shows, for example, that the brown-coal stations in Victoria, Australia, operate at near constant output 24/7, 365 days of the year. They supply a very significant portion of the base load requirement in eastern Australia, all other controllable power stations being used to supply the varying demand above the base load.

The daily variation in electricity demand is shown in two graphs. The first, titled "Electricity Demand (MW) for 29 June 2011" (Figure 8), shows a snapshot for a single day in some detail. The second, (Figure 9) shows the variation during a period of a whole year as "2010 NEM Wind Power and Total Demand" (Miskelly [17]). These graphs, particularly the latter (see the curve referred to as "Demand" from the Legend), show that the base load demand requirement never falls below about 17,000 MW.

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[11] See, for example, the Wikipedia entry on the UK National Grid at: http://en.wikipedia.org/wiki/National_Grid_%28Great_Britain%29 . Under the heading "May 2008 Incident", the almost concurrent outages of the Sizewell "B" nuclear power station and that of the large Longannett coal-fired powerstation are mentioned.

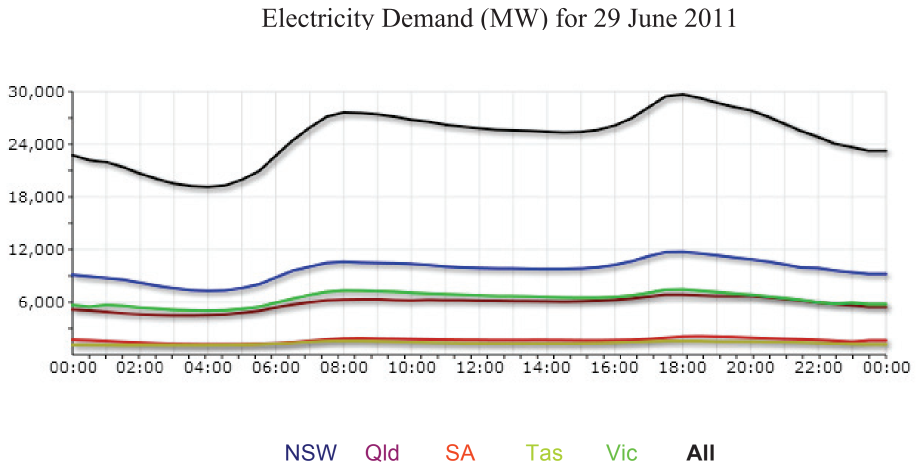

Figure 8. Electricity Demand (MW) for 29 June 2011 (reproduced courtesy Miskelly [17])

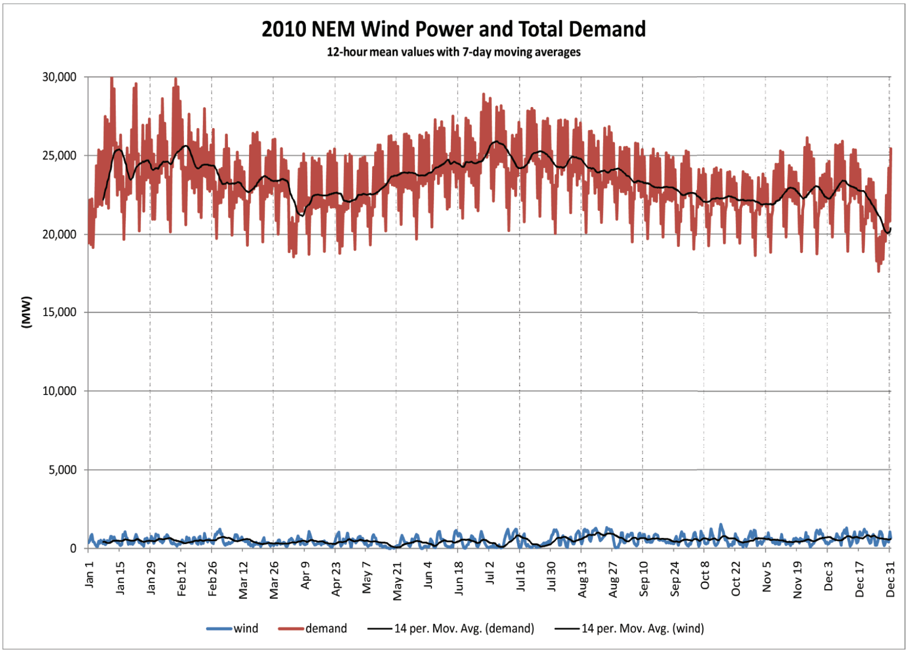

Figure 9. Total Electricity Demand (MW) as 12-hour mean values (red curve), and corresponding wind farm output, lower blue curve, with corresponding 7-day moving averages (black curves), during calendar year 2010 (reproduced courtesy Miskelly [17])

Figures 1 and 2 of this report show that the output of wind farms is extremely variable. As well as the catastrophic drops to near-zero identified above, at other times the combined output routinely varys over several hundred megawatts, both up and down, often over very short timescales. The combined wind farm input into the grid is acting on grid operation in a way that can be likened to that of a pseudo-random noise generator of the kind often used in signal tracing applications in audio and other amplifiers. Given then that the wind generation is merely injecting the equivalent of electrical noise into the grid, the implementation of a very expensive noise abatement strategy – for example, the use of the continual rapid ramping up and down of new-build open-cycle gas turbines (OCGT) – is required to deal with what is a nuisance similar to noise injection into an audio amplifier. As the wind installed capacity is presently some 1900 MW – much larger than any individual coal-fired generator on the same grid - this erratic behaviour becomes to be of far greater concern than the failure of a single large-capacity coal-fired generator. With Australian government policy guidelines aiming at a 20% penetration of renewables - an amount well in excess of present wind installed capacity – the behaviour shown by the year-2010 operational data shows that such increases in desired wind capacity can only exacerbate what is already an unacceptable situation.

The 17,000 MW (approximately) of base load demand requirement (see the upper curve in Figure 9), has to be supplied, constantly and continuously, but of necessity, by other, reliable and controllable generation. As discussed earlier, Figure 3, and in particular, the yield curve of Figure 6, show that wind generation cannot meet this requirement.

Additionally, the daily variations in the demand, called the shoulder and peak demand requirements, also remain to be supplied by schedulable, controllable generation.

It is argued by wind's proponents (see for example Goggin [11] and Milligan [14]), that wind generation supplies some portion of these demand components. However, the stochastic nature of wind generation leaves gaps in supply that must be met by schedulable, controllable generation. This is another way of saying that wind generation's electrically noisy behaviour has to be managed by the expensive use of controllable, backup generation.

The daily variations in demand are relatively predictable. The grid controller has access to extensive demand history profiles, profiles which vary in a fairly predictable fashion with the time of year, time of day, and daily weather conditions. Section 2.5.2 in AEMO [6] provides a general discussion of the control strategies. In contrast, the instantaneous variation of wind energy is not so predictable. Indeed, the AEMO[6], at Section 5.4.1 states:

> *"The significant growth of wind generation over recent years, and the variability of wind over a short period of time, means that transmission network and power system management is becoming more challenging"*.

Clearly, a very considerable additional effort is now being devoted by the grid controller to manage the variation in wind's contribution to the grid, a contribution which an inspection of the wind curve in Figure 9 shows is marginal at best. This curve just above the x-axis is the same wind data as that in Figure 3 plotted to the different scale of Figure 9.

The scale of the wind prediction problem should not be underestimated. The requirement is that successful second-by-second prediction of windspeed at the local level at all wind farms on the grid is required. This is no simple task.

The requirement to constantly ramp this controllable generation up and down to cover wind's vagaries may also reduce the emissions savings attributed to wind generation. Kaffine *et al* [20] highlight this concern. These authors identify that wind generation's inherent intermittency requires fast-acting backup generation, but that the choice of the necessary backup generation plant actually made at any given time on a grid is seen to be quite a complex matter. They show that where the main components of the generation mix on a particular grid are coal-fired and gas-fired generation, with the former being the larger part of the mix (as is the case in eastern Australia), then for small wind penetration, the faster-acting, more flexible gas-fired generation is used to deal with wind's volatility, but that, as wind penetration increases, the actual mix of plant used for backup changes, and changes depending on the system load, and time of day. In their conclusion, Kaffine *et al* (*ibid.*), having shown that any emissions savings are critically dependent on the generation mix in the particular grid, conclude that as wind penetration increases, it may be that greater emissions savings accrue as more coal-fired generation becomes involved in the backup role, but that, conversely, these expected emissions savings may be eroded by the increased magnitude of the required cycling of the thermal plant. Their analysis uses hourly sampling so that the use of 5-minute data, should it have been available to Kaffine *et al* (*ibid.*), may have resulted in a different conclusion. These authors did not examine the use of OCGT vs CCGT as to whether one or the other was the more effective candidate gas generation technology to backup wind.

FAST-ACTING BACKUP GENERATION – CCGT OR OCGT?

Section VI of GE Energy [21] shows, using long-term operational data, that, in grids with high wind penetration, OCGT displaces CCGT as the former's flexibility for fast starts and high ramp rates becomes important in such generator mix regimes to deal with wind's intermittency. The paper also indicates that there is a significant loss in thermal efficiency during those periods requiring the fast ramp rate flexibility.

WIND'S REQUIREMENT FOR TRANSMISSION AUGMENTATION

As a result of the impact on the South Australian grid of the additional volatility resulting from the addition of the large wind generation fleet, the AEMO has proposed the building of two very long, high-capacity transmission lines from South Australia to the eastern States for the sole purpose of balancing the effects of wind's volatility on that portion of the grid in South Australia, (Swift [22, 23]). Wind energy penetration has already reached the 20% target in South Australia (AEMO [6], pp. vii). The cost of this management scheme would be of the order of several billion $AUD. For reasons discussed later, extending such a scheme to deal with the increased penetration of wind energy into the eastern States (proposed by several State governments to address their clean-energy targets), is unlikely to be effective, but clearly would involve very substantial additional costs in construction of additional inter-State interconnectors.

More recently, Chapman [24, 25], of the AEMO has provided costings of the likely transmission augmentations required to deal with this increasing wind penetration. These show estimates of the order of $AUD4 - 10 billion. As far as can be determined, these estimates are based on wind output averages, so are likely to be conservative, that is, low.

A recent study by Inhaber [26] indicates that the costs of CO_2 savings rise substantially with increasing penetration of wind capacity on the grid. Using the Inhaber (*ibid.*) methodology, Lang [27] has provided an explanation of the cost consequences of increasing wind penetration in the eastern Australian context. The very expensive AEMO transmission augmentation "solution" mentioned above is the kind of prohibitive cost item identified by Inhaber (*ibid.*).

EVIDENCE FOR A SECOND SEPARATE METEOROLOGICAL IMPACT MECHANISM

While this paper was in preparation, the eastern Australian grid has experienced the arrival of a large high pressure system sitting over its entire extent. An examination of the AEMO data for this period showed that, throughout most of the daylight hours of Saturday 28 May 2011, the output of the entire wind generation fleet across the grid was zero or close to zero.

The occurrence of this type of event at the same time of the year in 2010 (18 – 21 May), is also apparent from an examination of Figure 3. Meteorologists (Clark, [28], Miskelly, [29], Wikipedia [30], Carberry *et al* [31]), indicate that this may be due to the migration of the Sub-Tropical Ridge across the southern portion of the eastern Australian grid, the region in which the reported wind farms are located. This is a region of high pressure and hence stable, calm air. It migrates latitudinally across Australia during the Autumn and Spring periods. In the Spring it migrates from a position slightly north of the 30th parallel southward towards the pole. In the Autumn it moves northward again. See: http://en.wikipedia.org/wiki/Subtropical_ridge . In the Australian context, the following link at the Commonwealth Bureau of Meteorology site is both helpful and authoritative:
http://www.bom.gov.au/lam/climate/levelthree/ausclim/ausclimsa.htm .

The occurrence of such periods of fine weather, extended in both time and geographic extent, shows the inadvisability of building wind farms to replace coal-fired base load power stations. The presence of 50,000 or even 100,000 windmills across eastern Australia during such fine-weather events would also yield very little output, because there is no wind anywhere within such high pressure systems during these periods (see the Appendix for an analysis). These are the numbers of windmills being proposed by, for example, the Zero Carbon Australia 2020 initiative. (Wright, Hearps *et al*, [32]) [12]

Furthermore, the wind turbines themselves require electric power to operate various internal systems, such as wind direction monitoring, the directional control motors, lubricating oil temperature control, etc. The standing power consumption

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[12] In a critique of BZA 2020, Trainer [33] states: "Several studies have shown that over large areas wind's contribution often falls to around zero. (Oswald, Raine and Ashraf-Bull, 2008, Coelingh, 1999, Sharman, 2005, and Davey and Coppin, 2003.)".

required to provide for the operational requirements of all wind turbines during such conditions could be of the order of several hundred megawatts for such a large fleet, all of which power would have to be provided by fossil-fuelled generation via the grid. This is another serious consequence resulting from wind's common-mode failure, and is a far worse scenario than the failure of a "large coal or nuclear plant". Unlike the latter, not only can there be no backup wind generation available to cover the contingency, but it is also a far more serious problem because a far larger amount of backup plant capacity has to be found than that resulting from the failure of one conventional power station. At present, the largest single fossil-fired generation unit on the eastern Australian grid is 660 – 700 MW. (There are no nuclear plants in Australia.) The wind installed capacity already exceeds 1900 MW and often, as the graphs show, can be producing up to 1500 MW at a given instant – a figure far in excess of that which has to be found for the failure of a conventional generator.

This high frequency of common-mode failure, and the power requirements of wind turbines even while idle at such times, may require levels of replacement fossil-fuel standby capacity that approach the total installed capacity of the entire wind farm fleet.

It is also noted that there is a significant number of events where the wind output does not fall to near-zero, but nonetheless falls dramatically over a MW range which again is significantly greater than the installed capacity of the largest single coal-fired generation unit on the eastern Australian grid. The occurrence of these power spikes constitutes a very significant new challenge to the maintenance of grid operational stability and security, a challenge that was most likely unknown prior to the introduction of wind plant.

This real-life scenario also demonstrates that the geographic-dispersion-provides-sufficient-smoothing hypothesis has no credence. Should policymakers continue to pursue a scheme to have wind generation equal to or to exceed 20% total installed generation capacity, across the entire eastern Australian grid, with the view that fossil-fuelled plant might be retired, then these frequent power excursions will not only continue to occur, but will become considerably larger. The continued occurrence of such, larger, excursions may well nullify any benefit arising from the AEMO's already-mentioned expensive "grid augmentation" proposal, (Swift, [23]), designed to improve grid system stability in South Australia. The proposed grid-wide 20% penetration of renewables, where wind energy is the major component, may merely spread what is presently a stability problem largely confined to South Australia, to a much larger one that is spread right across south eastern Australia. Providing interconnections from sub-region to sub-region, where each subregion is struggling to deal with wind's volatility, all of which are part of the larger region which the analysis shows is also subject to wind's volatility, is very likely not going to be an effective strategy to solve the resulting system stability problems. Achieving a 20% renewables target then, while maintaining a secure and reliable electricity supply on the eastern Australian grid, is likely to prove difficult to achieve. No Australian grid can expect to have the luxury of interconnections to larger grids in neighbouring countries. Nations such as Denmark, Spain, etc., where the renewables installed capacity already meets or exceeds the 20% figure, are, unlike the eastern Australian grid, supported by substantial interconnections to adjacent, larger grid systems, where renewables penetration is a significantly smaller component. For example, Sharman [34] has shown that Denmark, at times of high wind generation and low local demand, is forced to export substantial amounts of its wind-generated power to these adjacent regions, often at very low prices, (due to market conditions prevailing at such times), so that its wind farms can continue to operate. Similarly, more recently, the AEMO [6], has shown that, while South Australia has a percentage of wind generation exceeding 20%, it similarly is reliant on its interconnections to the eastern States for the necessary export of wind-generated output during similar periods. It is noted that to enable the installation of further wind generation in South Australia, the AEMO ([6], *ibid.*) proposes significant augmentation to both of the interconnectors to the eastern States to deal with what it refers to as "the challenging control issues" brought about by such increases (in wind generation installed capacity).

The AEMO [6], at page vii, estimates the expected wind farm contributions to be 5% and 3.5 % respectively for summer and winter during periods of peak demand. These values are percentages of the installed wind farm capacity in South Australia, (which at the time of publication of the AEMO SA Supply/Demand Outlook 2011 ([6]), was 1150 MW, some 21% of total installed generation capacity in South Australia). These percentages indicate that little reliance can be placed on wind generation during these critical periods.

POTENTIAL FOR ARTIFACTS DUE TO WIND FARM "CLUSTERS"

The wind farms are spread across almost the full east to west extent of the eastern Australian grid, a distance of over 1200 km.; and a distance of over 500 km. south from a line connecting the Cathedral Rocks wind farm in the west to the Capital wind farm in the east, to the most southerly wind farm at Woolnorth on the northwest tip of Tasmania. Referring to the map of Figure 10, within this present configuration of wind farms, the largest "cluster" of installed capacity is in South Australia. A concern is that synchronicity in operational behaviour may result from those wind farms in a cluster being within the same wind regime. The distances across the SA "cluster" are large. From Cathedral Rocks in the west to the easternmost wind farm in SA, Waterloo, is a great circle distance of 362 km. From the northernmost wind farm, again at Waterloo, to the southernmost, at Canunda, the distance is 533 km. For scale purposes, these distances are comparable to the area of the nation of Denmark.

Table A.1 shows that there is a significant amount of wind generation, Capital, Cullerin, (in a NSW "cluster"), Woolnorth (Tas.), and Challicum Hills, Portland, Waubra, Yambuk, all in Victoria, totalling some 782 MW, that is situated well to the east of the South Australian "cluster". The distances between the wind farms at the extremes of the region follow.

The east-west extent: Capital (NSW) – Cathedral Rocks (SA): 1277.5 km.

The north-south extent, being the distance along a line of longitude from the most southerly wind farm (Woolnorth in Tasmania), to the point on a line joining Waterloo (SA) and Cullerin (NSW) - the two most northerly wind farms in the group. From the figure above this latter set of coordinates would be (-34.00, 144.70), yielding a great circle distance[13] of: 741.4 km.

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[13] Great Circle distances calculated using an on-line calculator: http://williams.best.vwh.net/gccalc.htm

Given the large distances involved, even within the "cluster" that might be called the wind farms in South Australia, and that several of the wind farms in the eastern States are as large or larger than those in South Australia, the suggestion that one cluster of wind farms in South Australia might have the dominant effect, without a much more detailed analysis, is not something that can be stated with certainty.

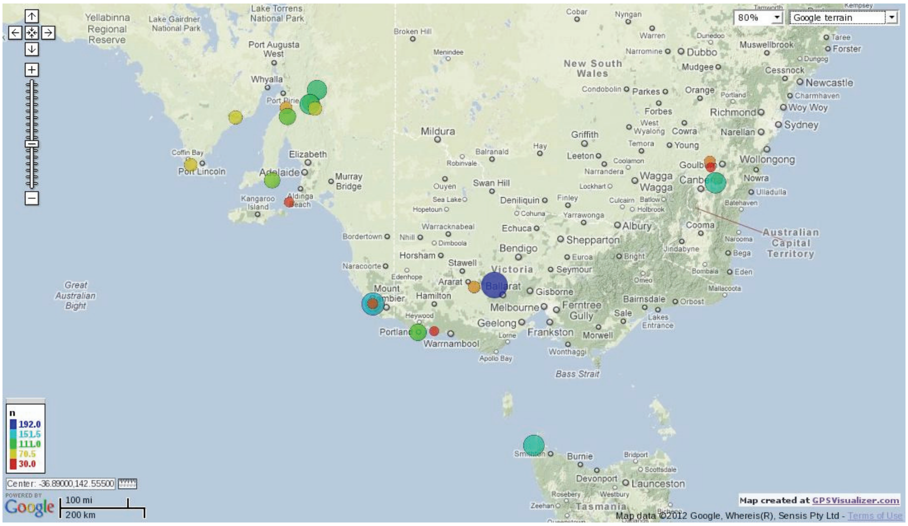

Figure 10. Wind farm locations on the Eastern Australian grid. Circle diameter shows relative installed capacity. Appendix Table A.1 data was used for map generation with GPSVisualizer (www.gpsvisualizer.com).

CONCLUSION

Engineers are required to do more than merely analyse and report on natural phenomena. They are required to create practical solutions to real world problems. In so doing they must test and design systems ensuring that they have addressed the worst case scenarios. As a result, they may not concentrate merely on average values. With these requirements firmly in mind, to the electrical engineer, a careful scrutiny of the available wind farm operational data shows that, on the eastern Australian grid, it is not possible for wind energy ever to displace dispatchable, reliable generation supplying the base load demand. In this regard, an examination of the graphs comprising Figure 3 clearly indicates that the proposal by some Australian policymakers to replace major coal-fired power stations with a fleet of wind farms is not technically achievable.

Additionally, the analysis shows that further increased wind penetration, even if spread evenly across the eastern Australian grid, will result in an increasing contribution to grid instability, potentially making wind energy an increasing threat to grid operational security and reliability. To continue a policy strategy to increase wind penetration across the eastern Australian grid, to seek to meet a target of some 20% installed capacity, as has already been achieved in South Australia, (with the presumption that wind may thereby meet 20% of base load requirements), has the potential to be a dangerous strategy.

To address the increased instability due to wind, a fleet of fast-acting OCGT generation plant may well be required to back up wind's intermittency. The use of a significantly greater proportion of this form of generation, rather than the more thermally-efficient CCGT, in the gas-fired generation plant mix may lead, seemingly paradoxically, to both higher gas consumption and higher GHG emissions from the resulting OCGT/CCGT generation mix than if wind generation was not included in the generation portfolio.

As the eastern Australian grid is:

- the world's most geographically dispersed single interconnected grid,
- as the present wind farm fleet is dispersed across it at its widest portion in the east-west direction, that is, in the direction of the prevailing mesoscale atmospheric circulation,
- and that this fleet also occupies a significant region in the north-south direction, these conclusions are significant for grids worldwide.

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This paper is dedicated to the memory of Dr Alan Shaw, one of the finest of Britain's electrical engineers of his generation. During his long and productive life, in his many letters to newspapers, always courteous, always polite, Dr Shaw demonstrated the importance of making understandable to the wider public, the often abstruse concepts of electrical engineering.

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[14] A very readable summary of grid operation may be found at: http://en.wikipedia.org/wiki/Electric_power_transmission. Accessed 22 January 2012.

[15] See also http://en.wikipedia.org/wiki/Nyquist–Shannon_sampling_theorem, for a recent, very readable explanation of the theorem, and for the applicability to CD equipment design, see: http://en.wikipedia.org/wiki/Nyquist_frequency. Both sites accessed 22 January 2012.

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Appendix – Analysis of relevant meteorological events

An examination of the Australian Bureau of Meteorology (BOM) daily synoptic charts, issued for 11 am EAST (or EDT where relevant), for the dates in Figures 4a and 4b, the dates during calendar year 2010 where total wind farm output to the eastern Australian grid fell to below the MAL for significant periods, shows a constant theme: the presence of large, blocking, high pressure systems which are stagnated, or slow-moving, over the full extent of the eastern Australian grid on those dates. During such a meteorological event, it can be expected that there will be little or no wind anywhere within the region under the influence of the high pressure system, so that any addition to the wind farm fleet within the region would make no difference to the electrical output under such conditions. Whether there is one wind turbine, or 100,000 wind turbines, within the region, the output will be zero, because there is no wind to power them. Thus the cause of the "common-mode" failure for this particular form of power plant is identified.

Shown below are sets of data for two example events likely to be the result of the influence of the passage of the Sub-Tropical Ridge over the eastern Australian grid region. Shown are the 11 am synoptic charts for the days of 18 May 2010 and 27 May 2011, and the corresponding wind fleet electricity output for the 24-hour period of each of those days. These pairs of charts show some striking similarities. These events are the periods in each of the respective years during which the output of the entire wind farm fleet is zero for periods of several hours on each occasion. Each chart set shows a high pressure system geographically widely spread over southern and eastern Australia.

These weather systems are spread across the entire extent of southern Australia. It would seem reasonable to conclude that it is likely that, should there be wind farms spread across the entire extent of southern Australia, there would also be no output from any wind farms located anywhere in this much larger region at these times.

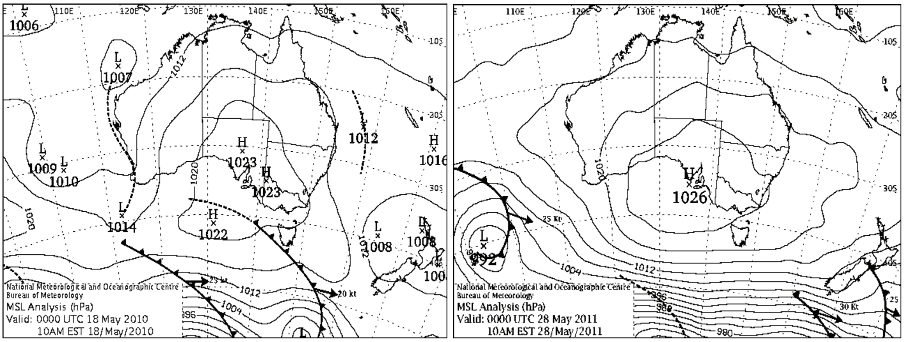

Figure A.1. Synoptic chart for 18 May 2010

Figure A.2. Synoptic chart for 28 May 2011

Synoptic Charts at 11am each day. (Reproduced courtesy Australian Bureau of Meteorology).

Total wind farm output (uppermost curve) for the full 24 hour period on the above dates:

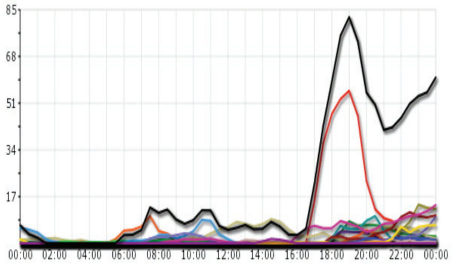

Figure A.3. Total wind farm output – 18 May 2010

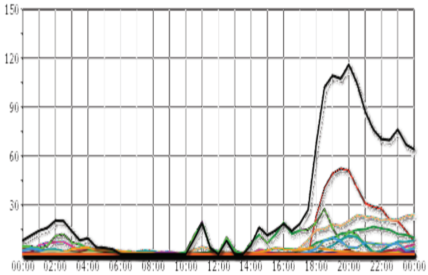

Figure A.4 Total wind farm output – 28 May 2011

These figures and Table A.2 above, are courtesy of Miskelly [17].

Wind farm installed capacities and locations on the eastern Australian grid are shown in Table A.1. The map of Figure 10 is constructed from this data.

Table A.1. Wind Farm Location & Capacity as of 31 December 2010[16].

AEMO ID	Name	State	Latitude	Longitude	Capacity (MW)	Capacity Factor (%)
captl_wf	captl_wf Capital Wind Farm	NSW	-35.15	149.53	140.00	26.7
cullrgwf	Cullerin Range Wind Farm	NSW	-34.81	149.40	30.00	39.2
cnundawf	Canunda Wind Farm	SA	-37.75	140.40	46.00	27.7
cathrock	Cathedral RocksWind Farm	SA	-34.76	135.54	66.00	30.0
clemgpwf	Clements Gap Wind Farm	SA	-33.50	138.10	56.70	32.1
hallwf1	Hallett Wind Farm 1	SA	-33.37	138.73	94.50	36.1
hallwf2	Hallett Wind Farm 2	SA	-33.52	138.87	71.40	36.6
lkbonny1	Lake Bonney Wind Farm 1	SA	-37.76	140.40	80.50	24.5
lkbonny2	Lake Bonney Wind Farm 2	SA	-37.76	140.40	159.00	22.7
lkbonny3	Lake Bonney Wind Farm 3	SA	-37.76	140.40	39.00	-
mtmillar	Mt Millar Wind Farm	SA	-33.70	136.74	70.00	27.3
nbhwf1	North Brown Hill Wind Farm	SA	-33.41	138.71	132.30	-
snowtwn1	Snowtown Wind Farm	SA	-33.69	138.13	99.00	37.0
starhlwf	Starfish Hill Wind Farm	SA	-35.57	138.16	34.50	24.1
waterlwf	Waterloo Wind Farm	SA	-33.10	138.91	129.00	-
wpwf	Wattle Point Wind Farm	SA	-35.10	137.73	90.75	30.4
woolnth1	Woolnorth Wind Farm	Tas	-40.68	144.70	140.00	37.7
challhwf	Challicum Hills Wind Farm	Vic	-37.38	143.09	53.00	27.1
portwf	Portland Wind Farm	Vic	-38.35	141.59	102.00	34.3
waubrawf	Waubra Wind Farm	Vic	-37.36	143.64	192.00	35.2
yambukwf	Yambuk Wind Farm	Vic	-38.33	142.04	30.00	28.1
				Total	1855.65	

Notes for Table A.1:

The North Brown Hill, Snowtown and Waterloo wind farms did not become operational until the second half of 2010. The total installed capacity for the first 6 months of 2010 was 1495.35 MW.

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[16] The AEMO did not publish data in 2010 for a number of small wind farms connected to the eastern Australian grid. These include Blayney (9.9 MW), Crookwell (4.8 MW), Hampden (1.32 MW), Kooragang (0.6 MW) in New South Wales; Windy Hill (12 MW) in Queensland; Codrington (18.2 MW), Toora (21 MW) and Wonthaggi (12 MW) in Victoria.