Future Ash Availability – Potential Consequences of Transformation of Australia's Energy Generation Portfolio to 2050

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SUMMARY

There is a high level of uncertainty regarding the generation technologies which will be used to provide for Australia's future electricity needs. A series of scenarios for these needs have been developed with various greenhouse gas and technology constraints imposed. Prediction of the generation portfolio under these scenarios demonstrates that no single technological solution will be optimal. Rather than a single solution it is believed that a technological mix will evolve dependant on the economic, policy and environmental restraints which emerge over the next fifty years. The outcomes of the different predicted mixes of technology are evaluated in terms of the quantity and types of ash and slag which may be available.

This evaluation has shown that ash quantities and availabilities are strongly dependant on generation technology selection. If no greenhouse gas (GHG) emissions restrictions are imposed Australia is predicted to be producing by 2050 around 2.4 times the current annual fly ash tonnage. If emission reductions are required and Integrated Gasification Combined Cycle (IGCC) and carbon capture and sequestration are adopted the potential mix of flyash and IGCC slag produced is predicted to be very different. In this scenario flyash production is largely overtaken by that of IGCC slag, although total ash and slag tonnages remain relatively steady. Conversely, if carbon sequestration proves infeasible and emissions reductions are mandated it is predicted that coal ash tonnages will decline to around 50% of current levels. In this situation further ash tonnage may be produced from biomass combustion although this material may have different properties to that produced from conventional coal fired power stations (Zevenhoven, 2001).

The information provided by the study has the potential to inform policy development leading to improved sustainability outcomes for the energy generation sector.

INTRODUCTION
There is a current high level of uncertainty as to the technologies which will be used to produce Australia's future electricity needs. Different researchers have produced varied visions of the future energy generation portfolio based on differing analysis techniques, predictions of future demand, views on the meaning of long term sustainability and effects of pollutants (Graham and Williams, 2003; Graham *et al.*, 2003; Cottrell *et al.*, 2003; Saddler, Diesendorf and Denniss, 2004). All the studies are predicated on the realisation that Australia must over the coming decades significantly curtail the emissions of greenhouse gases (principally CO_2), including those from electricity generation, as its national contribution to global initiatives to reduce the predicted impact of GHGs (AGO, 2002 , 2003).

There are significant differences between the studies in their predictions of Australia's future electricity requirements. These vary from 1.5-3.5% per annum increases (Graham *et al.,* 2003 for their low and high demand cases) to a very low energy future demand increase of 0.4% (Saddler *et al*, 2004, Scenario 2). Some scenarios considered require levels of infrastructure implementation which may be technologically infeasible (see in particular Cottrell *et al*. (2003) Scenarios D and E and Saddler *et al.* (2004) Scenario 2). This is particularly the case if upward pressure on energy supply from inevitable increases in population (ABS, 2001) was to be contained. Given also the central role that energy plays in driving economic productivity (Foran and Poldy, 2002), this suggests that achievement of the low supply growth scenarios may require substantial (and possibly unacceptable) social change to lifestyles.

The principal data used to examine the emissions implications in this paper are the time-series results for technology implementation developed by Graham *et al* (2003), but for comparative purposes particular end points analysed by both Saddler *et al.* (2004) and Cottrell *et al.*(2003) are also included.

GENERATION TECHNOLOGY OPTIONS SELECTION

It is not the purpose of the present paper to reexamine in detail the methodologies and resultant technological choices presented by the futures modellers, for this the reader should consult the original reports ((Graham and Williams, 2003; Graham *et al.*, 2003; Cottrell *et al.*, 2003; Saddler, Diesendorf and Denniss, 2004). However, it may be helpful to briefly describe the process from which the technology choices arose.

Economic optimisation (Graham and Williams, 2003 and Graham et al., 2003)
This approach set a range of potential GHG emission targets (including business as usual (BAU) with no GHG constraints) and then implemented a calculation using an algorithm to determine the technology mix which met the target at minimum cost. The technology portfolio available for selection by the algorithm was chosen to represent the most important technology options available including coal, gas and renewable (biomass, solar, photovoltaics, wind and hydro) based technologies.

Systems Assessment (Cottrell *et al.*, 2003)
Integrates work on externalities, experience and learning curves, technological modelling and life cycle analysis (LCA) with economic modelling to determine possible technological pathways to meet projected growth in electricity generation requirements. A wide range of technologies were considered but most of the options evaluated were limited to representative or relatively conservative combinations of technologies. The assessment includes coal based generation technologies, and other emergent fossil fuel based technologies. Wind generation was selected as the most economic non-hydro renewable technology.

Scenario Back-casting (Saddler *et al.*, 2004)
A future energy supply goal is assumed together with the patterns of supply and demand at that time, and then public policies which could result in achievement of those goals over the time available are described. The 2040 future described in this work assumes that by 2040 the supply capacity represented by all but the most recently installed coal fired power plants would have been replaced by either natural gas or wind powered generators.

BUSINESS AS USUAL

If electricity supply and demand was to continue, unrestrained by emissions considerations, predictions of CO_2e into the future varies between the various studies, depending largely on the growth assumptions used. Table 1 shows the BAU electricity supply (TWh) and CO_2e, if emissions were unrestrained, as estimated by Graham *et al.* (2003) and compared with those of Cottrell *et al.* (2003) for 2030 and Saddler *et al.* (2004) for 2040. The 1990 CO_2e levels are those associated with electricity generation estimated by the Australian Greenhouse Office (AGO, 2003).

The increases for CO_2e over 1990 levels shown in Table 1 reinforce the view that the Australian electricity generation market is likely to undergo significant change in response to international pressure to reduce overall greenhouse gas emissions. As even the lowest growth BAU scenario results in CO_2e increases of 88% above 1990 levels it is apparent that more radical solutions to generation technologies may need to be embraced if 1990 levels of greenhouse gas emissions were to be achieved whilst maintaining relatively even moderate level increases in energy demand.

Table 1. Predicted growth in electricity demand and resultant greenhouse gas emissions if CO_2e is unrestrained.

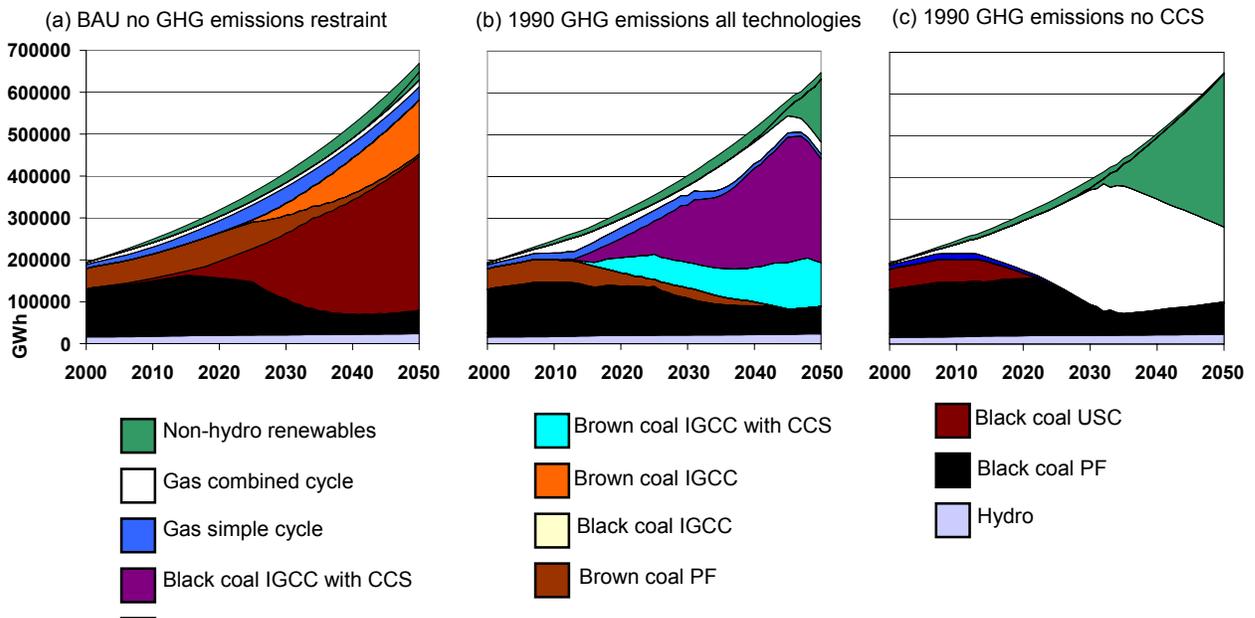| Model author	Year	Electricity demand (TWh)	Predicted increase in electricity demand (BAU)	CO_2e (Mtonnes/yr)	CO_2e Predicted increase over 1990 levels
AGO	1990		n.a.	129	n.a.
Cottrell *et al.*	2030	400	2.5%	281	118%
Graham *et al.*	2030	408	2.5%	303	135%
Saddler *et al.*	2040	352	1.3%	242	88%
Graham *et al.*	2040	523	2.5%	372	188%
Graham *et al.*	2050	669	2.5%	468	262%

The solution to this conundrum is seen by different lobbies at either end of the spectrum as being solved by either the adoption of the widespread use of carbon capture and sequestration (Coal21, 2004) or the near total replacement of coal combustion by generation with renewables and natural gas (Saddler *et al.*, 2004, Tarlo, 2002). If either solution were fully implemented it would be possible to radically reduce GHG emissions. Graham *et al.* (2003) have effectively modelled these solutions amongst a suite of scenarios covering a range of GHG emissions futures.

Figure 1 (a-c) shows a time series for technology share of the electricity generation market predicted by Graham *et al.* (2003) for three radically different future scenarios, these are:
(a) The BAU case when GHG emissions are unrestrained.
(b) The case when GHG are constrained to reach 1990 levels by 2050 but all modelled technologies are feasible (including carbon sequestration).
(c) The case when GHG are constrained to reach 1990 levels by 2050 but carbon capture and sequestration (CCS) proves not to be feasible.
For all three cases the change in electricity demand remains identical increasing by 2.5% annually over the time period modelled.

Figure 1 Predicted electricity generation technology share for three scenarios in the years 2000 – 2050 when supply demand increases by 2.5% pa (redrawn from Graham *et al.* (2003)

(a) BAU no GHG emissions restraint   (b) 1990 GHG emissions all technologies   (c) 1990 GHG emissions no CCS

Legend:
- Non-hydro renewables
- Gas combined cycle
- Gas simple cycle
- Black coal IGCC with CCS
- Brown coal IGCC with CCS
- Brown coal IGCC
- Black coal IGCC
- Brown coal PF
- Black coal USC
- Black coal PF
- Hydro

SOLID WASTE EMISSIONS

The outcomes of the different predicted mixes of technology from the three Scenarios have been evaluated in terms of the quantity and types of ash/slag which may be available. The results of this evaluation are shown in Figure 2. The evaluation has shown that ash quantities and availabilities are strongly dependant on generation technology selection. If no greenhouse gas emissions restrictions are imposed Australia is predicted to be producing by 2050 around 2.4 times the current annual fly ash tonnage of 12 Mt with minor amounts of IGCC slag (from brown coal). If emission reductions are required and IGCC and carbon capture and sequestration are adopted the potential mix of flyash and IGCC slag produced is predicted to be very different. In this scenario (b) flyash production is largely overtaken by that of IGCC slag, although total ash and slag tonnages remain relatively steady. Conversely, if carbon sequestration proves infeasible and emissions reductions are mandated it is predicted that coal ash tonnages will decline to around 50% of current levels, although further ash tonnage may be produced from biomass combustion (Zevenhoven, 2001).

The coal ash production prior to 2000 is based on Australian Ash Development Association (ADAA) time series data (ADAA, 2003). Predictions of coal ash and IGCC slag from 2000-2050 use Australia average coal ash figures with no allowance for increasing ash content in coming years. Any implementation of new technologies was not modelled by Graham *et al.*(2003) to occur before around 2012 and thus all scenarios follow a common path until that time.

Figure 2. Variation in flyash and IGCC emissions predicted for the years 2000-2050 for three electricity supply scenarios when supply demand increases by 2.5% pa (data prior to 2000, ABARE, 2003)
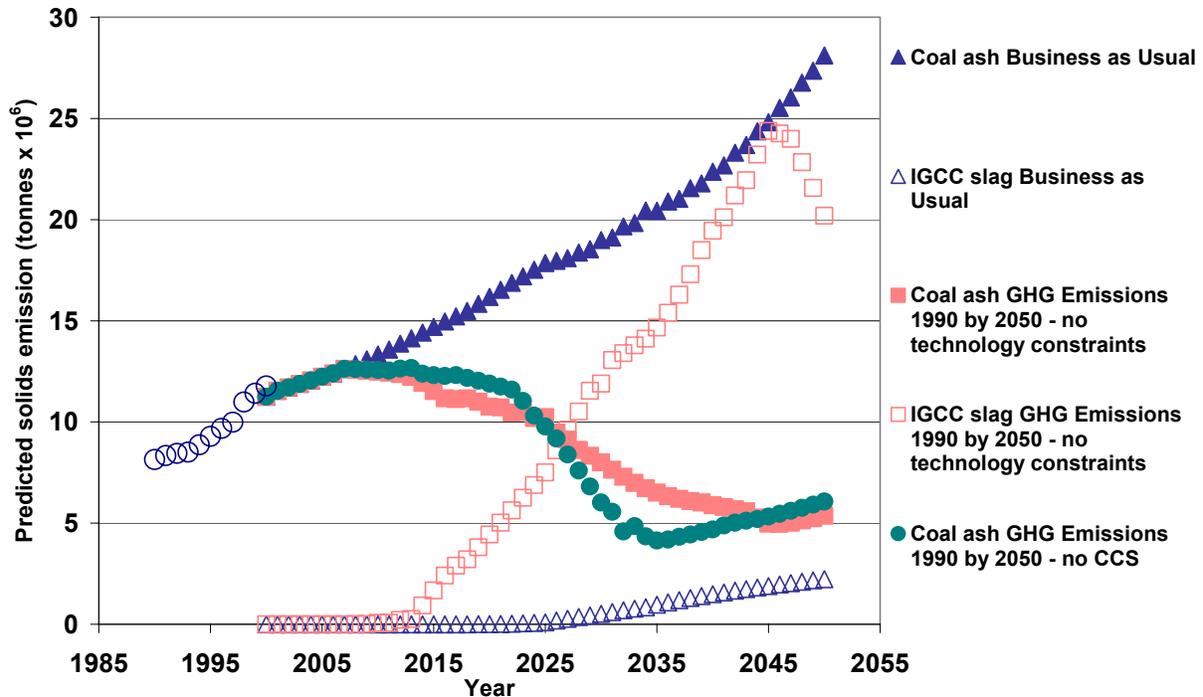
LOW GROWTH OPTIONS

There seems considerable merit in reducing GHGs by dampening electricity demand growth (NIEIR, 2004, Khatib, 2004). If the overall production is lower the need to impose increasingly stringent emission controls or adopt lower emission processes to achieve national emission targets is diminished. Restrictions on electricity demand growth could potentially arise due to exploitation of demand side management, lower distribution losses brought about through the extension of distributed generation schemes, the use of more efficient end use technologies brought about by mandated changes in standards or consumer driven through pricing signals driven by regulatory policy change.

Figures 3(a) and (b) show the predictions for optimum electricity generation technology mix if demand were reduced from 2.5% to 1.5% pa over the study period. This is shown both for (a) the BAU case and (b) for the case when emissions are restricted to 1990 levels and CCS is feasible. From the figures it can be seen that were this lower demand to be achieved it would have a significant effect on coal use and subsequent ash generation. In particular, even at the lower demand levels there is a significant shift predicted to efficient combined cycle gas generation when emission constraints are imposed [Fig 3 (b)].

Figure 3 Predicted electricity generation technology share for two scenarios in the years 2000 – 2050 when supply demand increases by 1.5% pa (redrawn from Graham *et al.* (2003)

(a) BAU no GHG emissions restraint   (b) 1990 GHG emissions all technologies

Legend:
- Non-hydro renewables
- Gas combined cycle
- Gas simple cycle
- Black coal IGCC with CCS
- Brown coal IGCC with CCS
- Brown coal IGCC
- Black coal IGCC
- Brown coal PF
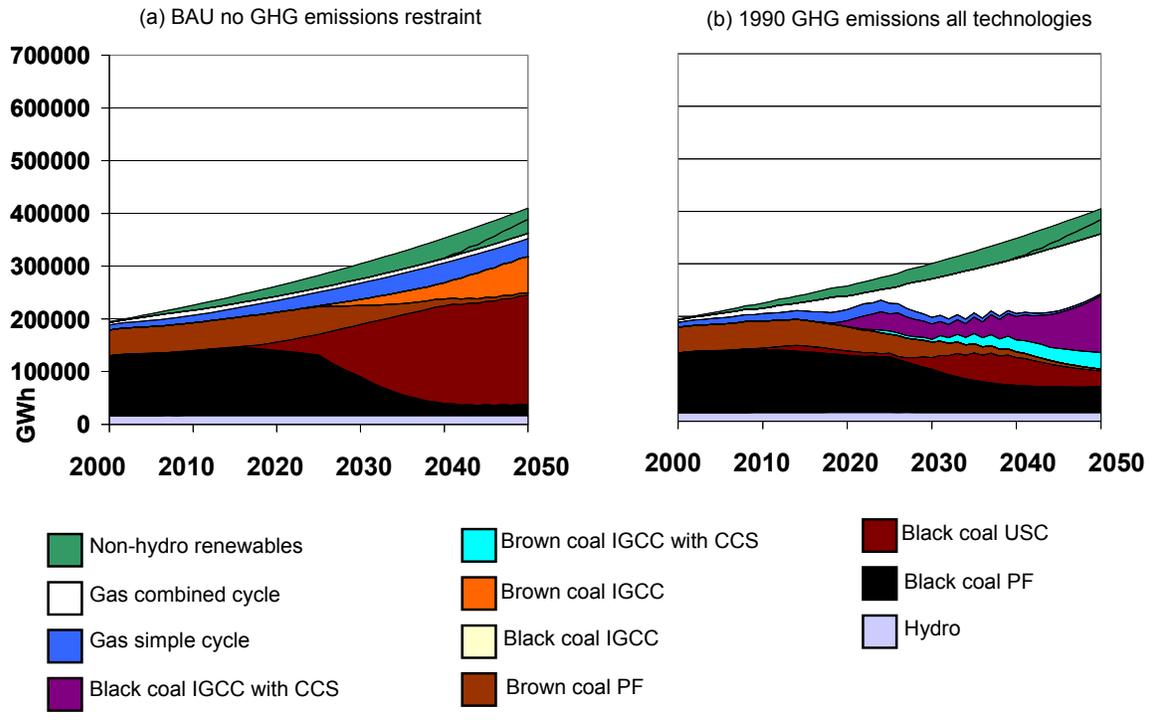- Black coal USC
- Black coal PF
- Hydro

Figure 4 shows the effect of the predicted technology changes on coal ash and IGCC slag generation at diminished electricity demand. When no emission constraints are imposed (low growth, BAU case) the coal ash produced is predicted to increase to1.3 times current levels by 2050 (~15 mtpy), with around 1 mtpy of IGCC slag also available. Were emission constraints imposed (and CCS was feasible) then coal ash production is predicted to decline to about half current levels by 2050 (~6 mtpy), but around 8.5 mtpy of IGCC slag would also be produced. If CCS were not feasible and emission constraints were imposed then it is expected that a result not unlike that shown in Fig. 1(c) would occur for this case (Graham *pers comm.*). This would result in significantly decreased amounts of coal ash being produced from base load black coal power generation, while all other generation capacity was either combined cycle gas or renewables producing no ash, unless biomass combustion becomes the renewable generation technology of choice.

A comparison for the year 2040 of the low growth generation technology mix predicted by Graham et al (2003) for the BAU case and that proposed by Saddler et al (2004) and the resultant coal ash and slag availability are shown in Table 2.

Figure 4. Variation in flyash and IGCC emissions predicted for the years 2000-2050 for two electricity supply scenarios when supply demand increases by 1.5% pa (data prior to 2000, ABARE, 2003).
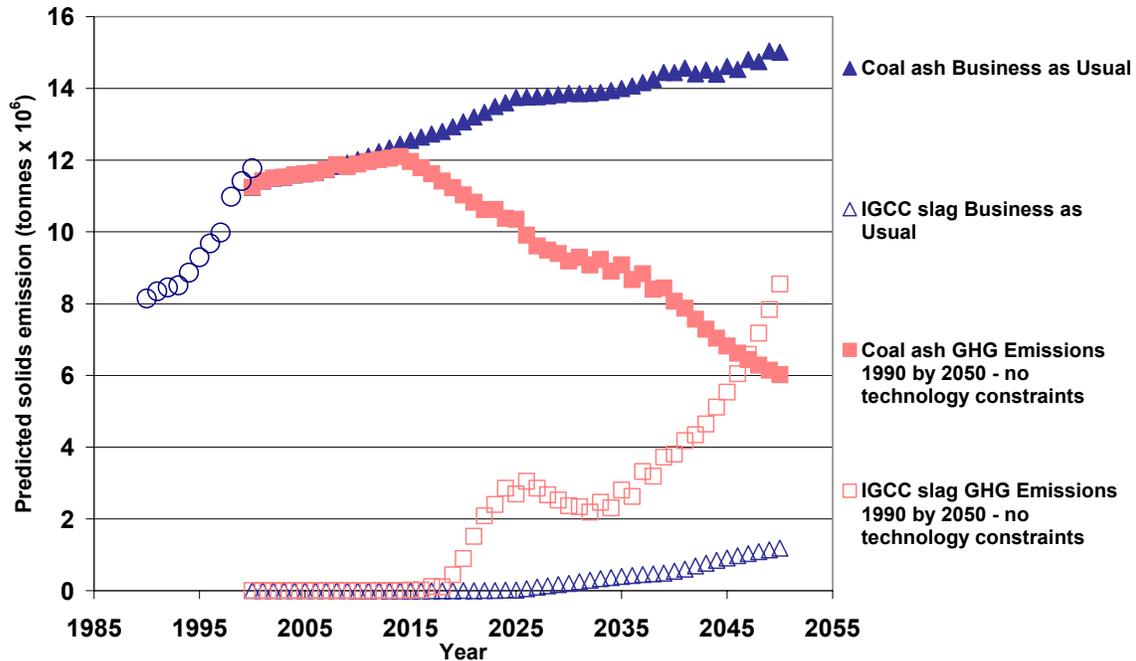
 Although in these two models of the energy generation system the distribution of energy sources varies, the amounts of ash and slag (~15 mtpy) calculated as being produced in 2040 are remarkably similar in both cases. For the predictions derived from Saddler's data a range of possible slag and ash amounts is given (12.5 – 15.9 mtpy) because the technology being proposed for coal combustion is unspecified. It follows that if more advanced and efficient technologies are used the amounts of slag and ash could be lower than if conventional PF combustion were carried out.

Table 2. Electricity generated by fuel source,(BAU cases) and resultant ash and slag quantities for two different models in the year 2040 at low energy use growth rates.

Model	Brown coal (GWh)	Black coal (GWh)	Gas (GWh)	Biomass (GWh)	Hydro (GWh)	Other renewables (GWh)	Total Generation (GWh)	Estimated Ash and Slag (tonnes x 10^6)
Graham et al	43697	208243	46492	37435	16515	818	352382	15.1
Saddler et al	61111	173611	64361	25639*	18889	8611	343611	12.5 -15.9**

* used in cogeneration   ** dependant on coal use technology (unspecified in Saddler)

POLICY IMPLICATIONS

In the context of the twin global drives to reduce greenhouse gas emissions and improve the overall sustainability of human development (Bennett *et al*, 2001, IPCC, 2001, AEP, 2004, Hoffert *et al,* 1998) it is unlikely that Australian energy use and pollutant evolution will remain unconstrained into the future. Except for the case (BAU) where emissions are unrestrained and growth continues at historic rates (2.5%) (ie a situation not expected to eventuate) any predicted increases in the amounts of coal ash over the next fifty years are relatively small. In all the other cases examined coal ash supply growth was either significantly restrained or diminished. In some cases this restraint or diminution of coal ash was predicted to be accompanied by the production of considerable tonnages of a further material (IGCC slag). This material requires development of end uses to prevent it becoming yet another waste stream.

The scenarios which have been developed therefore suggests that it is likely that the need for a national Australian market for coal ash or coal ash products will probably be diminished in the next fifty years. However, the extent of this diminution may also depend on availability of existing ash storage facilities. If the life of existing PF power generation plants is extended, the ash dams which were sized for the proposed life of the project in the initial designs may prove inadequate. This could result in a substantial rise in the cost of disposal, particularly if further land acquisitions are required to facilitate waste storage, making secondary processing to useful products more attractive (Kalyoncu, 2001).

UTILISATION OF IGCC SLAG

IGCC technology is the cornerstone of many of the near zero-emission coal-fuelled power plants proposed to implement GHG reduction strategies involving carbon sequestration (COAL21, 2004, USDOE, 2004). In endeavouring to develop IGCC as a long term sustainable energy production method, preemptive development of high tonnage end use strategies for IGCC slag prior to its large scale introduction would seem prudent.

To date, given the stage of IGCC process development, it is understandable that less work has been carried out on IGCC residue value-adding than for conventional fly ashes (USDOE, 2002, Adams, 2004). However, it is already apparent that the IGCC slag will in most instances require processing to remove unburned carbon to increase its marketability and to recycle the residual carbon to the combustion process. When carbon recovery/removal has been achieved from the IGCC waste, the remaining slag has been demonstrated to be useable in a wide range of building applications (Choudhry *et al*, 2001).

It is also possible that the vitreous nature of the IGCC slag by-product may lead to a greater level of market acceptability of the aggregate due to the reduced potential for

leaching of any residual trace elements from the glassy slag matrix (Piatak *et al,* 2004, Wilson, 1994).

CONCLUSIONS

There is a high level of uncertainty of the generating capacity technology mix which will apply in Australia over the next fifty years. Different studies have concluded that a wide range of growth rates for electricity supply (1.5-3.5%) are possible. For these various growth rates different scenarios can be constructed which model the effect of varying emission and fuel supply constraints. The predicted resultant solid waste products (fly ash and IGCC slag) from these scenarios have been determined.

The determinations suggest that Australian coal ash supply is likely to diminish over the next fifty years, except in the less likely situation of no future gaseous emission constraints. Under both moderate (2.5%) and low growth (1.5%) scenarios the amount of available coal ash is predicted to be approximately half (~6 mtpy) current levels by 2050. The amount of coal ash requiring ongoing use may also increase if the life of existing PF plant is extended beyond their original design life and ash dam capacity then becomes a system constraint.

A significant level of 'product' substitution may occur if IGCC became the generation technology used to produce a large amount of coal based electricity. The development of IGCC capacity is the cornerstone of many of the near-zero emission coal fuelled generation proposals. The development of high tonnage end use strategies for IGCC is required if coal in the near-zero emissions strategies is to contribute to a more sustainable society. While as might be expected less research has been carried out on IGCC slags than conventional flyashes, it appears that there is scope for ongoing use of the material once any unburnt carbon is removed or recovered.

The combination of the predictive modelling of technology uptake with calculation of emissions outcomes may assist policymakers to better examine the results of policy changes in the requirements for GHG mitigation as part of the ongoing debate on achieving sustainability for the electricity generation sector.

ACKNOWLEDGEMENT

REFERENCES

ABARE, 2003 Australian energy consumption, by industry and fuel type - energy units, Australian Bureau of Agriculture and Resource Economics, Canberra.

ABS, 2000 Population Projections, Australia, 1999 to 2101, Australian Bureau of Statistics, Canberra.

ADAA, 2003, Ash Development Association of Australia, Total ash production and beneficial usage – time series data, http://www.adaa.asn.au/statistics.htm

Adams, D., 2004 Utilisation of CFBC and IGCC residues, pub IEA Clean coal Centre, London, UK.

AEP, 2004 'AMERICAN ELECTRIC POWER (AEP): *Position Paper on Global Climate Change',*
http://www.aep.com/environmental/climate/docs/Climate_Change_Position_Paper.pdf

AGO, 2002 Tracking to the Kyoto Target: Australia's Greenhouse Emissions Trends 1990-2012, Australian Greenhouse Office, Canberra.

AGO, 2003. Stationary Energy Sector: Greenhouse Gas Emissions Projections 2003, Australian Government Interdepartmental Greenhouse Projections Group, Canberra, http://www.greenhouse.gov.au/projections/pubs/stationaryenergy2003.pdf

Bennett, E., Mingst, A., Simon, S. and Graedel, T., 2001, 'Improving the overall environmental performance of existing power generating facilities', *IEEE transactions on Energy Conversion*, 16, 3, pp234-238.

Choudhry, V., Kwan, S. and Hadley, S., 2001, 'Utilization of lightweight materials made from coal gasification slags', USDOE Final report, prepared by Praxis Engineers, Inc, Milpitas, California. http://www.osti.gov/energycitations/servlets/purl/785151-3ez3sb/native/785151.pdf?zone=ecd

COAL21, 2004 A Plan for Action for Australia: Reducing Greenhouse Gas Emissions Arising from the Use of Coal in Electricity Generation, March 2004, http://www.coal21.com.au/Media/COAL21_Action_Plan.pdf

Cottrell A., Nunn J., Palfreyman D., Urfer A., Scaife P., and Wibberley L. 2003, 'Systems assessment of future electricity generation options for Australia, Technology Assessment Report 32, CRC for Coal in Sustainable Development, Pullenvale, Queensland.

Foran B. and Poldy F, 2002 'Future dilemmas: Options to 2050 for Australia's population, technology, resources and environment , Ch 5 The Future of Energy', CSIRO Resource Futures Working Paper 02/01, http://www.cse.csiro.au/futuredilemmas

Graham P. W. and Williams D.J. 2003, 'Optimal technological choices in meeting Australian energy policy goals', *Energy Economics*, 25, 691-712.

Graham P., Dave N., Coombes P., Vincent D. and Duffy G. 2003, 'Options for electricity generation in Australia, Technology Assessment Report 31, CRC for Coal in Sustainable Development, Pullenvale, Queensland.

Hoffert, M. *et al*, 1998, 'Energy implications of future stabilization of atmospheric CO_2 content', *Nature*, 395, pp881-884.

IPCC, 2001, 'Climate change 2001:Mitigation, Summary Report for Policymakers', *A Report of Working Group III of the Intergovernmental Panel on Climate Change,* http://www.ipcc.ch/pub/wg3spm.pdf

Kalyoncu S. 2001, 'Coal combustion products', U.S. Geological Survey Minerals Yearbook, http://minerals.usgs.gov/minerals/pubs/commodity/coal/coalmyb01.pdf

Khatib, H., 2004, Energy considerations – global warming perspectives, address to the Energy Permanent Monitoring Panel of the World Federation of Sciences, Erice , Sicily , August, 2004. http://www.worldenergy.org/wec-geis/publications/default/speeches/spc040819hk.pdf

NIEIR, 2004 Impact of greenhouse policy on electricity demand, National Institute of Economic and Industry Research, Clifton Hill, Victoria, http://www.nemmco.com.au/nemgeneral/410-0046.pdf

Piatak, N., Seal II, R., Hammarstrom, J., 2004, Mineralogical and geochemical controls on the release of trace elements from slag produced by base- and precious-metal smelting at abandoned mine sites, *Applied Geochemistry*, 19, pp 1039-1064.

Saddler H., Diesendorf M. and Denniss R. 2004. 'A clean energy future for Australia', a study for the Clean Energy Future Group, http://www.wwf.org.au/News_and_information/Publications/PDF/Report/clean_energy_future_report.pdf

Tarlo, K., 2002, 'Why brown coal should stay in the ground: Greenhouse implications of the proposed expansion of brown coal exploration and mining in Victoria', Institute for Sustainable Futures, University of Technology, Sydney.

USDOE, 2002 Major Environmental Aspects of Gasification-Based Power Generation Technologies, Final Report, December 2002, U.S. Department of Energy, Office of Fossil Energy, National Technology Laboratory, Washington DC.

USDOE, 2004, '*FutureGen* - Tomorrow's Pollution-Free Power Plant ', http://www.fossil.energy.gov/programs/powersystems/futuregen/futuregen_fact_sheet_04.pdf

Wilson, L.J., 1994, Literature review on slag leaching, Canada Centre for Mineral and Energy Technology, Mineral Sciences Laboratories Division Report 94-3 (CR), Ottawa.

Zevenhoven, M., 2001, 'The Utilisation of Biomass Ash', Report 01-08, Faculty of Chemical Engineering, Åbo Akademi University, Finland, http://www.abo.fi/fak/ktf/cmc/publications/reports/01-08.pdf