CO_2 Emissions Savings from Wind Power in the National Electricity Market (NEM)

Submission to the Senate Select Committee on Wind Turbines

FINAL REPORT

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1. Executive Summary

This report examines the contribution of wind power to CO_2-e emissions reduction in the NEM in 2014. Using a generation dataset at 5-minute intervals, CO_2-e emissions time-series are estimated for each of 151 thermal generators, giving total emissions from fossil fuel plant of 169.7MtCO_2-e. The best empirical estimate is that wind power avoided 6.2MtCO_2-e, a reduction in total emissions of 3.5%. Wind power contributed 4.5% of system demand and therefore the emissions displacement effectiveness of wind power was 3.5%/4.5% or 78% in 2014.

Several factors acted to limit the effectiveness of wind power in reducing emissions in 2014. A significant fraction of South Australia's wind output displaced low-emissions gas generation. Wind power tended to displace black coal plant in New South Wales rather than higher emis-

sions brown coal plant in Victoria. Part-load inefficiency costs and system losses also degraded effectiveness.

Wind power becomes less effective in displacing emissions from thermal plant as installed capacity increases. The evidence in this study suggests that effectiveness in the NEM would fall to $\approx 70\%$ if the proportion of energy provided by wind is doubled from 2014 levels.

The emissions parameters for individual power stations available for this study are approximate, which means that the quantitative results are subject to increased uncertainty. Data requirements for an improved investigation are described and a detailed multi-year study using such data is warranted.

2. Overview of the NEM

De-carbonisation of electricity production is a major goal of environmental policy. Wind power generation (WPG) is an emissions reducing technology which works by displacing fossil fuel generation. Unlike renewable sources such as hydro-electric power, WPG is not dispatchable generation i.e. it is not controlled by the grid operator. Instead the thermal system must adapt continuously to the natural variability (intermittency) of WPG. As the complexity of this interaction has become better understood, early optimism about the efficacy of wind power in emissions reduction has reduced. Under normal priority dispatch rules for WPG, one unit of wind energy (1 MWh) displaces close to one unit of conventional generation (slightly less due to system losses). However this relation need not be valid for CO_2 displacement. For instance, wind might selectively displace more flexible, high marginal cost gas plant rather than baseload coal plant. In that case the displacement effectiveness[1] of WPG is less than unity. In addition to this selective displacement effect, part-load inefficiency costs, ramping and startup costs tend to become significant as the installed wind capacity increases. This reduces the effectiveness of wind power in meeting it's primary policy goal.

In this report, empirical calculations*[1]* of the effectiveness of the WPG in the NEM during 2014 are described. The objective is two-fold:

- determine which information is required to answer this question empirically for the NEM
- provide estimates of operational emissions savings based on the available data

Operational emissions savings can be defined as the difference between the observed emissions and what emissions would be in a no-wind scenario all else being equal. This

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[1] ratio of % CO_2 emissions savings to % WPG, see Section 4.1

quantity can be investigated empirically. Empirical methods can assess the impact of wind power on the existing grid but they cannot indicate whether the existing technology mix or grid configuration is optimal from an emissions perspective.

Economic dispatch models are the standard approach to modelling electricity grids. The advantage of dispatch models is that they allow various scenarios to be investigated for planning purposes taking grid capacity constraints into account etc. However, dispatch models do not readily distinguish between conventional scheduled generation and non-forecastable generation such as WPG. Empirical methods are a complementary approach which have the advantage that they are based on real-world data. As intermittent renewable energy sources have become more important, use of empirical methods has increased.

The NEM consists of 5 interconnected regions (QLD,NSW,VIC,SA,TAS). Energy sources can be classified into seven types: brown and black coal (lignite and bituminous coal), natural gas, distillate (kerosene, diesel etc), hydro, wind and biomass. High frequency (5-min) SCADA generation data are **archived by AEMO***[2]*. These data describe the "as-generated" output of 256 metered generators which contributed power to the NEM in 2014, with a combined capacity of 46.6GW.[2] Generation can also be measured as "sent-out" i.e. power net of auxiliary loads and actually dispatched to the grid. The "as-generated" SCADA data are more directly relevant for calculation of emissions. Note that some smaller non-scheduled generation is omitted from the SCADA dataset. Apart from this, the 2014 SCADA archive is very nearly complete with just 0.3% of the data records missing. As is evident from Figure 4.1, a diverse range of thermal generator types, capacities and technologies are present on the NEM. Coal is the dominant fuel. 65 coal plant with a combined capacity of more than 25GW, accounted for 75% of electricity production.

Table 2.1 summarises total generation by fuel and region in 2014.This was compiled using generator location and fuel type information given in Tables 4.1-4.3.

region	Biomass	Black Coal	Brown Coal	Distillate	Gas	Hydro	Wind	TOTAL
NSW		54.5		0.0	3.8	1.5	1.1	60.9
QLD	0.4	41.7		0.0	13.6	0.9		56.6
SA			2.6	0.0	5.3		4.1	11.9
TAS					0.8	9.8	0.9	11.5
VIC			46.6		2.2	1.9	2.5	53.2
TOTAL	0.4	96.2	49.2	0.0	25.7	14.0	8.7	194.1

Table 2.1: Total energy (TWh) generated by region and fuel type in 2014.

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[2] excluding pumped hydro capacity.

Figure 2.1 shows 5-minute time-series of NEM power generation by fuel type in 2014. Note the difference in vertical scales. Black coal is load-following, while hydro and gas also show peaking behaviour.

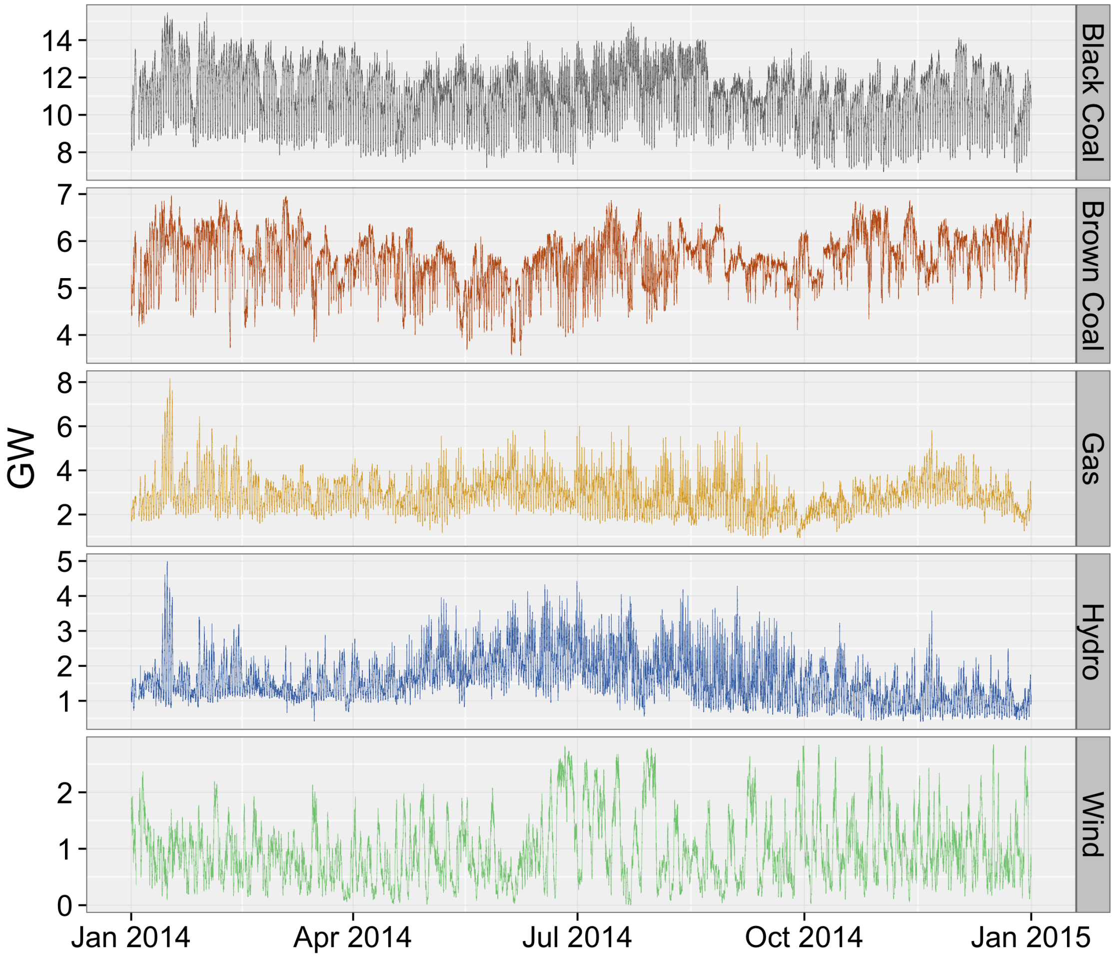

Figure 2.1: Total generation (GW) at 5-min intervals by fuel type from SCADA.

2.1 renewables

Wind provided 8.7TWh in 2014 or 4.5% of total energy generated. SCADA data is available for 34 wind farms with total installed capacity of 3394MW. These generated 970MW on average, which corresponds to a capacity factor of just under 29%. Capacity factors at regional level were 19%(NSW), 35% (TAS), 31%(SA) and 28%(VIC). Geographic diversification reduces the variability of total WPG relative to the output of individual wind farms. Nevertheless total wind power on the NEM remains highly variable or intermittent as can be seen from the bottom panel of Figure 2.1. The benefit of geographic diversification is limited despite the very large spatial scale of the NEM (∼5000km). There are two reasons for this: (1) WPG is concentrated in southern Australia where the wind resource is strongest and (2) weather systems correlate the output of wind farms even over very large distances (>1000km).

Hydro is a long established renewable energy source in Australia. It provided 13.6TWh or 7.2% of total NEM generation in 2014 (excluding pumped storage). More than 70% of hydro generation in 2014 was located in Tasmania. Like wind, hydro is a low-carbon renewable technology. However, unlike wind, hydro is dispatchable generation. Hydro plant are flexible and may operate as peaking plant or as base-load depending on seasonality (Figure 2.1). In contrast, there is virtually no correlation between non-dispatchable WPG and system demand. This situation is illustrated in Figure 2.2. Correlation coefficients between total generation (a proxy for system demand) and wind, hydro, gas and WPG were 0.01, 0.73, 0.82 respectively in 2014. Like system demand, WPG is an exogenous variable. It is an external quantity to which the grid has to adapt continuously.

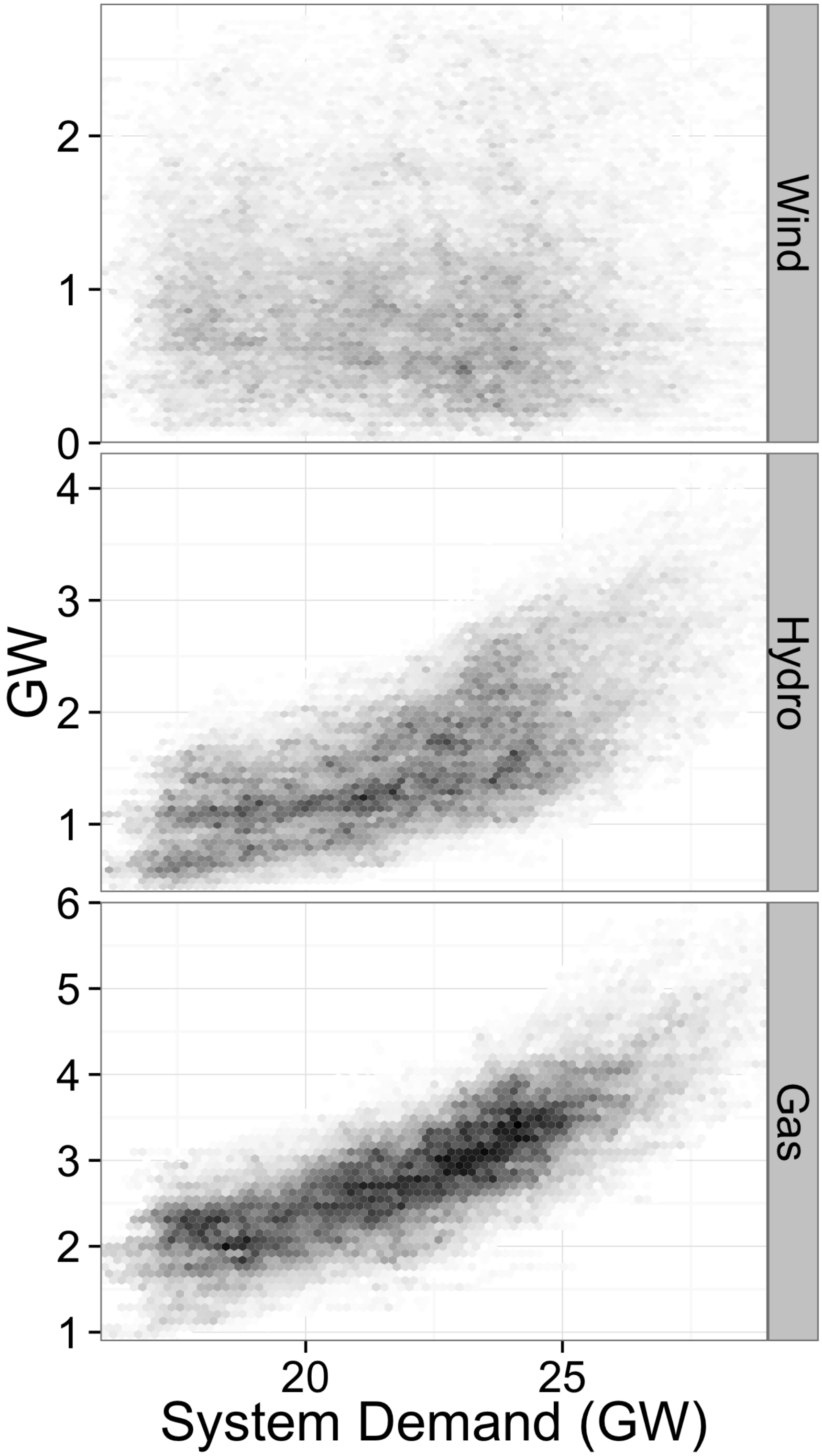

Figure 2.2: Generation by fuel type (GW) versus system demand (GW). Wind generation (top) is uncorrelated with demand.

2.2 fuel mix

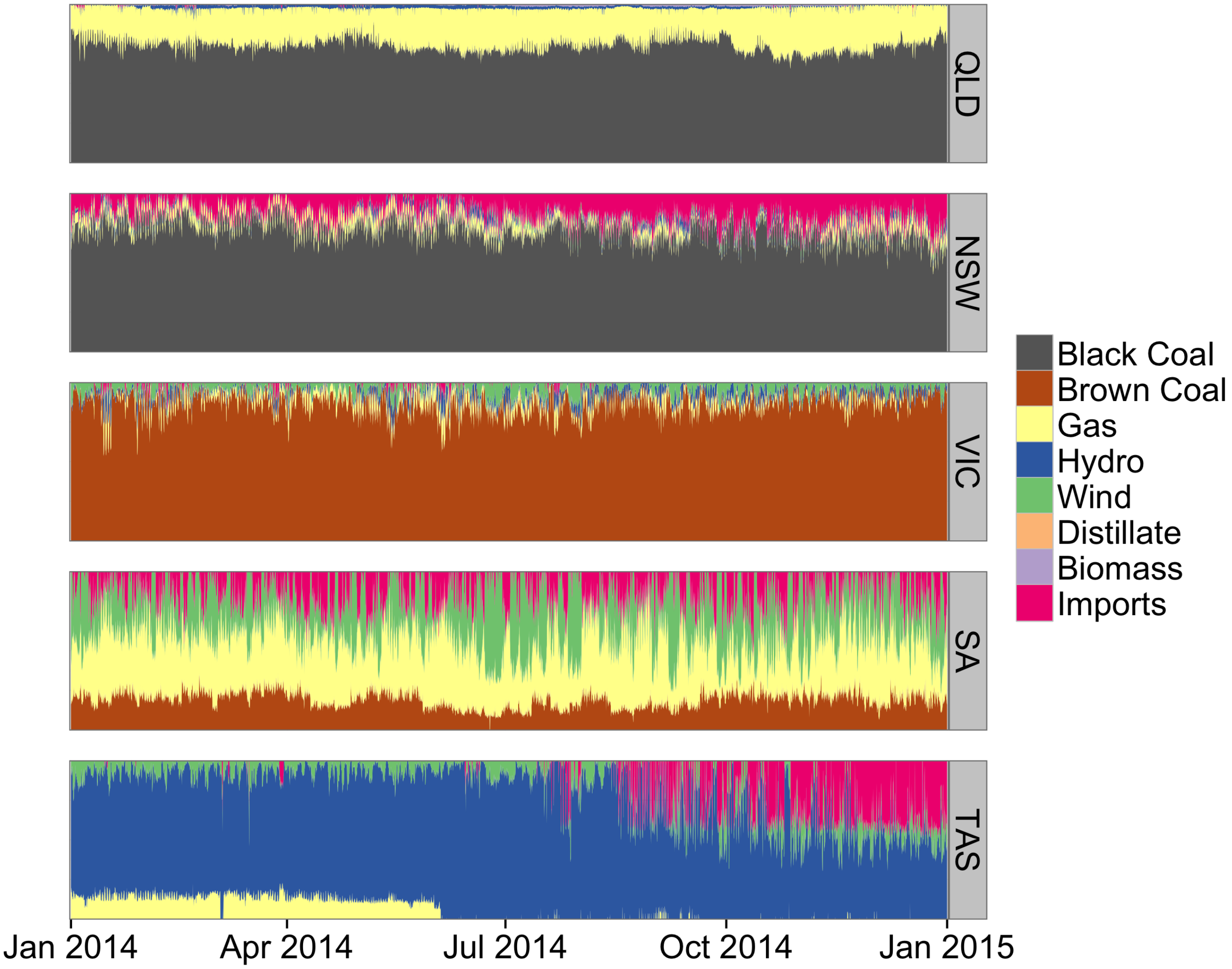

Figure 2.3: Hourly fuel mix plots for NEM regions in 2014.

Regional fuel mix plots (Figure 2.3) show the fraction of generation derived from each fuel type (including imports). QLD has a relatively stable mix between gas and black coal. NSW is almost always a net importer of power. WPG displaces both gas and imports strongly in SA. Hydro is dominant in TAS and the impact of the Tamar Valley CCGT outage from June 2014 is evident.

A simple measure of the displacement effect of WPG on other generation types can be obtained from the fuel-mix data, Table 2.2. By the definition of the fuel mix, the displacements sum to -1. In reality system losses mean that the displacement of scheduled generation by WPG is imperfect. Note also that no allowance is made for outages Section 2.3.

The high displacement of imports in SA and VIC in Table 2.2 signifies exports of WPG from these regions. On the other hand, wind power in TAS displaces hydro primarily with little impact on imports.

region	Black Coal	Brown Coal	Gas	Hydro	Imports
SA		-0.06 ± 0.01	-0.32 ± 0.02		-0.63 ± 0.03
VIC		0.03± 0.17	-0.26 ± 0.03	-0.17 ± 0.03	-0.60 ± 0.15
TAS			-0.08 ± 0.06	-0.99 ± 0.20	0.07 ± 0.22
NEM	-0.36 ± 0.05	-0.07 ± 0.06	-0.38 ± 0.04	-0.20 ± 0.05	

Table 2.2: Wind displacement fractions for NEM regions and for NEM as a whole from the fuel-mix data. By definition displacement fractions sum to -1.

2.3 outages

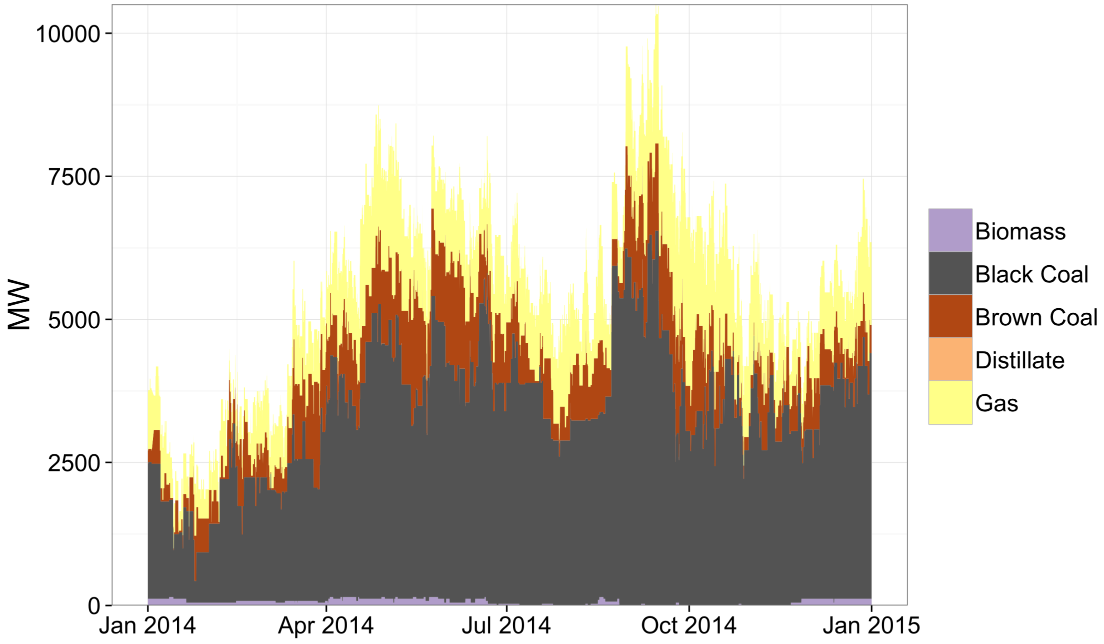

Figure 2.4: Thermal plant outages in the NEM in 2014.

Outages alter the fuel mix and play an important role in emissions variability. Aggregate outages also increase the effective system demand seen by available plant. Figure 2.4 shows the large variability in total outages in the NEM during 2014. Median availability factor for coal plant was ≈85%. Significant outages in 2014 include the shutdown of the 1GW Wallerawang plant and 50% availability factor at the 2GW Liddell plant in NSW. For load-following and base-load plant it is assumed that periods of zero generation longer than 12 hours are an outage event. These can be easily inferred from the generation data. It is not possible to infer outage events for peaking plant which operate intermittently. Here it is simply assumed that there are no outages for peaking plant. These assumptions were used in Figure 2.4 and are also used in Section 3.2.2.

2.4 inter-regional flows

Interconnectors link pricing regions in the NEM. 5-minute flow and loss data for six interconnectors are **archived by AEMO***[3]*.

NSW	SA	TAS	QLD	VIC
9.3	1.4	-0.9	-5.0	-5.5

Table 2.3: Net interchange (TWh) between regions. NSW and SA are net importers (+ve interchange).

Table 2.3 shows net energy interchange for each NEM region (TWh, +ve is net imports) in 2014. The numbers do not sum to zero because of system losses (exports > imports). NSW is a significant net importer of electricity through interconnection to QLD and VIC. Indeed a significant fraction of WPG from SA and VIC is exported to NSW where it displaces load-following coal plant. Positive flow through the VIC-NSW interconnector is correlated with WPG. In 2014 correlation between WPG and VIC-NSW interconnected flow was 0.42, while the correlation between WPG and interconnected losses was 0.36.

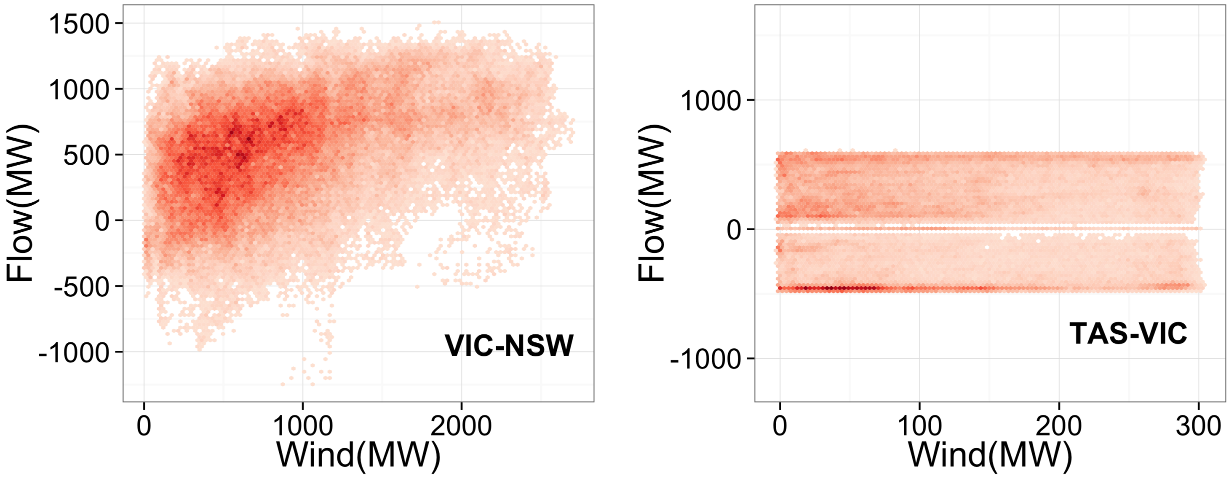

Figure 2.5: Left: VIC-NSW interconnector flow at 5-min intervals (MW) versus NEM wind power (excluding Tasmania) (MW). Right: TAS-VIC interconnector flow (MW) vs Tasmanian wind power (MW).

Losses are significant in the NEM. **AEMO estimate** that overall system losses in the transmission and distribution system are $\sim 10\%$. Figure 2.6 shows that periods of high WPG are associated with higher interconnection losses.

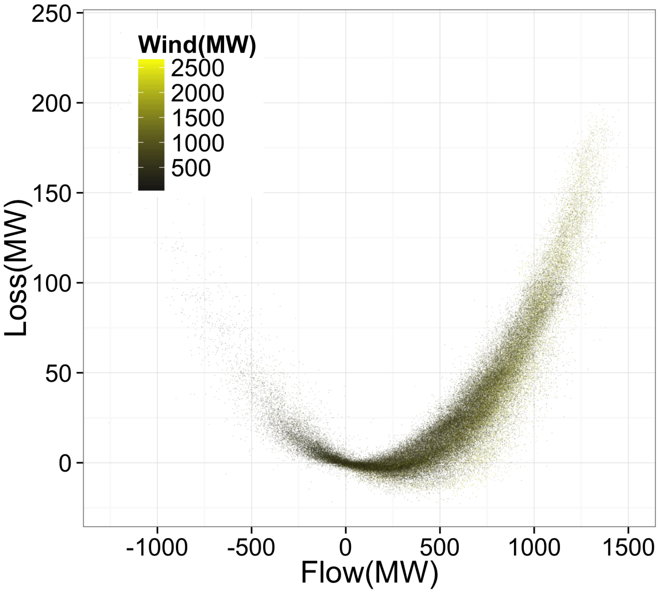

Figure 2.6: VIC-NSW interconnector losses at 5-min intervals (MW) vs interconnector flow (MW). Periods of high wind generation (highlighted) correlate with increased system losses.

Tasmania is connected via the Basslink HVDC interconnection to VIC. This has capacity 594MW for exports from TAS to VIC and 478MW for reverse flow. Interconnector flow is uncorrelated with Tasmania wind generation. This is consistent with the finding of Section 2.2 that TAS WPG displaces hydro generation. Losses through Basslink are $\approx$ 3-4%. The correlation between Tasmanian wind and Basslink flow is less than 0.02.

2.5 emissions

Greenhouse gas emissions associated with electricity production can be reported in different ways. "Scope 1" carbon accounting includes emissions directly associated with combustion of fuel while "scope 3" are indirect contributions associated with extraction and transport of the fuel. Minority greenhouse gas contributions can be included as carbon dioxide equivalents (CO_2-e). Following AEMO, emissions numbers quoted in this report are on a scope 1 plus scope 3 CO_2-e basis.

The SCADA generation data were used to calculate emissions from each generator at 5 minute intervals as described in Section 3.1. Results for 2014 summarised by fuel and region are given in Table 2.4.

region	Biomass	Black Coal	Brown Coal	Distillate	Gas	TOTAL
NSW		54.6		0.0	2.2	56.8
QLD	0.0	37.4		0.1	8.1	45.6
SA			2.8	0.0	3.8	6.6
TAS					0.3	0.3
VIC			59.0		1.4	60.4
TOTAL	0.0	92.0	61.8	0.1	15.8	169.7

Table 2.4: Calculated Scope 1+3 emissions (MtCO_2-e) by region and fuel in 2014.

Total emissions for the NEM were 169.7Mt, which equates to a mean emissions rate of 19.3ktCO_2-e per hour. Coal accounted for 91% of emissions (versus 75% of generation, Table 2.1). Table 2.4 and Table 2.1 give average emissions intensities by fuel and region shown in Table 2.5.

state	Biomass	Black Coal	Brown Coal	Distillate	Gas	Average
NSW		1.00		1.60	0.57	0.93
QLD	0.02	0.90		6.15	0.60	0.81
SA			1.06	1.18	0.73	0.55
TAS					0.42	0.03
VIC			1.27		0.62	1.14
Average	0.02	0.96	1.26	5.63	0.62	0.87

Table 2.5: Emissions intensities (tCO_2-e/MWh "as-generated") by fuel and region in 2014. Weighted average intensities are also shown. Emissions intensity in the NEM as a whole was 0.874tCO_2/MWh.

Note that these intensities are expressed with respect to "as-generated" energy (emissions intensities expressed with respect to "sent-out" energy would be higher, because sent-out energy is net of auxiliary loads). Brown coal has the highest average intensity of 1.26tCO_2-e/MWh, while gas has the lowest at 0.62tCO_2/MWh. Scope 3 emissions for black coal are considerably higher than those of brown coal (Tables 4.1-4.3) which tends to reduce the difference between black coal and brown coal.

Regional emissions intensity time-series are shown in Figure 2.7.

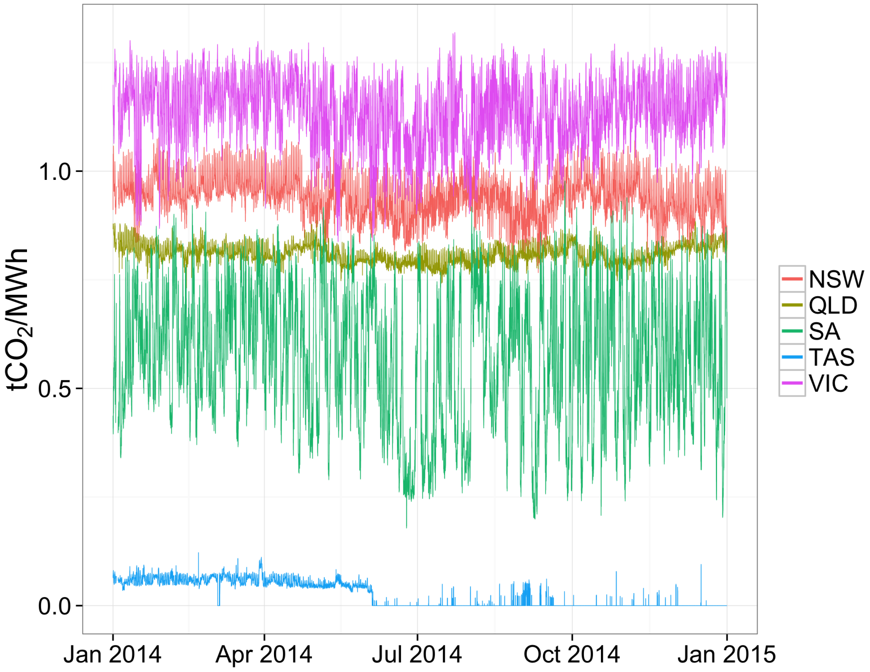

Figure 2.7: Estimated emissions intensity (tCO_2/MWh) time-series for NEM regions in 2014.

South Australia had extreme emissions intensity variability due to interplay of gas, WPG and interchange. QLD has the lowest variability consistent with the relative stability of the fuel mix Figure 2.3.

On average periods of high WPG are associated with lower NEM emissions intensity. Figure 2.8 shows scatterplots of grid emissions intensity at 5-min intervals versus fraction of total generation provided by wind, hydro and gas (for clarity, using binned scatterplots rather than plotting all 105,120 data points). The top panel shows lower emissions intensity as wind generation increases as expected. However this relationship is quite diffuse compared to hydro (middle panel). The comparison suggests that WPG is less effective in lowering emissions in the NEM than hydro.

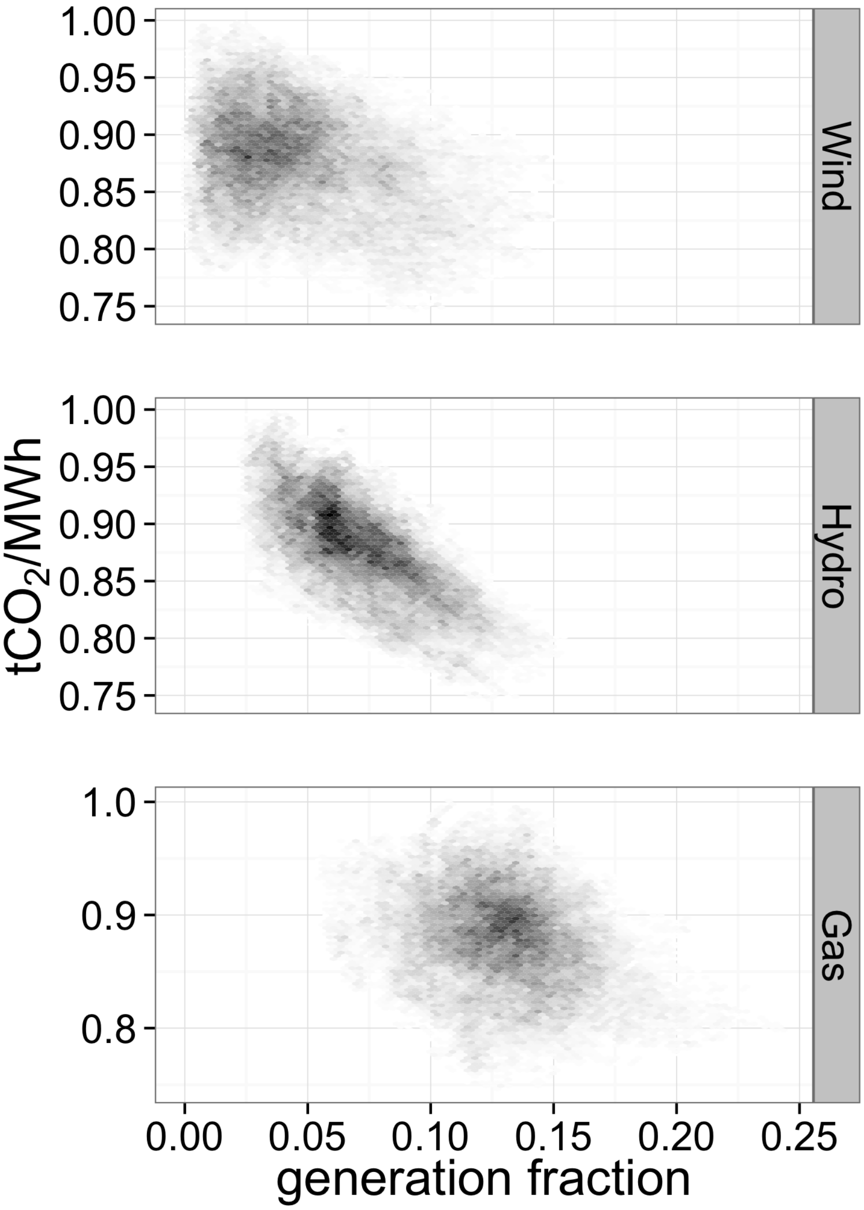

Figure 2.8: Emissions intensity(tCO_2/MWh) of the NEM in 2014 versus generation fractions.

A detailed calculation of emissions savings from displaced thermal plant is described in Section 3.2. However a simple estimate can be obtained by combining the mean emission intensities of Table 2.5 with the displacement fractions of Table 2.2. This gives savings $(-0.36 \times 0.96 - 0.07 \times 1.26 - 0.38 \times 0.62)$ = -0.67tCO_2-e/MWh. Alternatively, a straight line fit to the top panel of Figure 2.8 gives a slope of -0.51tCO_2-e/MWh. While these estimates are oversimplified, both suggest that emissions savings per unit wind energy are lower than grid average emissions intensity (0.87tCO_2-e/MWh Table 2.5).

3. Empirical Method

3.1 emissions models

The simplest model assumes a linear relationship between fuel energy consumption of a generator and it's output G. The hourly CO_2-e emissions rate is:

$$\text{emissions} = \frac{f}{\varepsilon}(aC + (1-a)G) \tag{3.1}$$

Here ε is "as-generated" generator efficiency, f is a scope 1 + scope 3 emissions factor (expressed in units tCO_2-e/MWh), C is the generator capacity and a is the zero-load fuel consumption expressed as a fraction of maximum load fuel consumption. $a > 0$ implies that the generator operates less efficiently under part load. Equation 3.1 can be combined with SCADA generation data to create 5-minute emissions time-series for each of the 151 thermal generators which supplied power to the NEM in 2014. An approximate **set of emissions parameters** were prepared by consultants ACIL-Allen *Fuel and Technology Cost Review Report*, 2014*[4]*. These parameters are used in this report and summarised in Tables 4.1-4.3. Examples of calculated 5-minute emissions time-series are given on the left hand side of Figure 3.2. Note that this procedure omits start-up and ramping emissions from power plant cycling. Also, emissions are set to zero during periods of zero generation, an assumption (zero generation implies zero fuel use) which is correct in most but not every case.

It is important to compare emissions calculated using Equation 3.1 with emissions reported using other methodologies. Annual scope 1 emissions from power stations in the NEM are published under the *National Greenhouse and Energy Reporting* scheme*[5]*, administered by the Clean Energy Regulator. These are based on actual fuel consumption determined on site, with fuel emissions factors determined locally. AEMO also report greenhouse gas emissions based on "sent-out" generation data. This methodology, called the *Carbon Dioxide Emissions Intensity Index* (**CDEII**)*[6]*, calculates emissions as a simple product of "sent-out" energy (available 1/2-hourly) and a generator-specific emissions intensity. Starting from June 2014 the CDEII emissions intensities at generator level have been reconciled closely with the NGER values.*[7]* Note that scope 3 emissions are included in CDEII but not in the NGER. The additional scope 3 fuel emission factors values are sourced from the National Greenhouse Accounts Factors workbook (**NGA**).*[8]*

Figure 3.1 compares emissions **reported by AEMO***[9]* to emissions calculated using Equation 3.1 and "as-generated" data. Despite different underlying generation datasets used, there is very good agreement. Total emissions agree to within 1%.[1]

Figure 3.1: June-December 2014 CO_2-e emissions reported by AEMO (using CDEII methodology) compared to emissions calculated using Equation 3.1 (denoted "Calc").

Emissions intensity of a generator can vary from one period to another due to differences in operating regime. Dividing Equation 3.1 by G gives:

$$\text{intensity} = \frac{f}{\varepsilon}\left(\frac{a}{CF} + (1-a)\right) \tag{3.2}$$

Equation 3.2 shows that emissions intensity depends on the inverse of the capacity factor (CF). WPG lowers capacity factor of a displaced plant and therefore increases the mean emissions intensity. This "part-load efficiency cost" becomes more significant as wind penetration increases.

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[1] In principle "as-generated" data are a better basis for calculation of emissions than "sent-out" generation data.

3.2 emissions avoided

3.2.1 hydro-wind

Hydro-wind systems need special consideration when calculating emissions avoided from wind power. When wind power displaces thermal plant there is a coincident reduction in emissions. There is no coincident emissions reduction when wind displaces hydro generation. However displaced hydro energy is stored and is therefore available to displace thermal plant at some later time.

Hydro accounted for 85% of Tasmanian electricity production in 2014 with 24 hydro generators providing baseload/load-following power. Wind produced 8% of total TAS generation. Table 2.2 suggests that almost all TAS wind displaces hydro. This is supported by Figure 2.5 which shows that flow through the Basslink interconnector is uncorrelated with Tasmanian WPG. Tasmanian hydro storage capacity is $\approx$ 15TWh, while **actual hydro energy stored** in 2014 was $\approx$ 4TWh.*[9]* Since Tasmanian WPG was only 0.95TWh, there is ample storage capacity and no constraints on the displacement of hydro by wind at current installed wind capacity.

If Tasmania were a stand-alone system without interconnection to the NEM, emissions avoided due to Tasmanian wind-hydro system would be close to zero. This implies that any emissions savings on the NEM must derive from Basslink flow. Mean Basslink flow was 100MW in 2014, while mean TAS WPG was 108MW. Thus mean flow would have been reversed (-8MW net imports) in the absence of TAS wind power. Detailed calculations including the impact of Basslink flow on emissions from individual power plant is described in the next Section 3.2.2. A rough estimate (assuming that the hydro-wind system displaces emissions at grid average intensity via increased Basslink flow) gives emissions avoided by Tasmanian WPG $\approx$ 0.8MtCO_2.

Hydro plays a minor role outside of Tasmania, where it provided just 2% of energy generated and operates as peaking or seasonal load-following plant. A contribution to emissions savings from displaced non-TAS hydro plant is estimated in Section 3.2.3.

3.2.2 regression

Empirical methods can be used to relate emissions from individual generators to 4 covariates:

- total system demand
- total system outages
- total wind power generation excluding Tasmania
- flow through the TAS-VIC interconnector

The first three covariates are exogenous variables, largely outside the control of the grid operator or other market participants.[2] As discussed in Section 3.2.1, TAS-VIC interconnector flow is also included as an explicit covariate to account for the impact of the Tasmanian hydro-wind system.

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[2] Although WPG may be curtailed by a grid operator in some circumstances, Figure **??** shows that curtailment was not significant in the NEM in 2014.

Each generator responds differently to changes in the covariates. For example, a load-following coal plant is likely to be found in a high emissions state when system demand is high, system outages are high, WPG is low and Basslink flow is negative (i.e. flow is from VIC to TAS). On the other hand, base-load generators are less sensitive to effective system demand and WPG. In addition to generator characteristics, the response also depends on grid constraints and interconnection. For example, a QLD CCGT plant is likely to be less responsive to changes in WPG compared to a CCGT plant in SA.

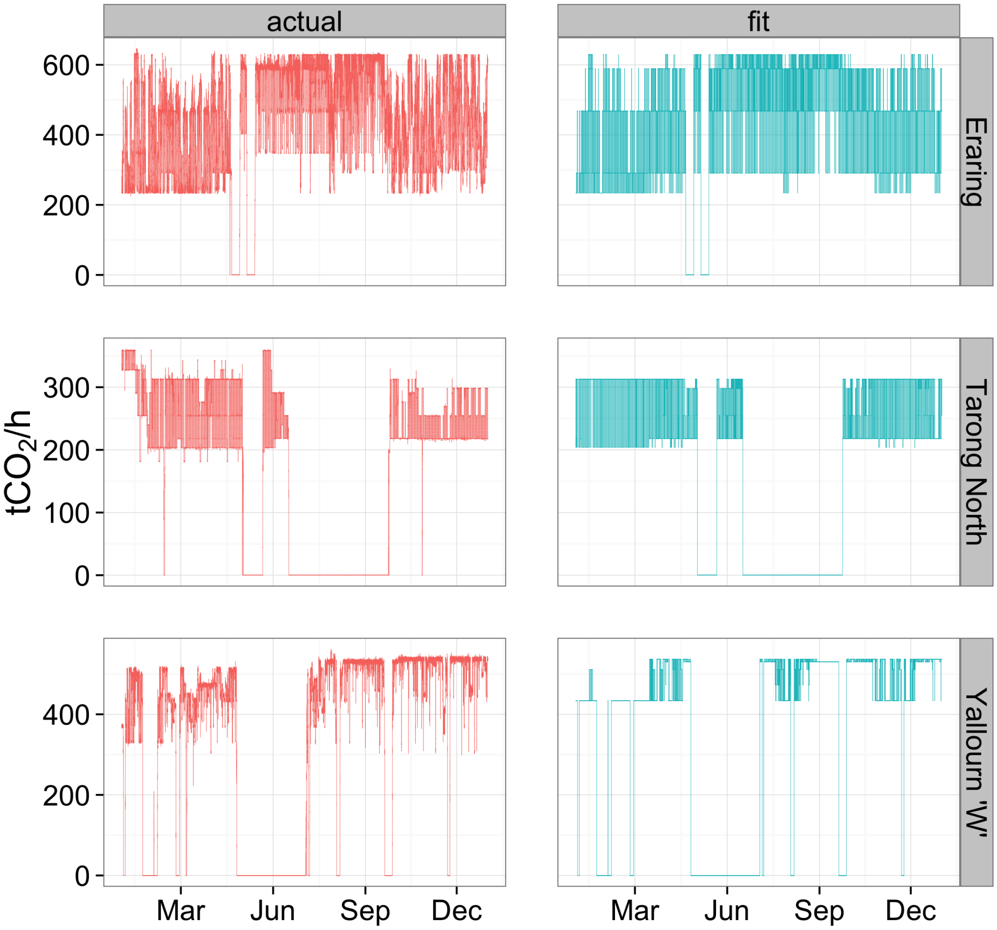

Figure 3.2: Examples of regression model fits to emissions time-series. Top: Eraring 1. Middle: Tarong North. Bottom: Yallourn 'W' power stations. Left: emissions. Right: most probable state logistic regression fit.

Regression fits*[10]* were created for all grid-connected thermal generators using the four linear covariates above. Outage periods were determined for each generator (described in Section 2.3) and these periods are excluded from the regression fit. Thermal plant do not respond smoothly to changes in effective demand. A rigid response where a generator switches between a set of discrete states can be modelled using multi-level logistic regression. This model can give semi-realistic descriptions of the generator output as shown in Figure 3.2.

Regression models can be used to assess the sensitivity of emissions to changes in WPG, keeping other covariates (system demand and outages) unchanged. For example, emissions in the absence of WPG can be calculated by setting non-Tasmanian WPG to zero and decreasing Basslink flow by an amount equivalent to mean TAS WPG (108MW). The resulting emissions savings for each generator are given in Tables 4.4-4.6. Results (excluding peaking plant, see Section 3.2.3) are summarised in Table 3.1. Savings aggregated up to power station level are summarised graphically in Fig 4.2.

region	Black Coal	Brown Coal	Gas	TOTAL
NSW	2.10		0.01	2.11
QLD	0.74		0.12	0.86
SA		0.24	0.22	0.46
TAS			-0.00	-0.00
VIC		1.72	0.11	1.83
TOTAL	2.84	1.96	0.46	5.26

Table 3.1: Summary of emissions avoided ($MtCO_2$) by region and fuel from non-peaking thermal plant in 2014.

From Table 3.1, total emissions avoided at non-peaking thermal plant were $5.26MtCO_2$ in 2014. This accounts for most of the savings due wind power on the NEM. The significant saving arising at NSW coal plant reflects imports of WPG from SA and VIC. Some emissions savings also arise in QLD because exports from QLD to NSW are displaced by WPG.

3.2.3 peaking plant

Peaking plant (primarily of OCGT and hydro) typically operate when system demand exceeds a threshold value or to ensure frequency stability. The response of peaking plant to system demand is non-linear both at an individual generator level and also collectively (see Figure 4.3). Empirical estimates of emissions savings from wind power at individual thermal peaking plant can be problematic.The reason is that peaking plant often contain periods of intermittent generation. As a consequence, spurious correlations (or anti-correlations) can arise between intermittent WPG and emissions. A better approach in this case is to model thermal peaking plant emissions as a whole. Fortunately, outage effects are less significant for individual peaking plant (availability factors are generally higher) and therefore it is less important to keep track of outages at individual plant as done in Section 3.2.2.

Multi-variate regression for thermal peaking plant can be created using the same covariates as Section 3.2.2 but including non-linear terms in system demand.This approach yields aggregate savings of $0.60 MtCO_2$-e versus total thermal peaking plant emissions of $2.06 MtCO_2$-e. In percentage terms emissions avoided from peaking plant is far higher than found in Section 3.2.2 for load-following plant. In fact percentage savings are comparable to the capacity factor for WPG. This is plausible because, when periods of high system demand and high WPG coincide, the requirement for peaking generation is reduced.

Outside of Tasmania, hydro power on the NEM has characteristics of peaking and seasonal load-following plant. The displacement of this generation by WPG can be estimated using the same regression model described above. Assigning this displaced generation an emissions intensity of 0.8tCO2-e/MWh, gives additional savings of $\approx$ 0.35MtCO2. Total emissions avoided from thermal and non-TAS hydro plant is therefore $0.95 MtCO_2$-e or 14% of total emissions avoided.

Table 3.2 summarises emissions avoided broken down by plant characteristic.

type	emissions	avoided	% avoided
baseload	94.99	2.45	2.5%
loadfollowing	72.67	2.81	3.7%
peaking	2.06	0.60	24.3%
hydro*	-	0.35	-
TOTAL	169.7	6.2	3.5%

Table 3.2: Emissions savings ($MtCO_2$-e) in 2014 by generation type. Emissions saving fractions at peaking plant are far higher than for other types of plant. Hydro* indicates non-Tasmanian hydro plant.

3.3 discussion

Total emissions avoided by WPG on the NEM in 2014 were found to be $6.2 MtCO_2$-e (Table 3.2) compared to actual emissions $169.7 MtCO_2$ (Table 2.4). Emissions in a no-wind scenario were therefore $175.9 MtCO_2$-e and WPG reduced emissions by 6.2/175.9=3.5%. WPG produced 8.7TWh (Table 2.1) compared to total energy generated in the NEM 194.1TWh. Therefore while WPG provided 8.7/194.1=4.5% of energy generated, it reduced emissions by a lesser fraction 3.5%. The *effectiveness* of WPG in terms of emissions reduction is the ratio 3.5:4.5 or 78%.

An equivalent way to express this finding is to note that average emissions intensity in the absence of wind power is $175.9 MtCO_2$-e/194.1TWh = $0.91 tCO_2$-e/MWh while emissions avoided per unit wind energy is $6.2 MtCO_2$-e/8.7TWh = $0.71 tCO_2$-e/MWh. The ratio 0.71:0.91 is equivalent (within rounding error) to the effectiveness of 78% quoted above.

Several factors act to degrade effectiveness of WPG. Firstly, wind power selectively displaces lower emissions plant such as SA gas plant or even NSW black coal in preference to higher emissions brown coal plant in VIC. Secondly, wind power generation is correlated with relatively higher system losses (Section 2.4). Thirdly, the part-load efficiency cost can be quantified by re-calculating emissions savings with the parameter a in Equation 3.1 set to zero, keeping all other parameters unchanged. Total emissions are lowered to 163.5MtCO2 while savings due to wind power increase to 6.86MtCO2. This equates to effectiveness of 89% i.e. part-load efficiency costs explain half the observed loss of effectiveness. This effect of part-load efficiency may be enhanced because only a small subset of the thermal plant are involved in balancing wind power (see Figure 4.2).

Unlike dispatch models, empirical methods have limited ability to predict behaviour when large changes are made to the grid (as this requires extrapolation beyond the range of observations). However, the explanation of WPG effectiveness in terms of selective displacement and part-load efficiency cost gives insight into the impact of, say, doubling wind penetration to $\sim$10% with no other system changes. Assuming the NEM operates as it did in 2014, selective displacement is unchanged while part-load efficiency cost is doubled. Therefore a reasonable guess is effectiveness $\lesssim$ 70% at 10% wind penetration.

It is important to emphasise that the above results are best estimates only. They are subject to two independent sources of error: *a*) statistical uncertainty *b*) unknown biases in emissions parameters. The latter are discussed in Section 3.4. Figure 3.3 illustrates the main findings of this report along with estimated statistical uncertainty.[3] Note that effectiveness of 100% would correspond to savings of 8MtCO_2-e and emissions savings per unit wind energy of 8MtCO_2/8.7TWh = 0.92tCO_2/MWh. This slope lies outside the 95% confidence interval illustrated in Figure 3.3. Within the current framework, it can be said that the hypothesis that wind power effectiveness was 100% in 2014 can be rejected.

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[3] Statistical confidence intervals were determined using a bootstrap method. For practical reasons confidence intervals were estimated using a simplified linear regression model rather than the full multi-level logistic model of Section 3.2.2.

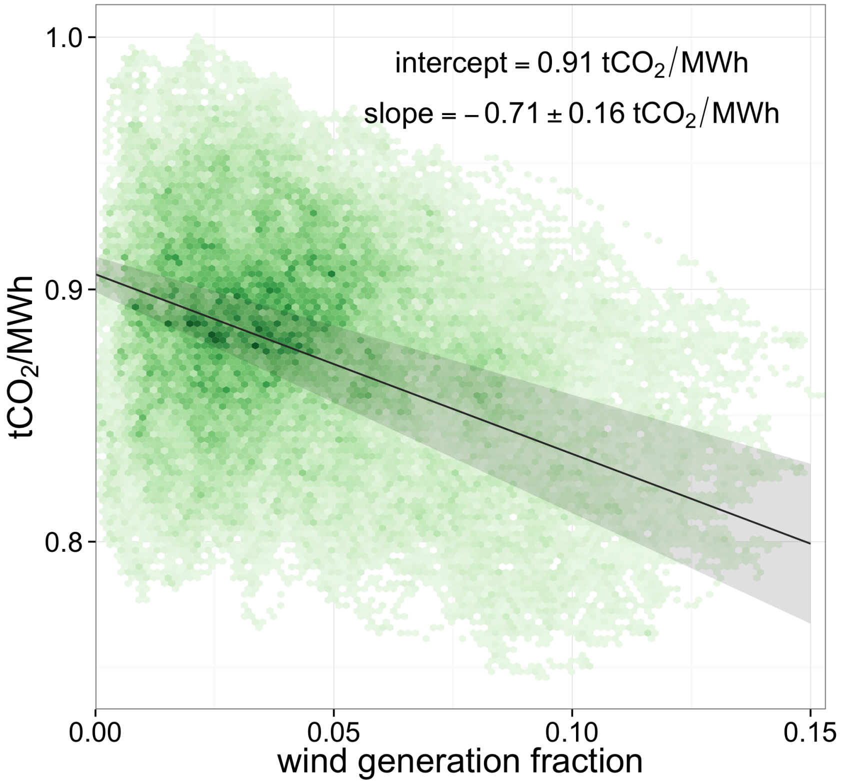

Figure 3.3: Emissions intensity (tCO2-e/MWh) versus wind penetration at 5-min intervals compared to the findings of this report. The "intercept" corresponds to mean NEM emissions intensity in the absence of wind power, and "slope" corresponds to emissions avoided per unit wind energy. The grey region indicates the width of the statistical 95% confidence intervals from bootstrap.

3.4 limitations and suggested future work

This report describes the findings of an empirical study into emissions reductions associated with wind power on the NEM in 2014. While wind power reduced operational CO_2-e emissions, it's effectiveness is evidently less than 100% (Figure 3.3).

It is a concern that the quantitative findings in this report are subject to unknown biases in the emissions parameters used to describe individual generators. For example, in the dataset available for this study*[4]* (Table 4.1-4.3), the zero-load parameter (a appearing in Equation 3.1) has a value 10% for all coal power stations. While this may be a reasonable average, it is unrealistic to assume that diverse coal plant share the same part-load efficiency characteristics. Moreover, Figure 4.2 indicates that 80% of the estimated CO_2 savings arose from just 12 power stations (or 20 generators, primarily coal). The effectiveness of wind power is likely to depend strongly on the detailed emissions characteristics of this subset of power stations. Therefore these need to be known as accurately as possible. In addition, the linear model Equation 3.1 is an oversimplification. Several more parameters are needed to describe the fuel consumption characteristics fully.

The input data could be improved in several ways. The most valuable emissions information is actual fuel used by individual generators at short time intervals. If sufficient, this data could be related to wind generation directly. If not sufficient, even low frequency (e.g. monthly) fuel use information is valuable for calibration and verification of emissions models. Emissions could also be calculated from SCADA generation data (as done here) but using more completely parameterised heat-rate curves. For example, power engineers often specify energy input-output curves of a generator in terms of a set of significant output capacity points (MW) and incremental heat rate slope between these capacity points. Another data issue concerns use of "as-generated" data as a proxy for total system demand in Section 3.2.2. There are reasons to believe that "sent-out" market data, which is net of auxiliary loads, may give more accurate results. "Sent-out" generation data were not available for this report.

In summary, the following additional data should be incorporated into a future study:

[1] actual fuel consumption data for individual generators at the shortest available time intervals. Even limited or incomplete data of this type is valuable for emissions model calibration and verification.

[2] emissions parameters for individual generators including
  (a) zero-load energy consumption data (GJ/h)
  (b) incremental heat rate slopes between capacity points for all generators (GJ/MWh).
  (c) hot, warm and cold start-up energy costs (GJ) and associated thermal relaxation times.
  (d) confidence intervals on the parameters where appropriate

[3] "sent-out" market data (e.g. $\frac{1}{2}$-hourly) for each generator, to complement "as-generated" SCADA data used in this report.

[4] multi-year data (e.g. 2011-2014) could reduce statistical uncertainty and give information about variability of wind power effectiveness.

4. Additional material

4.1 GLOSSARY

AEMO: Australian Energy Market Operator

"As generated": supply measured at the generator terminals, representing the entire output from a generator. Suitable data for calculation of emissions.

Auxiliary load: electric power used on-site or self-load of a power plant

Availability Factor: amount of time that a generator is available to produce electricity over a certain time interval, divided by the time interval.

Base-load: power plants which supply a dependable and consistent amount of electricity, meeting the minimum demand.

Bootstrapping: a method of error or confidence interval estimation obtained by repeated sub-sampling of the data.

Capacity Factor: total amount of energy a generator produces during a period of time, divided by the amount of energy the generator could have produced at full (nameplate) capacity.

Capacity: the maximum output or name-plate output of a generator (MW).

CCGT: combined cycle technology uses both gas and steam turbine cycles in a single plant to produce electricity with high conversion efficiencies and low emissions.

CDEII: Carbon Dioxide Equivalent Intensity Index (CDEII). AEMO's formal framework for reporting of greenhouse gas emissions.

CO_2-e versus CO_2 emissions: carbon dioxide equivalent is the conversion of a quantity of a greenhouse gas into an equivalent quantity of CO_2 that has the same atmospheric greenhouse impact. For example, 1kg of emitted nitrous oxide has a higher global warming potential than 1kg of carbon dioxide. Here, only combustion-derived carbon dioxide is considered and therefore CO_2-e and CO_2 are equivalent for the purposes of this report.

Dispatchable/non-dispatchable: sources of electricity that can/cannot be dispatched at the request of power grid operator AEMO

DUID: dispatchable unit identifier

Effectiveness: the ratio of (% emissions reduction) to (% of wind energy).

In terms of total energy generated G, total wind energy generated WPG, emissions savings ΔCO_2 and actual total grid emissions CO_2^{actual}, this can re-expressed as:

$$\begin{aligned}\text{Effectiveness} &= \left(\frac{\Delta CO_2}{CO_2^{actual} + \Delta CO_2}\right) \div \left(\frac{WPG}{G}\right)\\ &= \left(\frac{\Delta CO_2}{WPG}\right) \div \left(\frac{CO_2^{actual} + \Delta CO_2}{G}\right)\\ &= \frac{\text{emissions savings per unit wind energy}}{\text{no-wind emissions intensity}}\end{aligned}$$

Thermal efficiency: a generator's thermal efficiency is the fraction of fuel energy input that is actually converted into electricity.

Emissions factor, combustion: CO_2 or CO_2-e emissions from combustion of a specific thermal energy unit of fuel (e.g. tCO_2/TJ or $kgCO_2/GJ$). Used to calculate Scope 1 emissions.

Emissions emissions, fugitive: fuel emissions factor (tCO_2/TJ) used to calculate Scope 3 emissions associated with extraction and transport of the fuel.

Emissions Intensity: CO_2 emissions rate (tCO_2/h) divided by power output (MW) of a generator, often averaged over a period of time. May refer to an individual or group of generators or to the NEM as a whole.

Exogenous variable: exogenous variables are not systematically affected by changes in the other variables of the system e.g. wind is an exogenous variable because wind affects coal generation but not the other way around.

Fuel mix: fractions of total generation derived from the different fuel sources as a function of time. Fuel mix fractions sum to 1.

Heat rate: the fuel energy input needed for a power plant to produce one unit of electrical energy output e.g GJ/GWh. Generally a function of power output.

Intermittent Generation: a generating unit whose output is not readily predictable, including wind turbine generators, some run-of-river hydro-generators etc

Joule(J): unit of energy. 1TJ = 10^{12}J=277.77 MWh

Load-following: or mid-merit power plant, is a power plant that adjusts its power output as demand for electricity fluctuates throughout the day

Logistic regression: probabilistic statistical classification model where the state of the system depends on external covariates or driving variables.

Non-market generation: A generator whose sent-out generation is purchased in its entirety locally or at the same network connection point under a power purchase agreement.

Non-scheduled generation: AEMO classification of generators with capacity less than 30MW which do not participate in central dispatch

OCGT: Open cycle gas turbine. A gas or liquid fuel combustion turbine often used as peaking plant. Less efficient than CCGT but with rapid low-cost startup.

Peaking: power plants that generally run only when there is a high demand for electricity. May be operated periodically or intermittently.

Regression model: a statistical process for estimating the relationships among variables

SCADA: "supervisory control and data acquisition system". Used by grid operators such as AEMO to control remote plant. This system is the source of the 5-min 'as-generated' generation data used in this report.

Scheduled/semi-scheduled generation: AEMO classify generation with intermittent output and with an aggregate nameplate capacity of 30 MW or more as semi-scheduled.

Scope 3 emissions: emissions associated with extraction and transport of fuel to power plant.

Scope 1 emissions: emissions associated with direct combustion of fossil fuel, excluding indirect sources of emissions.

"Sent-out": supply as measured at the generator's grid connection point, therefore excluding auxiliary loads.

Steam sub/super-critical: refers to low and high pressure steam turbines, the latter operating at higher efficiency.

Watt(W): unit of power 1W = 1J/s.

Wind Penetration: fraction of all generation provided by wind power over a certain time interval.

WPG: refers to either wind power generation (MW), or wind energy generation (MWh) depending on the context.

4.2 parameters

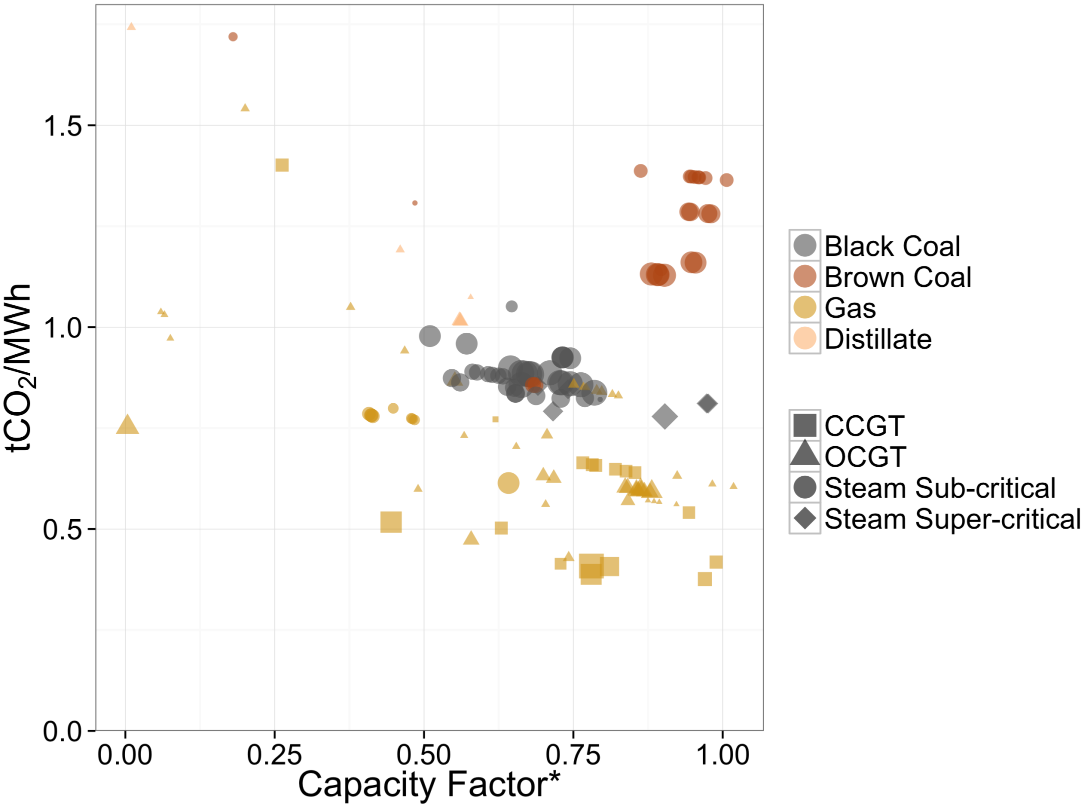

Figure 4.1: Estimated emissions intensity versus modified capacity factor for individual generators. Symbol areas represent generator capacity, symbol colours represent fuel type, and symbol shapes represent technology. Brown coal plant have high capacity factor and highest emissions intensity. CCGT have the lowest emissions. The new super-critical steam coal plant operate at high capacity and with relatively lower emissions intensity. There is a trend for increasing emissions intensity with decreasing capacity factor. The modified capacity factor is capacity factor excluding outage periods or Capacity Factor divided by Availability Factor.

DUID	name	fuel	region	technology	a	ε	C	f_1^*	f^*
AGLHAL	Hallett	Gas	SA	CCGT	0.3	0.242	180	57.24	67.44
AGLSOM	Somerton	Gas	VIC	OCGT	0.3	0.242	160	49.06	52.96
ANGAS1	ANGASTON	Distillate	SA	ICE	0.3	0.283	30	69.70	75.00
ANGAS2	ANGASTON	Distillate	SA	ICE	0.3	0.283	20	69.70	75.00
APS	Anglesea	Brown Coal	VIC	Steam Sub-critical	0.1	0.296	165	92.43	92.83
BARCALDN	Barcaldine	Gas	QLD	CCGT	0.3	0.283	37	78.56	86.16
BBTHREE1	Bell Bay Three	Gas	TAS	OCGT	0.3	0.299	35	51.30	51.30
BBTHREE2	Bell Bay Three	Gas	TAS	OCGT	0.3	0.299	35	51.30	51.30
BBTHREE3	Bell Bay Three	Gas	TAS	OCGT	0.3	0.299	35	51.30	51.30
BDL01	Bairnsdale	Gas	VIC	OCGT	0.3	0.343	47	50.02	53.92
BDL02	Bairnsdale	Gas	VIC	OCGT	0.3	0.343	47	50.02	53.92
BRAEMAR1	Braemar	Gas	QLD	CCGT	0.3	0.303	168	48.02	55.62
BRAEMAR2	Braemar 2	Gas	QLD	CCGT	0.3	0.303	168	49.82	57.42
BRAEMAR3	Braemar	Gas	QLD	CCGT	0.3	0.303	168	48.02	55.62
BRAEMAR5	Braemar	Gas	QLD	CCGT	0.3	0.303	173	48.02	55.62
BRAEMAR6	Braemar	Gas	QLD	CCGT	0.3	0.303	173	48.02	55.62
BRAEMAR7	Braemar	Gas	QLD	CCGT	0.3	0.303	173	48.02	55.62
BW01	Bayswater	Black Coal	NSW	Steam Sub-critical	0.1	0.382	660	91.82	101.02
BW02	Bayswater	Black Coal	NSW	Steam Sub-critical	0.1	0.382	660	91.82	101.02
BW03	Bayswater	Black Coal	NSW	Steam Sub-critical	0.1	0.382	660	91.82	101.02
BW04	Bayswater	Black Coal	NSW	Steam Sub-critical	0.1	0.382	660	91.82	101.02
CALL_A_4	Callide A	Black Coal	QLD	Steam Sub-critical	0.1	0.397	30	94.19	96.49
CALL_B_1	Callide B	Black Coal	QLD	Steam Sub-critical	0.1	0.397	350	94.19	96.49
CALL_B_2	Callide B	Black Coal	QLD	Steam Sub-critical	0.1	0.397	350	94.19	96.49
CG1	Colongra GT	Gas	NSW	OCGT	0.3	0.323	181	58.94	72.44
CG2	Colongra GT	Gas	NSW	OCGT	0.3	0.323	181	58.94	72.44
CG3	Colongra GT	Gas	NSW	OCGT	0.3	0.323	181	58.94	72.44
CG4	Colongra GT	Gas	NSW	OCGT	0.3	0.323	181	58.94	72.44
CPP_3	Callide Power Plant	Black Coal	QLD	Steam Super-critical	0.1	0.388	420	96.57	98.87
CPP_4	Callide Power Plant	Black Coal	QLD	Steam Super-critical	0.1	0.388	420	96.57	98.87
CPSA	Condamine	Gas	QLD	CCGT	0.3	0.495	144	62.45	70.05
DDPS1	Darling Downs	Gas	QLD	CCGT	0.3	0.489	644	57.12	64.72
DRYCGT1	Dry Creek	Gas	SA	OCGT	0.3	0.263	52	58.36	68.56
DRYCGT2	Dry Creek	Gas	SA	OCGT	0.3	0.263	52	58.36	68.56
DRYCGT3	Dry Creek	Gas	SA	OCGT	0.3	0.263	52	58.36	68.56
ER01	Eraring	Black Coal	NSW	Steam Sub-critical	0.1	0.377	720	90.21	99.41
ER02	Eraring	Black Coal	NSW	Steam Sub-critical	0.1	0.377	720	90.21	99.41
ER03	Eraring	Black Coal	NSW	Steam Sub-critical	0.1	0.377	720	90.21	99.41
ER04	Eraring	Black Coal	NSW	Steam Sub-critical	0.1	0.377	720	90.21	99.41
ERGT01	Eraring	Distillate	NSW	ICE	0.1	0.377	42	69.70	75.00
GB01	Broken Hill	Distillate	NSW	OCGT	0.3	0.283	25	69.70	75.00

Table 4.1: Parameters used to estimate CO_2-e emission time-series for thermal generators (Equation 3.1). a is zero-load emissions expressed as a fraction of maximum load emissions. ε is "as-generated" efficiency, C is generator capacity (MW). f_1^* is combustion emissions factor (units tCO_2/TJ). f^* is sum of combustion and fugitive emissions factor. In Equation 3.1 f corresponds to $f = f^*/277.78$ (1 TJ = 277.78 MWh)

DUID	name	fuel	region	technology	a	ε	C	f_1^*	f^*
GERMCRK	German Creek	Gas	QLD	ICE	0.3	0.323	45	55.60	55.60
GSTONE1	Gladstone	Black Coal	QLD	Steam Sub-critical	0.1	0.383	280	90.35	92.65
GSTONE2	Gladstone	Black Coal	QLD	Steam Sub-critical	0.1	0.383	280	90.35	92.65
GSTONE3	Gladstone	Black Coal	QLD	Steam Sub-critical	0.1	0.383	280	90.35	92.65
GSTONE4	Gladstone	Black Coal	QLD	Steam Sub-critical	0.1	0.383	280	90.35	92.65
GSTONE5	Gladstone	Black Coal	QLD	Steam Sub-critical	0.1	0.383	280	90.35	92.65
GSTONE6	Gladstone	Black Coal	QLD	Steam Sub-critical	0.1	0.383	280	90.35	92.65
HVGTS	Hunter Valley	Distillate	NSW	OCGT	0.3	0.283	50	69.70	75.00
HWPS1	Hazelwood	Brown Coal	VIC	Steam Sub-critical	0.1	0.244	200	94.81	95.21
HWPS2	Hazelwood	Brown Coal	VIC	Steam Sub-critical	0.1	0.244	200	94.81	95.21
HWPS3	Hazelwood	Brown Coal	VIC	Steam Sub-critical	0.1	0.244	200	94.81	95.21
HWPS4	Hazelwood	Brown Coal	VIC	Steam Sub-critical	0.1	0.244	200	94.81	95.21
HWPS5	Hazelwood	Brown Coal	VIC	Steam Sub-critical	0.1	0.244	200	94.81	95.21
HWPS6	Hazelwood	Brown Coal	VIC	Steam Sub-critical	0.1	0.244	200	94.81	95.21
HWPS7	Hazelwood	Brown Coal	VIC	Steam Sub-critical	0.1	0.244	200	94.81	95.21
HWPS8	Hazelwood	Brown Coal	VIC	Steam Sub-critical	0.1	0.244	200	94.81	95.21
INVICTA	Invicta cogen	Biomass	QLD	Steam Sub-critical	0.3	0.368	50	1.50	1.50
JLA01	Jeeralang A	Gas	VIC	OCGT	0.3	0.236	51	53.77	57.67
JLA02	Jeeralang A	Gas	VIC	OCGT	0.3	0.236	51	53.77	57.67
JLA03	Jeeralang A	Gas	VIC	OCGT	0.3	0.236	51	53.77	57.67
JLA04	Jeeralang A	Gas	VIC	OCGT	0.3	0.236	51	53.77	57.67
JLB01	Jeeralang B	Gas	VIC	OCGT	0.3	0.236	76	53.77	57.67
JLB02	Jeeralang B	Gas	VIC	OCGT	0.3	0.236	76	53.77	57.67
JLB03	Jeeralang B	Gas	VIC	OCGT	0.3	0.236	76	53.77	57.67
KPP_1	Kogan Creek	Black Coal	QLD	Steam Super-critical	0.1	0.412	744	87.03	89.33
LADBROK1	Ladbroke Grove	Gas	SA	OCGT	0.3	0.303	40	46.40	56.60
LADBROK2	Ladbroke Grove	Gas	SA	OCGT	0.3	0.303	40	46.40	56.60
LAVNORTH	Laverton North	Gas	VIC	OCGT	0.3	0.313	320	64.89	68.79
LD01	Liddell	Black Coal	NSW	Steam Sub-critical	0.1	0.356	500	90.91	100.11
LD02	Liddell	Black Coal	NSW	Steam Sub-critical	0.1	0.356	500	90.91	100.11
LD03	Liddell	Black Coal	NSW	Steam Sub-critical	0.1	0.356	500	90.91	100.11
LD04	Liddell	Black Coal	NSW	Steam Sub-critical	0.1	0.356	500	90.91	100.11
LOYYB1	Loy Yang B	Brown Coal	VIC	Steam Sub-critical	0.1	0.289	500	91.24	91.64
LOYYB2	Loy Yang B	Brown Coal	VIC	Steam Sub-critical	0.1	0.289	500	91.24	91.64
LYA1	Loy Yang A	Brown Coal	VIC	Steam Sub-critical	0.1	0.299	560	96.30	96.70
LYA2	Loy Yang A	Brown Coal	VIC	Steam Sub-critical	0.1	0.299	530	96.30	96.70
LYA3	Loy Yang A	Brown Coal	VIC	Steam Sub-critical	0.1	0.299	560	96.30	96.70
LYA4	Loy Yang A	Brown Coal	VIC	Steam Sub-critical	0.1	0.299	560	96.30	96.70
MACKAYGT	Mackay	Distillate	QLD	OCGT	0.3	0.283	30	69.70	75.00
MBAHNTH	Moranbah North	Gas	QLD	ICE	0.3	0.434	63	55.60	55.60
MINTARO	Mintaro	Gas	SA	OCGT	0.3	0.283	90	67.38	77.58
MOR1	Energy Brix Complex	Brown Coal	VIC	Steam Sub-critical	0.1	0.282	90	109.51	109.91
MOR2	Energy Brix Complex	Brown Coal	VIC	Steam Sub-critical	0.1	0.282	30	109.51	109.91
MOR3	Energy Brix Complex	Brown Coal	VIC	Steam Sub-critical	0.1	0.282	75	109.51	109.91
MORTLK11	Mortlake	Gas	VIC	OCGT	0.3	0.323	283	46.13	50.03
MORTLK12	Mortlake	Gas	VIC	OCGT	0.3	0.323	283	46.13	50.03
MP1	Mt Piper	Black Coal	NSW	Steam Sub-critical	0.1	0.389	700	93.29	102.49
MP2	Mt Piper	Black Coal	NSW	Steam Sub-critical	0.1	0.389	700	93.29	102.49
MPP_1	Millmerran	Black Coal	QLD	Steam Super-critical	0.1	0.393	426	90.52	92.82
MPP_2	Millmerran	Black Coal	QLD	Steam Super-critical	0.1	0.393	426	90.52	92.82
MSTUART1	Mt Stuart	Distillate	QLD	OCGT	0.3	0.303	146	80.46	85.76
MSTUART2	Mt Stuart	Distillate	QLD	OCGT	0.3	0.303	146	80.46	85.76
MSTUART3	Mt Stuart	Distillate	QLD	OCGT	0.3	0.303	131	80.46	85.76
NPS	Newport	Gas	VIC	Steam Sub-critical	0.3	0.351	500	50.85	54.75
NPS1	Northern	Black Coal	SA	Steam Sub-critical	0.1	0.388	265	108.81	109.61
NPS2	Northern	Black Coal	SA	Steam Sub-critical	0.1	0.388	265	108.81	109.61

Table 4.2: Continuation of Table 4.1

DUID	name	fuel	region	technology	a	ε	C	f_1^*	f^*
OAKEY1	Oakey	Gas	QLD	OCGT	0.3	0.329	141	82.12	89.72
OAKEY2	Oakey	Gas	QLD	OCGT	0.3	0.329	141	82.12	89.72
OSB-AG	Osborne	Gas	SA	CCGT	0.3	0.442	180	61.74	71.94
PIONEER	Pioneer Sugar	Biomass	QLD	Steam Sub-critical	0.3	0.368	68	1.50	1.50
POR01	Port Lincoln	Distillate	SA	OCGT	0.3	0.283	50	67.90	73.20
POR03	Port Lincoln	Distillate	SA	OCGT	0.3	0.283	24	67.90	73.20
PPCCGT	Pelican Point	Gas	SA	CCGT	0.3	0.490	478	54.05	64.25
QPS1	Quarantine	Gas	SA	OCGT	0.3	0.337	24	64.45	74.65
QPS2	Quarantine	Gas	SA	OCGT	0.3	0.337	24	64.45	74.65
QPS3	Quarantine	Gas	SA	OCGT	0.3	0.337	24	64.45	74.65
QPS4	Quarantine	Gas	SA	OCGT	0.3	0.337	24	64.45	74.65
QPS5	Quarantine	Gas	SA	OCGT	0.3	0.337	128	64.45	74.65
REDBANK1	Redbank	Black Coal	NSW	Steam Sub-critical	0.1	0.318	150	105.03	114.23
ROMA_7	Roma	Gas	QLD	OCGT	0.3	0.303	40	55.88	63.48
ROMA_8	Roma	Gas	QLD	OCGT	0.3	0.303	40	55.88	63.48
RPCG	Rocky Point	Biomass	QLD	Steam Sub-critical	0.3	0.368	30	1.80	1.80
SITHE01	Smithfield	Gas	NSW	CCGT	0.3	0.432	176	57.66	71.16
SNUG1	Snuggery	Distillate	SA	OCGT	0.3	0.268	63	67.90	73.20
STAN-1	Stanwell	Black Coal	QLD	Steam Sub-critical	0.1	0.400	365	95.66	97.96
STAN-2	Stanwell	Black Coal	QLD	Steam Sub-critical	0.1	0.400	365	95.66	97.96
STAN-3	Stanwell	Black Coal	QLD	Steam Sub-critical	0.1	0.400	365	95.66	97.96
STAN-4	Stanwell	Black Coal	QLD	Steam Sub-critical	0.1	0.400	365	95.66	97.96
SWAN_E	Swanbank E	Gas	QLD	CCGT	0.3	0.485	385	51.89	59.49
TALWA1	Tallawarra	Gas	NSW	CCGT	0.3	0.515	460	51.28	64.78
TARONG#1	Tarong	Black Coal	QLD	Steam Sub-critical	0.1	0.393	350	94.00	96.30
TARONG#3	Tarong	Black Coal	QLD	Steam Sub-critical	0.1	0.393	350	94.00	96.30
TARONG#4	Tarong	Black Coal	QLD	Steam Sub-critical	0.1	0.393	350	94.00	96.30
TNPS1	Tarong North	Black Coal	QLD	Steam Super-critical	0.1	0.417	443	96.49	98.79
TORRA1	Torrens Island A	Gas	SA	Steam Sub-critical	0.3	0.316	120	50.04	60.24
TORRA2	Torrens Island A	Gas	SA	Steam Sub-critical	0.3	0.316	120	50.04	60.24
TORRA3	Torrens Island A	Gas	SA	Steam Sub-critical	0.3	0.316	120	50.04	60.24
TORRA4	Torrens Island A	Gas	SA	Steam Sub-critical	0.3	0.316	120	50.04	60.24
TORRB1	Torrens Island B	Gas	SA	Steam Sub-critical	0.3	0.337	200	49.12	59.32
TORRB2	Torrens Island B	Gas	SA	Steam Sub-critical	0.3	0.337	200	49.12	59.32
TORRB3	Torrens Island B	Gas	SA	Steam Sub-critical	0.3	0.337	200	49.12	59.32
TORRB4	Torrens Island B	Gas	SA	Steam Sub-critical	0.3	0.337	200	49.12	59.32
TVCC201	Tamar Valley CCGT	Gas	TAS	CCGT	0.3	0.495	208	56.41	56.41
TVPP104	Bell Bay Three	Gas	TAS	OCGT	0.3	0.299	58	51.30	51.30
URANQ11	Uranquinty	Gas	NSW	OCGT	0.3	0.323	166	52.23	65.73
URANQ12	Uranquinty	Gas	NSW	OCGT	0.3	0.323	166	52.23	65.73
URANQ13	Uranquinty	Gas	NSW	OCGT	0.3	0.323	166	52.23	65.73
URANQ14	Uranquinty	Gas	NSW	OCGT	0.3	0.323	166	52.23	65.73
VP5	Vales Point B	Black Coal	NSW	Steam Sub-critical	0.1	0.373	660	87.25	96.45
VP6	Vales Point B	Black Coal	NSW	Steam Sub-critical	0.1	0.373	660	87.25	96.45
VPGS	Valley Power	Gas	VIC	OCGT	0.3	0.242	300	54.79	58.69
WW7	Wallerawang C	Black Coal	NSW	Steam Sub-critical	0.1	0.356	500	85.51	94.71
WW8	Wallerawang C	Black Coal	NSW	Steam Sub-critical	0.1	0.356	500	85.51	94.71
YABULU	Townsville	Gas	QLD	OCGT	0.3	0.474	160	56.09	63.69
YABULU2	Townsville	Gas	QLD	OCGT	0.3	0.474	82	56.09	63.69
YARWUN_1	Yarwun CoGen	Gas	QLD	CCGT	0.3	0.347	160	51.30	58.90
YWPS1	Yallourn	Brown Coal	VIC	Steam Sub-critical	0.1	0.261	360	96.96	97.36
YWPS2	Yallourn	Brown Coal	VIC	Steam Sub-critical	0.1	0.261	360	96.96	97.36
YWPS3	Yallourn	Brown Coal	VIC	Steam Sub-critical	0.1	0.261	380	96.96	97.36
YWPS4	Yallourn	Brown Coal	VIC	Steam Sub-critical	0.1	0.261	380	96.96	97.36

Table 4.3: Continuation of Table 4.2

4.3 emissions avoided by generator

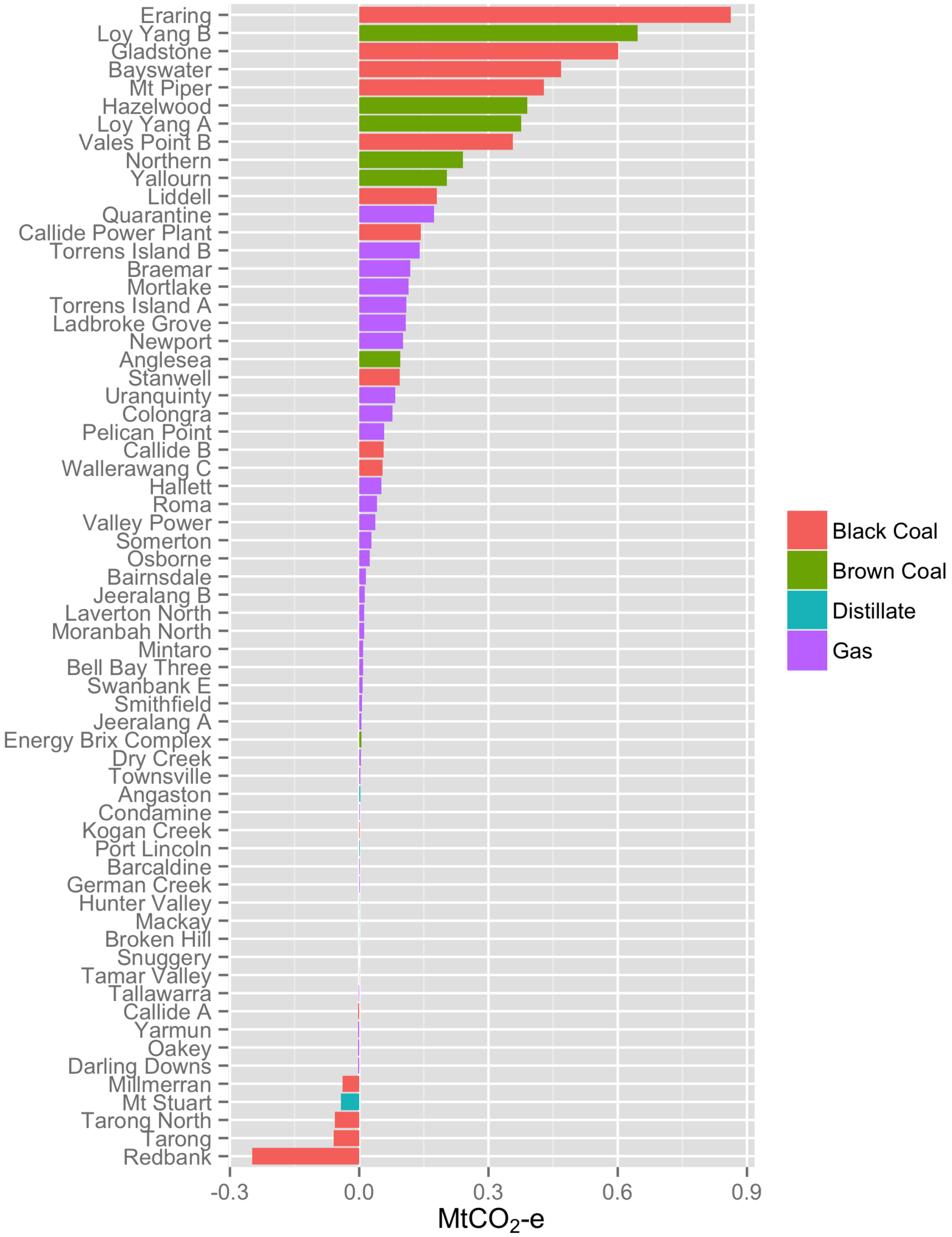

Figure 4.2: CO$_2$-e emissions avoided at thermal power stations due to wind power in 2014. Just 12 power stations accounted for 80% of emissions savings.

DUID	region	fuel	technology	type	emitted	avoided
LOYYB2	VIC	Brown Coal	Steam Sub-critical	baseload	4669697	376260
LYA3	VIC	Brown Coal	Steam Sub-critical	baseload	5036857	313846
LOYYB1	VIC	Brown Coal	Steam Sub-critical	baseload	3950502	269907
NPS1	SA	Brown Coal	Steam Sub-critical	baseload	1379426	140317
GSTONE3	QLD	Black Coal	Steam Sub-critical	baseload	1132820	126214
GSTONE6	QLD	Black Coal	Steam Sub-critical	baseload	1171115	122866
YWPS1	VIC	Brown Coal	Steam Sub-critical	baseload	2885691	110702
GSTONE4	QLD	Black Coal	Steam Sub-critical	baseload	1258764	100856
GSTONE1	QLD	Black Coal	Steam Sub-critical	baseload	1170920	100644
NPS2	SA	Brown Coal	Steam Sub-critical	baseload	1379858	100280
APS	VIC	Brown Coal	Steam Sub-critical	baseload	1466318	95458
HWPS1	VIC	Brown Coal	Steam Sub-critical	baseload	2229183	93106
HWPS2	VIC	Brown Coal	Steam Sub-critical	baseload	1874568	86656
HWPS8	VIC	Brown Coal	Steam Sub-critical	baseload	2096979	80500
STAN-3	QLD	Black Coal	Steam Sub-critical	baseload	2131113	57622
YWPS2	VIC	Brown Coal	Steam Sub-critical	baseload	3280173	49693
HWPS6	VIC	Brown Coal	Steam Sub-critical	baseload	2054781	49312
CALL_B_1	QLD	Black Coal	Steam Sub-critical	baseload	633150	42745
TORRB2	SA	Gas	Steam Sub-critical	baseload	348838	42343
STAN-2	QLD	Black Coal	Steam Sub-critical	baseload	1938491	41881
LD02	NSW	Black Coal	Steam Sub-critical	baseload	1691820	41252
YWPS4	VIC	Brown Coal	Steam Sub-critical	baseload	4172421	28135
TORRB4	SA	Gas	Steam Sub-critical	baseload	344561	28089
OSB-AG	SA	Gas	CCGT	baseload	887950	24326
LYA2	VIC	Brown Coal	Steam Sub-critical	baseload	4882644	18803
GSTONE2	QLD	Black Coal	Steam Sub-critical	baseload	869867	15981
YWPS3	VIC	Brown Coal	Steam Sub-critical	baseload	4084712	14948
HWPS5	VIC	Brown Coal	Steam Sub-critical	baseload	2153333	14010
HWPS3	VIC	Brown Coal	Steam Sub-critical	baseload	1789847	13836
CALL_B_2	QLD	Black Coal	Steam Sub-critical	baseload	1935285	13507
BRAEMAR7	QLD	Gas	CCGT	baseload	431726	10406
STAN-1	QLD	Black Coal	Steam Sub-critical	baseload	2026230	2324
CPSA	QLD	Gas	CCGT	baseload	440774	1494
KPP_1	QLD	Black Coal	Steam Super-critical	baseload	4474790	1480
GERMCRK	QLD	Gas	ICE	baseload	199728	1000
MOR2	VIC	Brown Coal	Steam Sub-critical	baseload	10927	710
CALL_A_4	QLD	Black Coal	Steam Sub-critical	baseload	117839	-2010
YARWUN_1	QLD	Gas	CCGT	baseload	791136	-2215
HWPS4	VIC	Brown Coal	Steam Sub-critical	baseload	1916581	-2557
LD01	NSW	Black Coal	Steam Sub-critical	baseload	1880043	-3435
STAN-4	QLD	Black Coal	Steam Sub-critical	baseload	1742848	-8385
TARONG#1	QLD	Black Coal	Steam Sub-critical	baseload	1852329	-8853
LYA1	VIC	Brown Coal	Steam Sub-critical	baseload	4667481	-8915
MPP_2	QLD	Black Coal	Steam Super-critical	baseload	2984503	-13300
TARONG#4	QLD	Black Coal	Steam Sub-critical	baseload	808765	-14087
MPP_1	QLD	Black Coal	Steam Super-critical	baseload	2680455	-25024
TARONG#3	QLD	Black Coal	Steam Sub-critical	baseload	1410301	-36562
TNPS1	QLD	Black Coal	Steam Super-critical	baseload	1651637	-56182
TOTAL					94997171	1716454

Table 4.4: Emissions avoided (tCO$_2$-e) at baseload generators in 2014 (positive numbers savings

DUID	region	fuel	technology	type	emitted	avoided
ER04	NSW	Black Coal	Steam Sub-critical	loadfollowing	3670238	261210
ER01	NSW	Black Coal	Steam Sub-critical	loadfollowing	4078600	258313
VP6	NSW	Black Coal	Steam Sub-critical	loadfollowing	3692931	222143
MP2	NSW	Black Coal	Steam Sub-critical	loadfollowing	4045401	220411
BW01	NSW	Black Coal	Steam Sub-critical	loadfollowing	4176337	214504
ER03	NSW	Black Coal	Steam Sub-critical	loadfollowing	3878657	213250
MP1	NSW	Black Coal	Steam Sub-critical	loadfollowing	4070542	208805
BW02	NSW	Black Coal	Steam Sub-critical	loadfollowing	4097546	155556
GSTONE5	QLD	Black Coal	Steam Sub-critical	loadfollowing	1194559	134087
VP5	NSW	Black Coal	Steam Sub-critical	loadfollowing	2332530	133905
ER02	NSW	Black Coal	Steam Sub-critical	loadfollowing	3199887	129275
LD04	NSW	Black Coal	Steam Sub-critical	loadfollowing	2371957	84185
CPP_4	QLD	Black Coal	Steam Super-critical	loadfollowing	2245797	82699
BW04	NSW	Black Coal	Steam Sub-critical	loadfollowing	3621512	79029
MORTLK11	VIC	Gas	OCGT	loadfollowing	468456	72330
CPP_3	QLD	Black Coal	Steam Super-critical	loadfollowing	1957821	59839
LD03	NSW	Black Coal	Steam Sub-critical	loadfollowing	2011373	57553
PPCCGT	SA	Gas	CCGT	loadfollowing	1018222	57370
WW8	NSW	Black Coal	Steam Sub-critical	loadfollowing	632844	56528
HWPS7	VIC	Brown Coal	Steam Sub-critical	loadfollowing	1259375	55147
LYA4	VIC	Brown Coal	Steam Sub-critical	loadfollowing	4363422	52138
MORTLK12	VIC	Gas	OCGT	loadfollowing	508509	41728
TORRB1	SA	Gas	Steam Sub-critical	loadfollowing	367628	41446
BRAEMAR3	QLD	Gas	CCGT	loadfollowing	595537	32620
TORRB3	SA	Gas	Steam Sub-critical	loadfollowing	262049	28436
BRAEMAR6	QLD	Gas	CCGT	loadfollowing	583079	27181
BRAEMAR5	QLD	Gas	CCGT	loadfollowing	548948	22688
BRAEMAR1	QLD	Gas	CCGT	loadfollowing	593758	21723
BW03	NSW	Black Coal	Steam Sub-critical	loadfollowing	4013726	19204
SWAN_E	QLD	Gas	CCGT	loadfollowing	1104960	7590
SITHE01	NSW	Gas	CCGT	loadfollowing	677740	6681
MOR1	VIC	Brown Coal	Steam Sub-critical	loadfollowing	173149	4253
BRAEMAR2	QLD	Gas	CCGT	loadfollowing	310414	3218
TVCC201	TAS	Gas	CCGT	loadfollowing	305357	-383
TALWA1	NSW	Gas	CCGT	loadfollowing	1214058	-1664
WW7	NSW	Black Coal	Steam Sub-critical	loadfollowing	162470	-2838
DDPS1	QLD	Gas	CCGT	loadfollowing	1915205	-2969
REDBANK1	NSW	Black Coal	Steam Sub-critical	loadfollowing	948188	-248205
TOTAL					2062575	775179

Table 4.5: Emissions avoided (tCO_2-e) at load-following generators in 2014 (positive numbers are savings).

DUID	region	fuel	technology	type	emitted	avoided
NPS	VIC	Gas	Steam Sub-critical	peaking	179590	101150
QPS5	SA	Gas	OCGT	peaking	89881	61851
LADBROK2	SA	Gas	OCGT	peaking	93477	57343
AGLHAL	SA	Gas	CCGT	peaking	55967	50857
LADBROK1	SA	Gas	OCGT	peaking	82005	50724
TORRA4	SA	Gas	Steam Sub-critical	peaking	36762	39616
VPGS	VIC	Gas	OCGT	peaking	52868	37917
QPS3	SA	Gas	OCGT	peaking	33014	30639
CG3	NSW	Gas	OCGT	peaking	22238	30080
TORRA2	SA	Gas	Steam Sub-critical	peaking	39306	29284
QPS4	SA	Gas	OCGT	peaking	27902	28359
AGLSOM	VIC	Gas	OCGT	peaking	15381	27917
QPS1	SA	Gas	OCGT	peaking	32368	27630
URANQ13	NSW	Gas	OCGT	peaking	52357	26314
QPS2	SA	Gas	OCGT	peaking	26680	25544
URANQ12	NSW	Gas	OCGT	peaking	45406	25299
TORRA3	SA	Gas	Steam Sub-critical	peaking	46968	25193
CG2	NSW	Gas	OCGT	peaking	14245	24531
ROMA_8	QLD	Gas	OCGT	peaking	76131	22734
URANQ11	NSW	Gas	OCGT	peaking	73468	18420
ROMA_7	QLD	Gas	OCGT	peaking	84693	18327
CG4	NSW	Gas	OCGT	peaking	28806	18278
TORRA1	SA	Gas	Steam Sub-critical	peaking	26694	15105
URANQ14	NSW	Gas	OCGT	peaking	61553	13668
LAVNORTH	VIC	Gas	OCGT	peaking	10302	11950
MBAHNTH	QLD	Gas	ICE	peaking	212165	11194
BDL01	VIC	Gas	OCGT	peaking	34579	10106
MINTARO	SA	Gas	OCGT	peaking	12043	9608
TVPP104	TAS	Gas	OCGT	peaking	8029	6126
BDL02	VIC	Gas	OCGT	peaking	72001	5279
JLB01	VIC	Gas	OCGT	peaking	10563	4718
JLB03	VIC	Gas	OCGT	peaking	7815	4660
JLB02	VIC	Gas	OCGT	peaking	7856	4139
CG1	NSW	Gas	OCGT	peaking	3260	3812
YABULU	QLD	Gas	OCGT	peaking	94558	3575
DRYCGT3	SA	Gas	OCGT	peaking	3551	2937
JLA02	VIC	Gas	OCGT	peaking	3023	1784
JLA04	VIC	Gas	OCGT	peaking	2973	1723
ANGAS1	SA	Distillate	ICE	peaking	920	1656
POR01	SA	Distillate	OCGT	peaking	943	1133
DRYCGT2	SA	Gas	OCGT	peaking	1453	1113
BARCALDN	QLD	Gas	CCGT	peaking	3735	1073
BBTHREE2	TAS	Gas	OCGT	peaking	1077	1056
JLA03	VIC	Gas	OCGT	peaking	2219	1034
ANGAS2	SA	Distillate	ICE	peaking	568	969
BBTHREE1	TAS	Gas	OCGT	peaking	1174	778
JLA01	VIC	Gas	OCGT	peaking	2402	733
BBTHREE3	TAS	Gas	OCGT	peaking	982	682
HVGTS	NSW	Distillate	OCGT	peaking	476	415
MACKAYGT	QLD	Distillate	OCGT	peaking	10654	320
GB01	NSW	Distillate	OCGT	peaking	168	262
OAKEY2	QLD	Gas	OCGT	peaking	46119	111
SNUG1	SA	Distillate	OCGT	peaking	254	0
POR03	SA	Distillate	OCGT	peaking	49	0
DRYCGT1	SA	Gas	OCGT	peaking	264	-183
YABULU2	QLD	Gas	OCGT	peaking	47201	-503
OAKEY1	QLD	Gas	OCGT	peaking	29058	-2415
MSTUART1	QLD	Distillate	OCGT	peaking	5424	-5531
MSTUART2	QLD	Distillate	OCGT	peaking	12667	-5707
MSTUART3	QLD	Distillate	OCGT	peaking	114152	-31508
TOTAL					2062575	775179

Table 4.6: Emissions avoided (tCO_2-e) at peaking generators in 2014 (positive numbers are savings). A more accurate estimation of aggregate emissions avoided from peaking plant is discussed in Section 3.2.3.

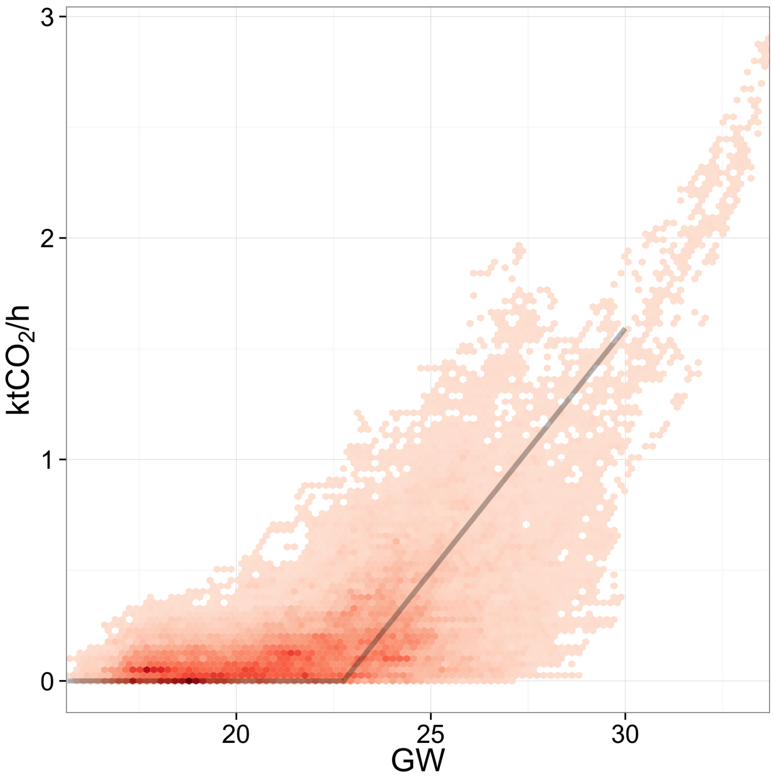

Figure 4.3: Emissions from thermal peaking plant (ktCO$_2$-e per hour) vs system demand (total NEM generation). Use of peaking plant increases when system demand exceeds $\sim$ 23GW.

4.4 data & references

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