CO2 abatement cost with electricity generation options in Australia

By
Peter Lang
2 November 2011

Introduction

What is the cost of carbon dioxide (CO2) emissions abatement with the various electricity generation technologies being considered for Australia?

The abatement cost of a technology depends on many factors such as the engineering characteristics of the electricity grid to which the new technology will be connected, the geographic location and many others. One important factor often not mentioned is the reference case against which the abatement cost is calculated. The abatement cost for a new technology is only meaningful when compared with another new technology or with an existing generator it would 'displace'; e.g. nuclear compared with a new coal power station or nuclear compared with an existing power station.

The Electric Power Research Institute (EPRI, 2010) report http://www.ret.gov.au/energy/Documents/AEGTC%202010.pdf for the Australian Department of Resources, Energy and Tourism provides data that allows CO2 abatement costs to be estimated for a range of new technologies. Unfortunately, the report is complex and opaque in parts.

The purpose of this paper is twofold:

1. to summarise in tabular form the relevant information from the EPRI report so others can access it easily and produce levelised cost of electricity (LCOE) figures under differing assumptions, particularly using the NREL LCOE calculator http://www.nrel.gov/analysis/tech_lcoe.html .

2. to calculate and compare the CO2 abatement costs for a range of new technologies for each of three 'displaced' technologies.

This paper does not attempt to calculate the effects of carbon price on the LCOE or CO2 abatement costs, because:

1) the EPRI report does not include the effects of carbon price - nor feed in tariffs, renewable energy certificates and other subsidies - so incorporating the effect of CO2 pricing, and other incentives and disincentives in the analysis would require many additional assumptions, and
2) the purpose of this paper is to show the abatement costs for the various technologies so options can be compared and so the cost of incentives and disincentives (including carbon pricing), which would be needed to make each technology viable, can be made visible.

Methodology

The CO2 abatement cost is calculated for seven new electricity generation technologies, selected from the EPRI report. The seven new technologies are:

1. Coal (black, without CCS).
2. Coal (black, with CCS)
3. Nuclear
4. CCGT (Combined Cycle Gas Turbine)
5. OCGT (Open Cycle Gas Turbine)
6. Wind (wind class 5, 100 x 2 MW)
7. Solar thermal (Central Receiver, 6h storage, DNI = 6)

The abatement cost for each is calculated by comparison with each of three 'displaced' technologies:

1. Hazelwood, brown coal power station, Victoria (1,600 MW, commissioned 1964 to 1971)
2. Liddell, black coal power station, NSW (2,000 MW, commissioned 1971 to 1973)
3. A new black coal plant, without CCS; (this is same as #1 in the list of new technologies).

Most input data are taken from EPRI (2010) http://www.ret.gov.au/energy/Documents/AEGTC%202010.pdf ; these are summarised in Appendix 1. To bring the figures up to date and to aid in international comparisons, costs presented in Table 1 have been converted from 2009 A$ to 2011 US$; these are in Appendix 2. Details of the costings, including the exchange rates and inflation rates used, are included. The calculation steps and results are presented.

CO2 Abatement Cost is the difference in LCOE divided by the difference in CO2 emission intensity (EI):

$$\text{CO2 abatement Cost} = (LCOE_{new} - LCOE_{displaced}) / (EI_{displaced} - EI_{new})$$

The data needed for calculating LCOE for each technology, using the NREL simplified LCOE calculator http://www.nrel.gov/analysis/tech_lcoe.html, are provided in the Appendices.

The capital cost is one of the inputs needed for the LCOE calculation. The capital cost figure needed is the Total Capital Required (TCR). But the TCR figure is not given in the EPRI report. As such, the method of estimating it, including the inputs and intermediate calculation results, are presented in Appendix 1.

The CO2 emissions intensity (EI) presented in the EPRI report includes only the emissions from burning the fuel in the generator. Fugitive emissions are not included. Nor do the emissions intensities include the higher emissions intensities produced when load-following; e.g. when cycling power up and down to back-up for intermittent renewable energy generators.

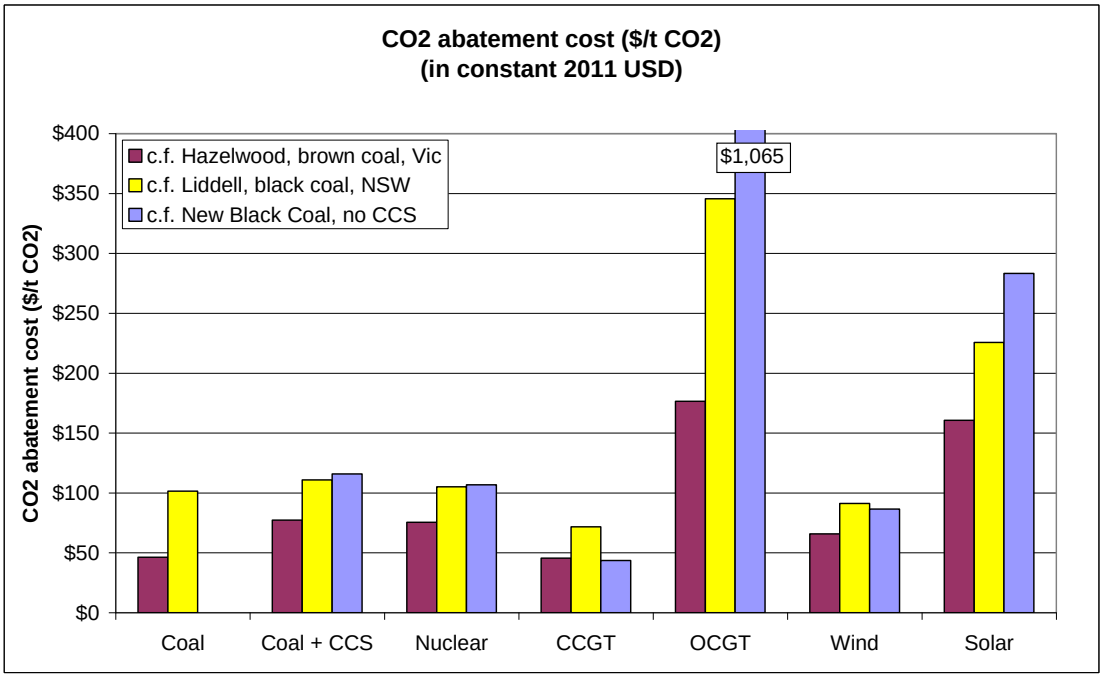
The emissions intensities (EI) for Liddell and Hazelwood power stations are 1.08 t/MWh and 1.53 t/MWh (sent out) respectively (ACIL-Tasman (2009), Table 18 http://www.aemo.com.au/planning/419-0035.pdf). These EIs include fugitive emissions (whereas the EPRI EIs do not). This causes an error in the calculated abatement costs. In the ACIL Tasman report, fugitive emissions comprise 10% to 27% of EI for gas, 2% to 9% for black coal and 0.3% for brown coal.

The LCOE for Liddell and Hazelwood are 'Commercial in Confidence', so I've used $30 and $28 respectively, which are figures I've seen stated for the 'equivalent LCOE' for the remaining plant life.

Results

The CO2 abatement costs are summarised in Figure 1.

Figure 1: CO2 abatement cost for seven selected new technologies (named on the horizontal axis) compared with each of three 'displaced' technologies (named in the legend). Abatement costs are in US$/tonne CO2 (constant, 2011 US$).



The inputs and intermediate calculation results are in Appendix 1 (in 2009 A$) and Appendix 2 (in 2011 US$). The data in Figure 1 is from Table A2-5.

Table A1-2 and A2-2 show the proportion of "Capital" (i.e. TCR) that EPRI apparently assumed for 'Owners Costs', including 'Allowance for Funds Used During Construction' (AFUDC).

The ratio TCR/TPC is given in Tables A1-3 and A2-3. This ratio shows how much higher the TCR is than TPC for each technology. For example, for nuclear the TCR is 1.93, or 93% greater than TPC.

Discussion

This report uses the EPRI (2010) figures for LCOE and emissions intensity. These are the figures being used in Australian government reports such as ABARE (2010) and for the Treasury modelling of the carbon tax and ETS. Some discussion of the figures and assumptions is warranted.

The *Total Plant Cost* figure in the EPRI report is confusing because it is not the full capital cost used to calculate LCOE. The capital cost figure needed for calculating LCOE is the *Total Capital Required*, which includes *Owner's Costs*. Back-calculating from the figures provided reveals the amount of Owner's Costs EPRI used in their LCOE analyses. This cost is significant. It is 93% higher than the Total Plant Cost for nuclear, 88% higher for CCGT, 45% higher for coal, and 41% higher for solar thermal. The EPRI report does not make clear the basis of the Owner's Costs or the assumptions. For example, the construction period is not stated?

EPRI uses 85% for the average lifetime capacity factor for mature technologies such as coal, gas and nuclear. However it also uses 85% for immature technologies such as carbon capture and storage, and assumes capacity factors for Wind (36.6%) and Solar Thermal (31.6% with 6 hours storage) that appear to be based on the best possible figures, rather than the average achievable over a plant's life. It is difficult to understand how these capacity factors could be realized in practice over the plant life.

The emissions intensities do not include fugitive emissions and appear to be for the technology running at optimum efficiency, rather than average efficiency. The abatement costs for Wind and Solar are probably understated, because the capacity factors assumed seem to be unreasonably high.

The reason the OCGT abatement costs are high is because EPRI used a capacity factor of 10% for the calculation of LCOE. This is because OCGT is economic at capacity factors up to about 14% due to its high fuel costs (IPART, 2004, Exhibits 1-2 and 1-3
http://www.ipart.nsw.gov.au/documents/Pubvers_Rev_Reg_Ret_IES010304.pdf)

If we assume wind or solar are backed up with OCGT, it is clear, without needing to do detailed calculations, that wind and solar with back-up are a high-cost way to avoid emissions.

Of the options considered, CCGT is clearly the least cost way to abate CO2 emissions. For example, if we are making a decision about new baseload capacity we might compare between a new baseload coal plant without CCS and other options. From Figure 1, the CO2 abatement cost, compared with new black coal, is $44/t CO2 for CCGT and $107/t CO2 for nuclear.

Based on the EPRI figures, nuclear cannot be justified in Australia at this time because it is too expensive. For nuclear to be an economically viable option, the impediments that are causing the EPRI estimates for the cost of nuclear in Australia to be several times higher than in Korea need to be removed.

Conclusions

Of the options considered, CCGT is clearly the least cost way to abate CO2 emissions, given the EPRI assumptions.

The abatement cost with CCGT is about 40% of the abatement cost with nuclear.

Based on EPRI's estimates, nuclear is not economically viable in Australia because it is too expensive. This situation will remain while the impediments to low-cost nuclear remain in place.

Glossary

OCGT – Open Cycle Gas Turbine

CCGT – Combined Cycle Gas Turbine

CCS – Carbon Capture and Sequestration

CST – Concentrating Solar Thermal

EPRI – Electric Power Research Institute

NREL – National Renewable Energy Laboratory

LCOE – Levelised Cost of Electricity

TCR – Total Capital Required

TPC – Total Plant Cost

AFUDC – Accumulated [or Allowance for] Funds Used During Construction (Capitalised Interest)

References

ABARE (2010), *Australian Energy Projections to 2029-30*
http://adl.brs.gov.au/data/warehouse/pe_abarebrs99014434/energy_proj.pdf

ACIL-Tasman (2009), *Fuel resource, new entry and generation costs in the NEM*
http://www.aemo.com.au/planning/419-0035.pdf

EPRI (2010), *Australian Electricity Generation Technology Costs – Reference Case 2010*
http://www.ret.gov.au/energy/Documents/AEGTC%202010.pdf

Independent Pricing and Regulatory Tribunal (2004) *The long run marginal cost of electricity generation in NSW*
http://www.ipart.nsw.gov.au/documents/Pubvers_Rev_Reg_Ret_IES010304.pdf

NREL (2011), *Levelized Cost of Energy Calculator*
http://www.nrel.gov/analysis/tech_lcoe.html

South Carolina Electric & Gas Company (2011), *VC Summers Nuclear Station Units 2 and 3 (June 30, 2011)*
http://www.scana.com/NR/rdonlyres/A830A131-9425-46F1-B948-C8424530EE49/0/2011Q2BLRAReport.pdf

Appendix 1 – Input data and intermediate calculation results with costs in 'constant 2009 A$'

Appendix 1 summarises the significant data from the EPRI (2010) report for the seven technologies selected for this study. Costs are in 'constant, mid-2009 A$'.

Table A1-1 lists the values needed for input to the NREL LCOE Calculator, http://www.nrel.gov/analysis/tech_lcoe.html .

Table A1-1: Inputs for LCOE calculation (costs in 'constant 2009 A$')

	Coal	Coal + CCS	Nuclear	CCGT	OCGT	Wind	Solar
Book life (years)	30	30	30	30	30	20	30
Discount rate (WACC)	8.4%	8.4%	8.4%	8.4%	8.4%	8.4%	8.4%
Capital Cost ($/kW)	$4,400	$8,650	$11,100	$2,200	$1,110	$4,900	$9,150
Capacity Factor (%)	85%	85%	85%	85%	10%	36.6%	31.6%
Fixed O&M Cost ($/kW-y)	$33.10	$55.30	$146.90	$13.60	$9.30	$39.00	$73.00
Variable O&M Cost ($/MWh)	$4.60	$15.70	$6.10	$2.00	$2.50	$0.00	$0.00
Heat rate (kJ/kWh)	*9,480*	*12,673*	*10,900*	*7,269*	*10,841*	*0*	*0*
Heat rate (Btu/kWh)	8,985	12,012	10,331	6,890	10,275	0	0
Fuel Cost ($/GJ)	*$1.50*	*$1.50*	*$0.94*	*$9.00*	*$9.00*	*$0.00*	*$0.00*
Fuel Cost ($/MMBtu)	$1.58	$1.58	$0.99	$9.50	$9.50	$0.00	$0.00

1 Btu = 1.05506 kJ

The Capital Cost figure listed in Table A1-1, needed for calculating LCOE, is 'Total Capital Required' (TCR). But the TCR figure is not given in the EPRI report. So it must be back-calculated from the other data available in the report. The EPRI report provides the breakdown of LCOE by Capital, O&M and Fuel (Tables A1-2 and A2-2). This data was used to calculate the value EPRI used for TCR. The results are in Tables A1-3 and A2-3. These tables also give the ratio TCR/TPC. This shows how much higher the TCR is than TPC for each technology. For example, for nuclear the TCR is 1.93, or 93% greater than TPC, whereas for coal it is 48%.

Table A1-2: LCOE, the components of LCOE and their proportions (costs in 'constant 2009 A$')

LCOE components	**Coal**	**Coal + CCS**	**Nuclear**	**CCGT**	**OCGT**	**Wind**	**Solar**
Capital	$54	$107	$137	$27	$117	$141	$304
O&M	$9	$23	$26	$4	$13	$14	$26
Fuel	$14	$19	$10	$65	$98	$0	$0
CCS T&S		$18					
LCOE	$78	$167	$173	$97	$227	$155	$330
LCOE proportions							
Capital	69%	64%	79%	28%	52%	91%	92%
O&M	12%	14%	15%	4%	6%	9%	8%
Fuel	18%	11%	6%	67%	43%	0%	0%
CCS T&S		11%					

Table A1-3: Total Plant Cost (TPC), Owners costs and AFUDC, Total Capital Required (TCR)), and the ratio TCR/TPC. Costs are in 'constant 2009 A$'.

	Coal	Coal + CCS	Nuclear	CCGT	OCGT	Wind	Solar
Total Plant Cost ($/kW)	$2,967	$5,855	$5,742	$1,173	$801	$3,763	$6,475
Owners costs & AFUDC ($/kW)	$1,433	$2,795	$5,358	$1,027	$309	$1,137	$2,675
Total Capital Required ($/kW)	$4,400	$8,650	$11,100	$2,200	$1,110	$4,900	$9,150
TCR/TPC	1.48	1.48	1.93	1.88	1.39	1.30	1.41

Appendix 2 - Input data and intermediate calculation results with costs in 'constant 2011 US$'

The cost figures in Appendix 1 are in 'constant, mid-2009 A$'. In Appendix 2 they have been converted to 'constant, mid-2011 U$'. The conversion factors are in Table A2-6.

Table A2-1 lists the values needed for input to the NREL LCOE Calculator.

Table A2-1: Inputs for LCOE calculation (costs in 'constant 2011 US$').

	Coal	Coal + CCS	Nuclear	CCGT	OCGT	Wind	Solar
Book life (years)	30	30	30	30	30	20	30
Discount rate (WACC)	8.4%	8.4%	8.4%	8.4%	8.4%	8.4%	8.4%
Capital Cost ($/kW)	$3,650	$7,175	$9,207	$1,825	$921	$4,064	$7,590
Capacity Factor (%)	85%	85.0%	85%	85%	10%	36.6%	31.6%
Fixed O&M Cost ($/kW-y)	$27.46	$45.87	$121.85	$11.28	$7.71	$32.35	$60.55
Variable O&M Cost ($/MWh)	$3.82	$13.02	$5.06	$1.66	$2.07	$0.00	$0.00
Heat rate (kJ/kWh)	9,480	12,673	10,900	7,269	10,841	0	0
Heat rate (Btu/kWh)	8,985	12,012	10,331	6,890	10,275	0	0
Fuel Cost ($/GJ)	$1.24	$1.24	$0.78	$7.47	$7.47	$0.00	$0.00
Fuel Cost ($/MMBtu)	$1.31	$1.31	$0.82	$7.88	$7.88	$0.00	$0.00

1 Btu = 1.05506 kJ

Table A2-2: LCOE, the components of LCOE and their proportions (in 'constant, 2011 US$)

LCOE components	Coal	Coal + CCS	Nuclear	CCGT	OCGT	Wind	Solar
Capital	$45	$89	$114	$22	$97	$117	$252
O&M	$7	$19	$22	$3	$11	$12	$22
Fuel	$12	$16	$8	$54	$81	$0	$0
CCS T&S		$15					
LCOE	$65	$139	$143	$80	$188	$129	$274
LCOE proportions							
Capital	69%	64%	79%	28%	52%	91%	92%
O&M	12%	14%	15%	4%	6%	9%	8%
Fuel	18%	11%	6%	67%	43%	0%	0%
CCS T&S		11%					

Table A2-3: 'Total Plant Cost', 'Owners costs' and AFUDC, "Capital Cost" (Total Capital Required), and the ratio TCR/TPC. Costs are in 'constant 2011 US$'.

	Coal	Coal + CCS	Nuclear	CCGT	OCGT	Wind	Solar
Total Plant Cost ($/kW)	$2,461	$4,857	$4,763	$973	$664	$3,121	$5,371
Owners costs & AFUDC ($/kW)	$1,189	$2,318	$4,444	$852	$256	$943	$2,219
Total Capital Required ($/kW)	$3,650	$7,175	$9,207	$1,825	$921	$4,064	$7,590
TCR/TPC	1.48	1.48	1.93	1.88	1.39	1.30	1.41

Table A2-4: LCOE and emissions intensity for the 'displaced' technologies

Technology	LCOE ($/MWh)	EI (t/MWh)
Hazelwood, Vic	$28	1.53
Liddell, NSW	$30	1.08
New Black Coal, no CCS	$65	0.738

Table A2-5: CO2 abatement cost for the technologies listed in the column headings compared with a New Black Coal power station (without CCS) and with replacing Hazelwood and Liddell power stations. The costs are in 'constant, mid-2011 US$'.

	Coal	Coal+ CCS	Nuc-lear	CCGT	OCGT	Wind	Solar
Hazelwood, Vic							
CO2 emissions (t/MWh sent out)	0.738	0.101	0	0.376	0.622	0	0
LCOE difference ($/MWh)	$37	$111	$115	$52	$160	$101	$246
Emissions difference (t/MWh)	0.792	1.429	1.530	1.154	0.908	1.530	1.530
CO2 Abatement cost ($/t)	**$46**	**$77**	**$75**	**$45**	**$177**	**$66**	**$161**
Liddell, NSW							
CO2 emissions (t/MWh sent out)	0.738	0.101	0	0.376	0.622	0	0
LCOE difference ($/MWh)	$35	$109	$113	$50	$158	$99	$244
Emissions difference (t/MWh)	0.342	0.979	1.080	0.704	0.458	1.080	1.080
CO2 Avoidance cost ($/t)	**$101**	**$111**	**$105**	**$72**	**$346**	**$91**	**$226**
New Black Coal, w/o CCS							
CO2 emissions (t/MWh sent out)	0.738	0.101	0	0.376	0.622	0	0
LCOE difference ($/MWh)	$0	$74	$79	$16	$124	$64	$209
Emissions difference (t/MWh)	0.000	0.637	0.738	0.362	0.116	0.738	0.738
CO2 Abatement cost ($/t)	**N/A**	**$116**	**$107**	**$44**	**$1,065**	**$87**	**$283**

Table A2-6: Currency conversion factors and inflation rates

1 USD = AUD (mid 2009)	1.23
Inflation, 2010	3.17%
Inflation, 2009 to 2011	-1.11%
Inflation factor 2009 to 2011	1.02025
Inflation, 2009 to 2011	2.025%