Cost and Quantity of Greenhouse Gas Emissions Avoided by Wind Generation

By

Peter Lang

This paper contains a simple analysis of the amount of greenhouse gas emissions avoided by wind power and the cost per tonne of emissions avoided. It puts these figures in context by comparing them with some other ways of reducing greenhouse gas emissions from electricity generation.

The conclusion: wind farms connected to the National Grid provide low value energy at high cost, and avoid little greenhouse gas emissions.

The paper covers the following:

1. Background
2. Electricity generation cost per MW/h
3. Greenhouse gas emissions per MWh
4. Emissions avoided per MWh
5. Cost of emissions avoided per MWh
6. Comparison with other options to reduce emissions from electricity generation
7. Discussions
8. Conclusions
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Background

Wind power is intermittent, so either energy storage or constantly, instantly available back-up generation is required to provide constant power.

Wind power is proportional to the cube of the wind speed. So a small drop in wind speed causes a large drop in the power output. For a modern 2.1 MW wind turbine a 2 m/s drop in wind speed from 9 to 7 m/s halves the power output.

The wind speed is very variable. Figures 1 and 2 give examples of how variable it is.

Figure 1 – The variability of wind power

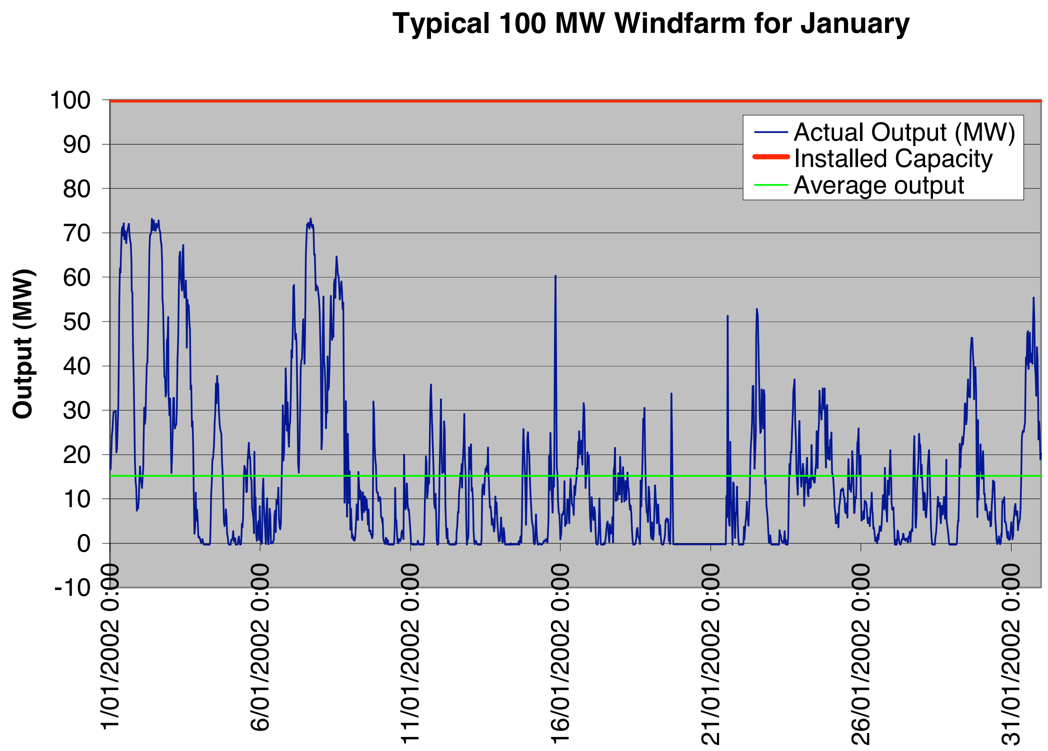
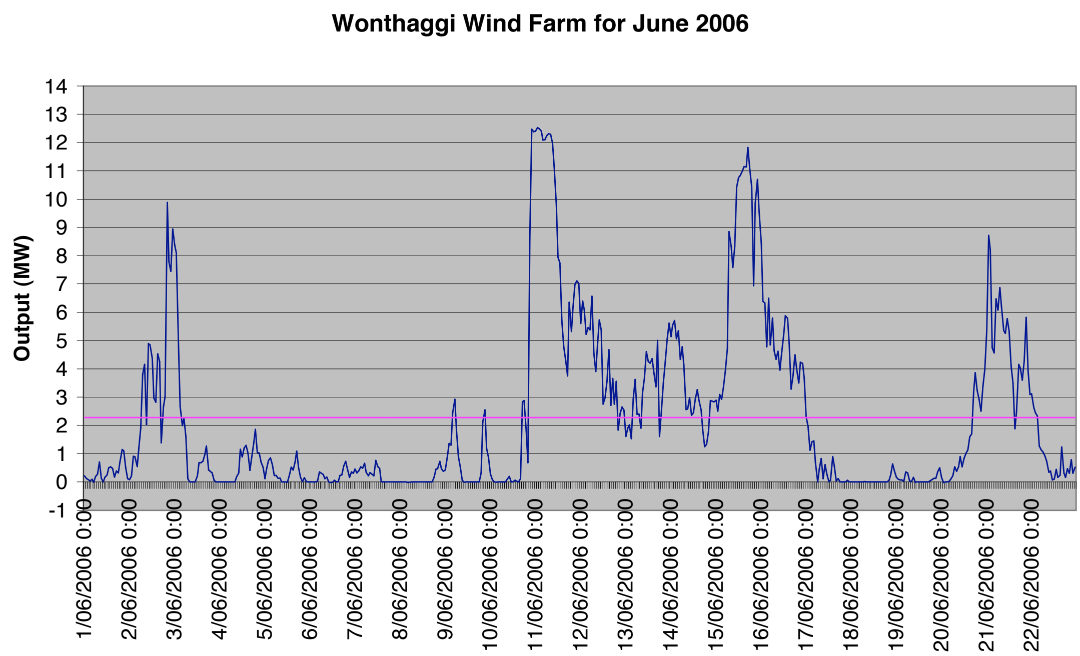


Figure 2 – the variability of wind power



Energy storage[1] is completely uneconomic for the amounts of energy required. So we must use back-up generation.

Constantly, instantly available back-up must be provided by reliable energy sources (to provide power whenever the wind speed drops). Coal, gas, hydro and nuclear power provide reliable power, but not all are suitable as back up generators for wind power.

Back-up generation is mostly provided by gas turbines in Australia. The reasons why gas provides the back-up rather than one of the other energy sources are:

1. We have insufficient hydro resources to provide peak power let alone provide back-up for wind power. Hydro energy has high value for providing peak power and for providing rapid and controllable responses to changes in electricity demand across the network. So our very limited hydro resource is used to generate this high value power.

2. Coal generates the lowest cost electricity and, therefore, coal generation is the last to be displaced when a new source of electricity becomes available (such as when the wind blows). That is, when wind energy is available it displaces the highest cost generator first. Coal is displaced last.

3. Coal generators cannot follow load changes rapidly. Brown coal power stations (as used in Victoria) are designed to run at full power all the time. They can only reduce power by venting steam, but they continue to burn the same amount of coal and hence produce the same amount of emissions whether or not they are generating electricity. Black coal power stations have some limited capability to follow the load but cannot follow the rapid changes in wind power.

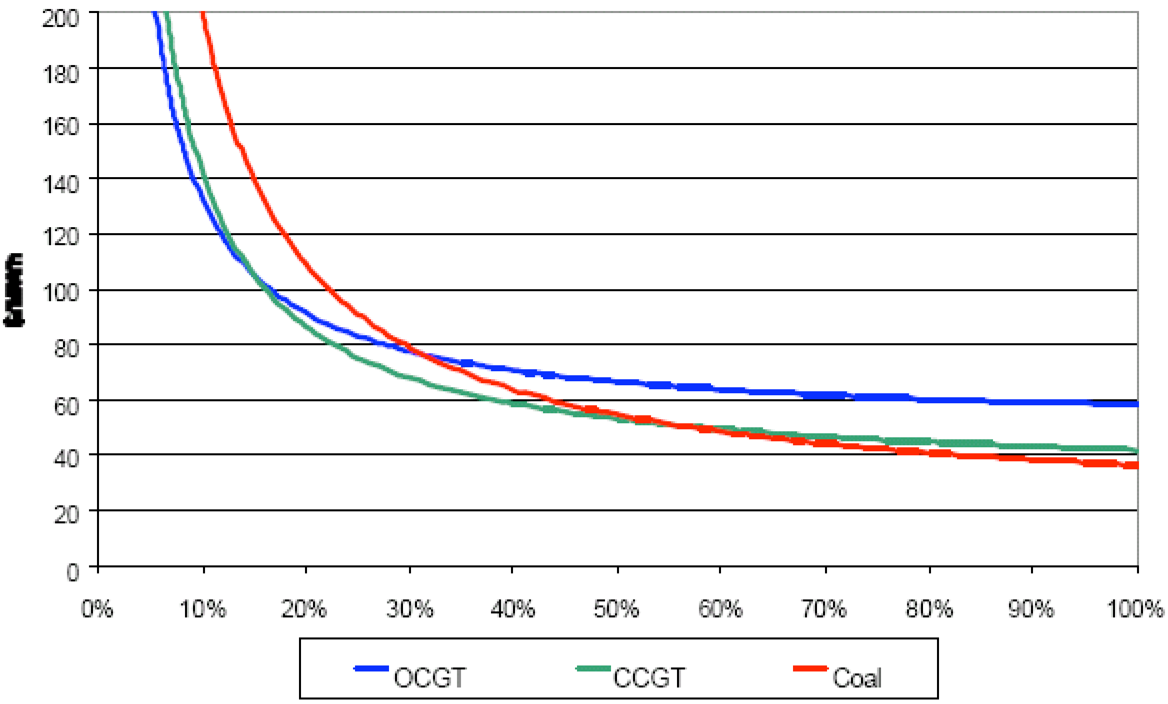
4. Gas turbines can follow load changes fairly well but not as rapidly as the wind power changes. Gas turbines power up and down like a turbo-prop aircraft engine, but with slower response. Next to hydro, gas turbines are best able to follow the load changes created by wind power.

5. There are two classes of gas turbine: Open Cycle Gas Turbine (OCGT) and Combined Cycle Gas Turbine (CCGT). OCGT has lower capital cost, higher operating costs, uses more gas and produces more greenhouse emissions than CCGT per MWh of electricity generated. OCGT follows load changes better than CCGT. OCGT produces electricity at less cost than CCGT at capacity factors less than about 15% (ie 15% of the energy it would produce if running full time at full power). CCGT has higher capital cost and needs to run at higher power and run for longer to be economic. CCGT is more efficient so it uses less gas and produces less greenhouse emissions. CCGT produces electricity at less cost than OCGT for capacity factors above about 15%. (See figure 3).

[1] http://www.greenhouse.gov.au/renewable/aest/pubs/aest-review.pdf , Fig 13, p28

Figure 3
Source: "Long Run Marginal Cost of Electricity Generation in NSW, A report to the Independent Pricing and Regulatory Tribunal, Feb 2004"

Exhibit 1-2 Medium New Entry Cost Scenario as a Function of Capacity Factor (Medium Scenario)



The study noted the cross over points in the cost versus capacity factor characteristic. These cross over points represent the capacity factors where one technology becomes more economic than the next. The optimal capacity factors and the corresponding new entry costs for each technology are shown in Exhibit 1-3 below.

Exhibit 1-3 Optimal Capacity Factors and Associated New Entry Cost (Medium Scenario)

	Thermal Coal	CCGT	OCGT
CF	100%	55%	14%
New Entry Cost	$36.2/MWh	$50.9/MWh	$109.0/MWh

6. The ideal arrangement (grossly simplified) is:

    a. Coal (and/or nuclear) generates base load power (24 hours per day);

    b. CCGT generates shoulder power (approximately 12 hours per day, but variable duration);

c. OCGT generates shoulder and peak power and follows the load changes (average less than 15% capacity factor);

d. Hydro generates peak power and provides stability to the grid.

7. If wind generation is available the power produced is highly variable and unscheduled so it needs to be backed up by OCGT. Although OCGT is called up to back up for wind, the energy produced by wind actually displaces CCGT generation mostly (see next section for explanation).

8. Because wind energy is variable, unreliable and cannot be called up on demand, especially at the time of peak demand, wind power has low value.

9. Because wind cannot be called up on demand, especially at the time of peak demand, installed wind generation capacity does not reduce the amount of installed conventional generating capacity required. So wind cannot contribute to reducing the capital investment in generating plant. Wind is simply an additional capital investment.

The Basis for Comparison

Wind generation displaces CCGT mostly. If we did not have wind power, CCGT would be the most economical and least greenhouse intensive way to generate shoulder power (non-continuous power). To explain, consider the following.

If governments did not mandate and subsidise wind power (by Mandatory Renewable Energy Targets and State based regulations and subsidies) then CCGT and OCGT would be installed in the optimum proportions to provide shoulder and peak generation (in excess of available hydro energy).

If governments mandate wind power then we will need more OCGT and less CCGT than without wind power. The substitution of OCGT for CCGT is (nearly) in proportion to the amount of wind capacity installed, not the amount of wind energy that will be generated. The reason is that the OCGT is required to back up for most of the wind power's maximum capacity, not for its average energy production. For example, if we install 100 MW of wind power, nearly 100 MW of OCGT must be installed instead of 100 MW of CCGT. (For more detailed explanation see "Security Assessment of Future UK Electricity Scenarios"[2]).

To estimate the cost of, and greenhouse emissions avoided by, wind generation we need to compare CCGT versus wind generation plus OCGT back-up.

[2] http://www.tyndall.ac.uk/research/theme2/final_reports/t2_24.pdf

Electricity Generation Cost per MW/h

The cost of electricity generation by gas turbines for various capacity factors[3] is listed below:

	Generation Cost ($/MWh)	
CF	**OCGT**	**CCGT**
100%	60	40
45%	70	54
30%	78	67
15%	105	100

The cost of wind generation at 30% capacity factor is about $90/MWh (this figure does not include the cost of back-up). The figure is derived from the proponent's case to the NSW Land and Environment Court for a Wind Farm at Taralga, from ESAA[4], and from actual costs for wind generation in South Australia and New Zealand.

Cost of Back up Generation for Wind

The figure of $90/MWh for wind does not include the cost of back up, nor the cost imposed on the generators, the grid, and distributors caused by the variable and unreliable power. Some of the costs not included in the figure for wind power are:

1. The cost of the investment in generator capacity required to meet peak demand. Nearly the full amount of fossil fuel and hydro generating capacity must be maintained to meet peak demand. The investment in wind displaces almost no capital investment in conventional generating plant.

2. The fossil fuel generators must charge a higher price for their electricity to recoup the fixed costs of their plant over a lesser amount of electricity supplied (ie as they power down when the wind blows)

3. The cost of maintaining 'spinning reserve' - keeping the generators running ready to power up as soon as the wind speed drops. The costs are: fuel, operation and maintenance, and return on capital invested.

4. The cost of fuel for powering up each time the wind changes.

5. Higher gas costs. Most of the gas price is in the pipes, not the price of the gas at the well head. The gas supply pipes need to be sized to run the gas turbines at full power. When the OCGT is operating as back-up for wind it produces less power than optimum. The fixed cost of the gas pipes is spread over less MWh generated by the gas turbine. So the cost of gas and hence the cost of electricity generated must be higher to give an economic return for the generator.

[3] "Long Run Marginal Cost of Electricity Generation in NSW; A report to the Independent Pricing and Regulatory Tribunal, Feb 2004", Exhibit 1.2.
[4] http://www.esaa.com.au/images/stories//energyandemissionsstudystage2.pdf

6. High-value, hydro-energy is wasted. With wind power connected to the grid extra hydro energy (some of it pumped to storage by coal fired plants during off-peak hours) has to be used to stabilise the grid, to provide fast response power when the OCGTs cannot power up fast enough, and to maintain a greater amount of spinning reserve. The rapid changes in wind power causes instability in the network. Some wind changes occur faster than the OCGT's can ramp up. Fast response hydro energy, from our limited reserves, is used to balance these load fluctuations.

7. The grid must be stronger to accommodate the greater variability imposed by the wind generators.

8. There are higher operational costs for the grid operators and distributors. For example, each distributor has a group dedicated to ensure the distributor buys enough renewable energy to meet its government mandated obligations. The full additional cost is millions of dollars per year and this is passed on to consumers in a higher price of electricity.

Assume that the cost of maintaining back up for wind generation is 50% of the cost of generating with the OCGT (i.e., $39/MWh based on the preceding figures and assumptions). Now we can calculate a cost of having wind power in the generation mix.

Option 1 – No Wind. CCGT generates 45% capacity factor – Cost: $54/MWh

Option 2 – Wind plus OCGT generates 45% capacity factor - Cost: $121/MWh (see table below)

	Capacity Factor	Rate $/MWh	Cost/MWh $/MWh
OCGT	15%	$105	$35
Wind	30%	$90	$60
OCGT Back-up for wind	30%	$39	$26
Total Wind and OCGT	45%		$121

The cost of CCGT is $54/MWh. The cost of wind including back-up is about $121/MWh. The difference is $67/MWh. This is the cost per MWh to avoid some CO2 emissions.

Analysis of a report by the UK Royal Academy of Engineering "The Costs of Generating Electricity"[5] gives similar figures.

	UK p/kWh	A$/MWh
CCGT	2.2	$51
OCGT	3.2	$74
Wind	3.7	$86
back up	1.7	$40
Wind with back up	5.4	$126

[5] http://www.raeng.org.uk/news/publications/list/reports/Cost_Generation_Commentary.pdf

Greenhouse Emissions per MWh

The University of Sydney's Integrated Sustainability Analysis report[6] provides the greenhouse gas emission intensity factors for wind in columns 2 and 3 below. The fourth column (for 30% capacity factor and 20 year economic life) is calculated by factoring from columns 2 and 3.

Capacity Factor	31.2%	23.1%	30%
Economic life (yr)	25	20	20
Emissions Factor (t CO2-e/MWh)	0.021	0.040	0.027

Source: http://www.pmc.gov.au/umpner/docs/commissioned/ISA_report.pdf

The greenhouse gas emission factors for gas turbines from the same report are:

Generator technology	**OCGT**	**CCGT**
Greenhouse gas emissions factor (t CO2-e/MWh)	0.751	0.577

Emissions Avoided per MWh

If CCGT generated the power, the emissions would be 0.577 t CO2-e/MWh.

If Wind and OCGT generate the same amount of power, the emissions would be 0.519 t CO2-e/MWh (see table below).

	CF	**Factor t CO2e/MWh**	**Emissions t CO2e/MWh**
OCGT	15%	0.751	0.250
Wind	30%	0.027	0.018
Back-up for wind (assumed 50% of OGCT)	30%	0.376	0.250
Total Wind and OCGT	45%		0.519

Therefore, the emissions avoided by wind are: 0.577 – 0.519 = 0.058 t CO2-e/MWh

We can compare this figure with figures derived from two other sources.

First, the "South Australian Wind Power Study"[7] provides an upper bound figure. This study modelled the effect of introducing wind generation in South Australia on the amount of fossil fuel generation and the long run and short run marginal costs of generation across the whole National Electricity Market. The study also modelled the amount of greenhouse gas emissions saved, but points out that several factors are not included in the analyses. The study determined the amount of CO2 emissions avoided by wind, excluding emissions from providing back up, is about 0.5 t CO2-e/MWh. This can be considered as an upper bound, because the modelling does not consider:

- Emissions from maintaining 'spinning reserve' with back up generators;

[6] http://www.pmc.gov.au/umpner/docs/commissioned/ISA_report.pdf

[7] "South Australia Wind Power Study" by Electricity Supply Industry Planning Council, March 2003.

- Emissions from powering up and running down the generators;
- Emissions from coal power stations when they are required to reduce power by venting steam (while they continue to burn coal and emit CO2 at their full rate);
- Emissions from generating the energy to provide reactive and feed-in power for the wind generators;
- Emissions from building, operating and maintaining the strengthened grid needed to support the distributed wind power generators;
- Emissions from the additional work required by the distributors;
- Emissions from coal power stations pumping water to pumped storage that then has to be used for rapid response back-up, for extra 'spinning reserve' and for stabilising the grid because of the variable power from wind turbines;
- The hydro energy resource on mainland Australia is limited and insufficient to provide for even our peak load energy needs. Any hydro energy used as back up for wind power must be replaced with OCGT generation. In effect, any hydro energy used for back up for wind has the same emissions as OCGT running as back up for wind.

The second source for comparison is the Royal Academy of Engineering report "The Cost of Generating Electricity"[8]. We can calculate the amount of emissions avoided by wind with back up from the information provided in the report.[9]

	Generation cost (UK p/kWh)			Emissions
	Carbon tax £0 / t CO2-e	Carbon tax £30 / t CO2-e	Difference	kg CO2e / kWh
CCGT	2.2	3.4	1.2	0.400[10]
OCGT	3.2	4.8	1.6	0.533
Wind	3.7	3.7	0	0.027
back up	1.7	1.7	0	0.283[11]
Wind with back up	5.4	5.4	0	0.310
Emissions avoided				**0.090**

So, we have three values for the amount of greenhouse gas emissions avoided by wind generation per MWh.

Basis of estimate	**t CO2 avoided /MWh**
Wind with OCGT back up displacing CCGT	0.058
Wind, excluding back up (SA Wind Power Study)[12]	0.5
Wind including back up (Royal Academy of Engineering, UK)	0.09

[8] http://www.raeng.org.uk/news/publications/list/reports/Cost_Generation_Commentary.pdf

[9] Using cost data from the Royal Academy of Engineering report (with and without a carbon tax), we can infer the emissions per kWh factor they used by taking the difference in cost per tonne CO2 and dividing it by the carbon tax cost per tonne CO2 (first two rows). Emissions for wind, back-up and wind with back-up are taken from the previous page. Emissions avoided (last row) are calculated by CCGT emissions minus emissions from wind with back-up.

[10] calculated as: Difference converted from p to £, divided by carbon tax, converted from t to kg

[11] calculated as: emissions from OCGT x cost of back-up / cost of OCGT

[12] "South Australia Wind Power Study" by Electricity Supply Industry Planning Council, March 2003.

Cost of emissions avoided per MWh

The cost of emissions avoided by wind power can be calculated from the figures in the preceding sections. The cost of emission avoided by wind is the cost of substituting wind power plus OCGT back-up for CCGT. We have three figures for the amount of emissions avoided. The higher emissions avoided (lower avoidance cost) is calculated from the results of a modelling analysis which does not include the emissions from back up. The two low figures for emissions avoided (higher avoidance cost) do include an allowance for the emissions from back up. The first is a simple analysis. The other is from a sophisticated study by the UK Royal Academy of Engineering.

Cost per MWh to substitute Wind with back-up for CCGT ($/MWh)	$67	$67	$74
Emissions avoided (t CO2-e/MWh)	0.058	0.5	0.09
Cost of emissions avoided ($t CO2-e avoided)	$1,149	$134	$830

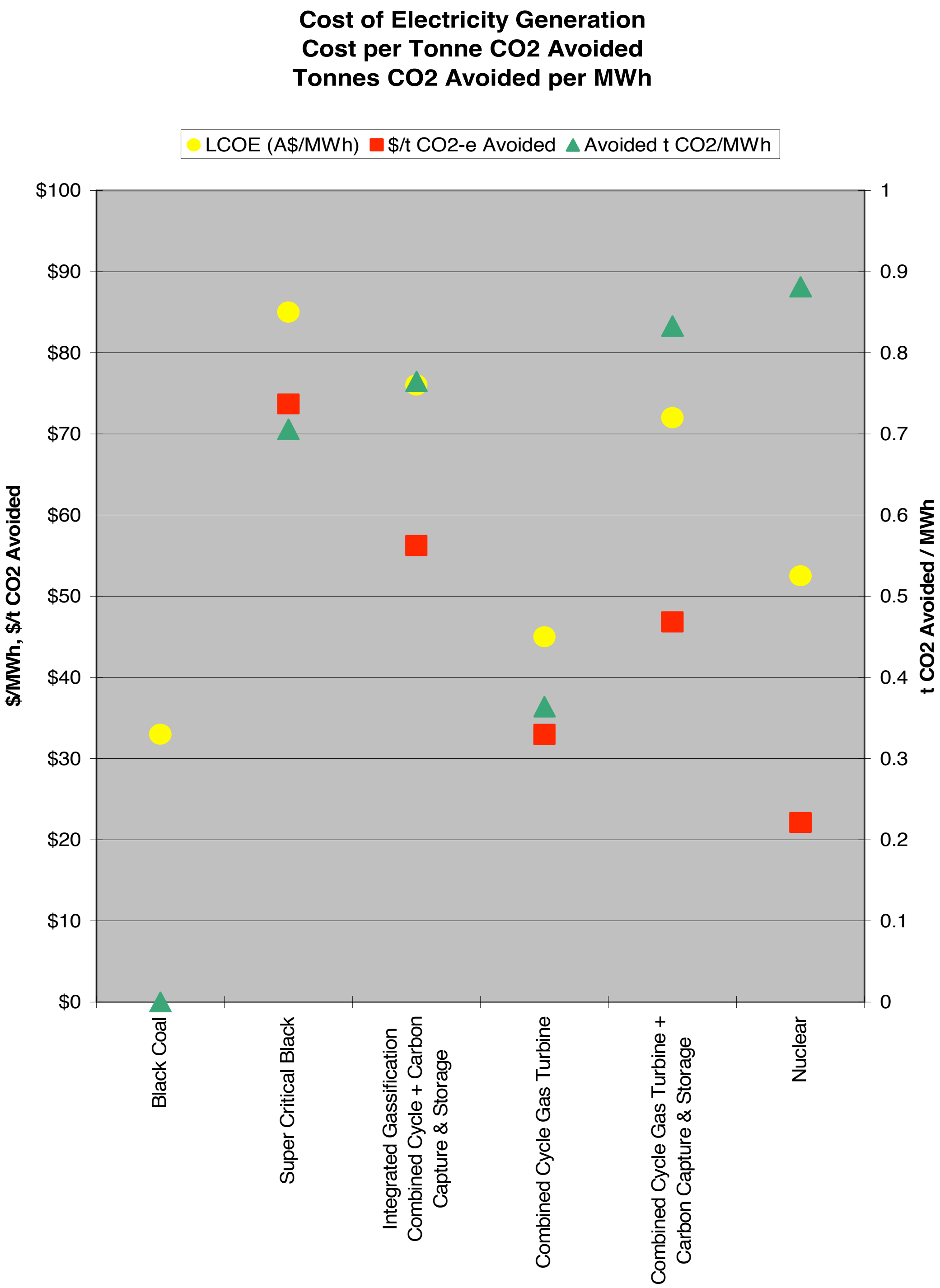
All three figures for the cost of emissions avoided by Wind power are high compared with alternatives.

Comparison with Other Options to Reduce Emissions from Electricity Generation

Figure 4 shows the cost of avoiding emission, and the amount of emissions avoided per MWh, by some new base load electricity generating technologies. Wind contributes to generating for shoulder (or non-continuous) power rather than base load so the figures are not directly comparable. But the figures do indicate that wind power is a costly way to reduce CO2 emissions (i.e., $134 to $1149 per tonne CO2-e avoided), and that the amount of emissions avoided by wind is negligible.

Nuclear power avoids the most emissions per MWh and is the least cost for doing so at about $22 per tonne of CO2 avoided (Figure 4).

Figure 4 - Projected cost of electricity, amount of emissions avoided and avoidance cost per MWh for future base load electricity generation technologies.
Source: calculated from the reports by EPRI[13] and University of Sydney Integrated Sustainability Analysis[14].



13 http://www.pmc.gov.au/umpner/docs/commissioned/EPRI_report.pdf
14 http://www.pmc.gov.au/umpner/docs/commissioned/ISA_report.pdf

The table below compares some technology options for reducing emissions. The technologies are ordered from highest to lowest cost of avoiding emissions (column 3).

	Emissions (t CO2-e / MWh	Emissions Avoided (t CO2-e avoided / MWh	Cost of Emissions avoided ($/t CO2-e avoided)
Wind (including back up generation) (Aus)[15]	0.519	0.058	$1149
Wind (including back up generation) (UK)	0.310	0.090	$830
'Clean Coal' (IGCC + CCS)	0.176	0.765	$56
Combined Cycle Gas Turbine + CCS	0.108	0.833	$47
Combined Cycle Gas Turbine	0.577	0.364	$33
Nuclear	0.060	0.880	$22

The table shows:

1. Wind power is the highest cost and nuclear the lowest cost for avoiding emissions (by a factor of about 50) (Column 3);
2. Wind power does not meet the Clean Energy Targets'[16] 200 kg/MWh test (Column 1);
3. Only nuclear and the fossil fuel technologies with carbon capture and storage meet the '200 kg/MWh test' (Column 1);
4. Only nuclear and the fossil fuel technologies with carbon capture and storage can make substantial reductions in emissions - i.e., can avoid more than 750 kg/CO2-e/MWh (Column 2). To put this in perspective, 750 kg/CO2-e/MWh is about 75% of the emissions from conventional coal fired generation. Coal fired generation produces about 76% of Australia's electricity and 89% of electricity's greenhouse gas emissions.

Discussion

The results are sensitive to the input parameters (capacity factors, emissions per MWh, costs per MWh, and the cost and emissions from back-up).

The capacity factor for wind generation in NSW should be less than the 30% used in this analysis (for example Crookwell 14.7% over 5 years and Blayney 22%).

[15] For wind back up generation the figures are:

Wind (excluding back up generation) (Aus)	0.027	0.500	$134

[16] The Federal Government recently announced national Clean Energy Targets to replace the state based renewable energy and emissions reductions schemes. The new national Clean Energy Target, requires that 30,000 GWh each year must come from low emissions sources by 2020. Low emission sources are those technologies that emit less than 200 kg of greenhouse gases per MWh of electricity generated.

These calculations suggest that wind generation saves little greenhouse gas emissions when the emissions from the back-up are taken into account.

Wind power, with emissions and cost of back-up generation properly attributed, avoids 0.058 to 0.09 t CO2-e/MWh compared with about 0.88 t CO2-e/MWh avoided by nuclear. The cost to avoid 1 tonne of CO2-e per MWh is $830 to $1149 with wind power compared with $22 with nuclear power. If the emissions and cost of back up generation are ignored then win power avoids about 0.5 t CO2-e/MWh at a cost of about $134/t CO2-e avoided. Even if the costs of and emissions from back up generation are ignored, wind is still over six time more costly that nuclear as a way to avoid emissions.

A single 1000 MW nuclear plant (normally we would have four to eight reactors together in a single power station) would avoid 6.9 million tonnes of CO2 equivalent per year. Five hundred 2 MW wind turbines (total 1000 MW) would avoid 0.15 to 1.3 million tonnes per year – just 2 to 20% as much as the same amount of nuclear capacity. When we take into account that we could have up to 80% of our electricity supplied by nuclear (as France has), but only a few percent can be supplied by wind, we can see that nuclear can make a major contribution to cutting greenhouse emissions, but wind a negligible contribution and at much higher cost.

Conclusions:

1. Wind power does not avoid significant amounts of greenhouse gas emissions.

2. Wind power is a very high cost way to avoid greenhouse gas emissions.

3. Wind power, even with high capacity penetration, can not make a significant contribution to reducing greenhouse gas emissions.

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About the Author

Peter Lang is a retired engineer with 40 years experience on a wide range of energy projects throughout the world, including managing energy R&D and providing policy advice for government and opposition. His experience includes: coal, oil, gas, hydro, geothermal, nuclear power plants and nuclear waste disposal (6.5 years managing a component of the Canadian Nuclear Fuel Waste Management Program).