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The Australian Electricity Industry and Climate Change: What role for geosequestration?

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Climate change has become a key driver for technology innovation in the electricity industry. A 50% global reduction in greenhouse emissions over this century appears necessary to avoid dangerous global warming. This will require a far-reaching transformation of our current, primarily fossil-fuel based, energy sector. Present technology options for electricity-related emissions abatement include energy efficiency, low-emission fossil-fuel generation and renewables. There is, however, a clear need for further technical progress in these options given the scale of change required.

There is now growing worldwide, and certainly Australian government, interest in the potential for novel coal-fired electricity generation and geosequestration technologies to reduce greenhouse emissions. This raises the question of how government policy can be used to drive innovation in promising yet unproven abatement technologies. A particular challenge for policy makers is balancing the risks in trying to 'pick winners' against the need to focus publicly funded efforts on the more prospective technology options. Technology assessments are required despite the many challenges, uncertainties and hence risks in attempting to model innovation.

In this paper we outline a simple framework for making such technology assessments. Its evaluation criteria are technical feasibility, delivered energy services (benefits), present and possible future costs, potential scale of abatement, and other possible environmental and societal impacts. These evaluations must factor in risks, the national or regional context facing policy makers – for example, the existing energy sector and R&D capabilities – as well as policy opportunities to drive progress.

We then apply this framework with a preliminary technology assessment for coal-fired generation with geosequestration. This assessment highlights some key remaining questions on the technical feasibility of this approach, its likely high yet uncertain costs, large potential scale of abatement and still significant environmental impacts. These findings are compared against other abatement options including energy efficiency, low-emission gas-fired generation and renewables. In contrast with geo-sequestration, these options have proven technical feasibility, demonstrated and highly competitive abatement costs, varied abatement potential and typically reduced environmental impacts.

Finally, we consider the possible Australian policy implications of these technology assessments. In our view, present innovation policy measures are inadequate and risk being inappropriately focussed on one promising yet unproven option – coal-fired generation with geosequestration. Considerable effort, public investment and time will be required just to determine what, if any, contribution this technology can make. Minimising the risks and maximising our opportunities for innovation in abatement technologies requires instead, a coherent innovation strategy that supports a portfolio of promising options. Policy measures must address the different innovation needs of these options – targeted R&D funding yet, critically, market deployment drivers for near-commercial technologies.

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Introduction

Climate change is one of the great policy challenges of our time. We risk causing irreversible damage to vital ecosystems, yet our policy efforts will have to overcome:

- the long time frame and global nature of this problem, and hence our policy response,
- our society's present dependence on low-cost fossil fuels – a far-reaching transformation of these energy systems is clearly required,
- important uncertainties in what this transformation will actually entail, and
- the many other important economic, environmental and societal factors associated with present, and possible future, energy systems.

The likely scale and timeline of required global emissions reductions is 50% over the next century, with developed countries potentially obliged to take greater cuts over a shorter time frame, than this (UK DTI, 2003). Most of these reductions will have to come from fossil fuel emissions (IPCC, 2001).

The IPCC (2001) identifies "technology as a more important determinant of future greenhouse gas emissions and possible climate change than all other driving forces put together." We already have a wide range of technologies for reducing energy related emissions through improved end-use energy efficiency and lower emission and renewable energy supply, (UNDP, 2002; IPCC, 2001). However, technical progress and innovation is essential as present options are almost certainly inadequate for the scale of change required.

The focus of this paper is the potential for novel coal-fired generation and geosequestration technologies to contribute to emissions reductions in the Australian electricity sector.

We first consider the role of government policy in driving technology innovation. A particular challenge for policy makers is balancing the risks of trying to 'pick winners' against the need to appropriately focus policy efforts for different technology options. We outline a simple framework for assessing emission abatement technologies to assist in this.

We then outline Australia's present innovation policy framework for climate change and the electricity sector. Of particular interest is the recent and growing government support for novel coal-fired generation and geo-sequestration technologies as Australia's most promising emissions abatement option.

To explore what rationale might lie behind this focus, we apply our simple technology assessment framework to this geosequestration option. It is then briefly compared against other abatement technology options including energy efficiency, gas-fired generation and renewables.

Finally, we consider how such technology assessments can inform the development of Australian innovation policy for climate change.

Innovation policy for climate change

Our options for emissions abatement now and into the future depend, of course, on what technologies are currently available, yet also on:

- the technical progress that might result from present competitive market pressures, and
- what progress and innovation might be driven by government policy efforts.

Innovation has two key themes, *invention* and *application*. Research and Development (R&D) and Demonstration[2] are key steps of the invention phase. Deployment is the key commercialisation step for moving an invention to possible widespread adoption.[3]

One clear government policy role is supporting socially beneficial 'invention' through publicly funded R&D into sustainable energy technologies.[4]

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[2] We use the term R&D&D as shorthand for Research, Development and Demonstration.

[3] Demonstration and Deployment are sometimes used interchangeably but are really quite different. "Demonstration produces results that are necessarily experimental and unreliable since the aim is to try out new techniques. Deployment required the opposite – reliable technologies that can deliver environmental and commercial results." (Watson, 2001).

[4] See for example, UK DTI (2001) "The rationale for Government funding of R&D applied both in the UK and internationally is based on the premise that social rates of return on some R&D, for example energy technologies that can contribute to environmental problems and which involve lengthy development timescales, are higher than private rates of return. Investment in these areas is therefore likely to be to low without Government support or intervention."

However, governments can also play a vital role in taking new sustainable energy technologies from invention (technical feasibility) through to full commercialisation. It is widely agreed that both supply-push (eg. demonstration projects) and demand-pull (market driven deployment) policies are required (Norberg-Bohm, 2000).

Finally, technology can be usefully seen as having 'hardware' (manufactured technology), 'software' (knowledge to use this equipment) and 'orgware' (institutional capacity) dimensions (IIASA, 2002). All of these dimensions are vital for technical progress, although their relative importance may vary with context. For example, new technologies that are radically different in approach from existing technologies (sometimes called "disruptive technologies") may require institutional change to permit successful widespread deployment. At least some greenhouse abatement technologies appear to have this characteristic.

Guidance for policy makers:

Policy makers attempting to drive innovation in greenhouse abatement technologies face some difficult questions, including:

- do particular energy sectors merit special attention – for example, energy efficiency, fossil fuel generation or renewables,
- are there highly promising technologies that merit targeted support – for example, LED lighting, wind power or geosequestration,
- how might different technologies progress in the future – for example, steady progress with established technologies, or potential breakthroughs with novel ones, and *hence*
- what overall policy framework and particular mechanisms are most likely to maximise our abatement capabilities in the longer term.

Innovation policy development must be undertaken in the face of considerable uncertainty. Formal risk management strategies can reduce risks and maximise opportunities for abatement technology innovation. Strategies include technology risk assessments and, critically, diversification (portfolio approaches).

A difficult balance must then be struck between the risks of governments attempting to pick winners against the need to focus limited public resources into our more promising options.

For R&D and demonstration funding, some form of assessment for different technology options will always be required.[5] For commercialisation support, some deployment measures can be made 'technology neutral' to an extent.[6] However, it is still necessary to balance the benefits of competition between options, against the benefits of targeting promising technologies for development support.[7]

Given a climate policy objective of delivering major longer-term emissions abatement, such technology assessments will need to consider:

- technical feasibility,
- delivered energy services (benefits),
- present costs where known, and possible future costs,
- potential scale of abatement delivered, and
- other economic, environmental and societal outcomes with use of the technology.

There are uncertainties and associated risks in all of these considerations. Also, policy makers must make such assessments with regard to their government's particular context – for example, existing national or regional energy sectors, available energy resources and R&D strengths. Perhaps the greatest challenge is that these factors can all respond to policy actions.

A number of tools can help with technology assessments. At their most simple, 'technologies that exist are, by definition, possible' and 'technology trends may continue'. More formally, there are methodologies including:

- bottom-up engineering and economic studies,
- technology road mapping,
- 'experience curves' analysis, and
- scenario analysis.

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[5] As noted by Watson and Scott (2001) "In principle, it is essential that the government does not 'pick winners'. A diverse portfolio of basic research, development, demonstration, and technologies should be supported to allow for large uncertainties associated with future directions of technical change, as well as rapidly shifting market conditions. It is, however, equally important that this need for diversity does not dilute public R&D effort because it is thought to be a good idea to do a bit of everything."

[6] For example, MRET gives market-driven support to a diverse range of near-commercial renewable technologies.

[7] The 'price' of particular new energy technologies can be greatly lowered through government support that drives learning from experience and economies of scale in its particular industry (Isoard and Soria, 2001)

Nevertheless, technology assessment remains a difficult challenge, while developing appropriate policies in response to these assessments is probably even harder.[8]

Australian climate change and innovation policy

The Australian Government's stated climate change objectives are to meet our Kyoto target and prepare Australia for the large-scale emissions reductions required over the coming century (Australian Government, 2002).

The Australian electricity sector currently contributes over 32% of national greenhouse emissions and has shown the highest growth in emissions of any sector over the last decade (Commonwealth of Australia, 2002).

While a number of policy measures targeting climate change and the electricity sector have been implemented, emissions are still projected to grow markedly over the coming decades (CoAG, 2002).

The modest target and generous land-use provisions negotiated by Australia in Kyoto mean that our Protocol commitment may actually be met without any significant change in the energy sector (Australia Institute, 2003). However, far greater efforts are clearly needed to achieve the major abatement from this sector required in the longer-term.

Innovation policy for climate change:

Australian policy support for R&D is largely delivered through various general Australian Research Council (ARC) competitive grants programs. There is also funding for Cooperative Research Centres (CRCs). At present, a number of these are directly electricity sector or climate change related – the CRC for Clean Power from Lignite, CRC for Coal in Sustainable Development, CRC for Greenhouse Accounting (largely focused on ecosystem sequestration) and CRC for Greenhouse Gas Technologies (focused on CO_2 capture and its geosequestration). There are, however, no CRCs or dedicated funding for energy efficiency or renewable energy.[9]

Direct Australian policy support for commercialisation of new electricity generation technologies includes the CRCs noted above, and various competitive grant schemes – for example, the Renewable Energy Commercialisation Program (RECP) Deployment support includes grant schemes such as the Photovoltaics Rebate Program and, most importantly, the Mandatory Renewable Energy Target (MRET). There is also some deployment support for energy efficiency including, for ecample, Minimum Energy Performance Standards (MEPS) and energy efficiency 'star rating' schemes (AGO, 2003).

Although there are difficulties in defining and measuring direct government spending in these areas, Australian support for sustainable energy appears to be low compared with many other developed countries (Australia Institute, 2003).

Support for geosequestration:

There is now growing Australian government interest and support for geosequestration of coal-fired electricity generation emissions as an abatement option. This includes (Tarlo, 2003):

- the inclusion of 'capture and sequestration of CO_2' as one of Australia's National Research Priorities,
- recent establishment of the CRC for Greenhouse Gas Technologies which will focus almost exclusively on CO_2 capture and geosequestration,
- leading role of CO_2 capture and geosequestration in the US-Australia Climate Action Partnership,
- strong support for this option given by various Australian Federal Ministers, and
- strong advocacy by a Prime Minister's Science Engineering and Innovation Council (PMSEIC) working group and Australia's Chief Scientist[10] in favour of the technology.

[8] Note that we do not include top-down CGE economic modelling in our list of formal methodologies. They generally have highly stylised and clearly inadequate models for exploring technology innovation (MacGill, 2003b).

[9] The Australian CRC for Renewable Energy was unsuccessful in obtaining additional funding in the latest competitive round.

[10] The PMSEIC Executive Officer is Dr Robin Batterham, Australia's part-time Chief Scientist and also the Chief Technologist for Rio Tinto Corporation.

An important question, then, is whether the Australian government is now attempting to 'pick winners'. Furthermore, what formal assessments of Australia's different technology abatement options justify this apparent focus?

The PMSEIC *Beyond Kyoto* report:

PMSEIC is "the Government's principal source of independent advice on issues in science, engineering and innovation" (PMSEIC, 2003). It was recently given the task of reporting on opportunities to utilise and develop emission reduction technologies appropriate for Australia.

Its (PMSEIC, 2002) report, *Beyond Kyoto – Innovation and Adaptation*, considered a range of generation options for emission abatement including coal-fired Integrated Gasification Combined Cycle (IGCC) plant with geosequestration, Combined Cycle Gas Turbines (CCGT), Distributed Energy Systems (DES) and Renewables. These were classified as current, near-term and longer-term options, and compared on costs and potential abatement.

The report concluded that "within the foreseeable future only carbon capture and geosequestration has the potential to radically reduce Australia's greenhouse signature" and therefore recommended that the Government "establish a national program to scope, develop, demonstrate and implement near zero emissions coal based electricity generation."

Technology assessment of geosequestration:

The authors have previously critiqued this *Beyond Kyoto – Innovation and Adaptation* report (MacGill, 2003). We have particular concerns with its technology assessment of the different abatement options – both in terms of the incomplete criteria used for comparison, and its data estimates for the different technologies. For example, there is little account of the very different risk profiles of the options, and the cost estimates for coal-fired generation with geosequestration are not supported by the international literature.

In this paper, we present some preliminary work on a risk-based assessment of coal-fired electricity generation and geosequestration opportunities for Australia.

We consider, in turn:

- technical feasibility,
- delivered services (benefits),
- present costs, and possible future costs
- potential scale of abatement, and
- other possible societal outcomes.

Technical assessment – coal-fired generation with geosequestration

Technical feasibility:

Coal-fired steam turbines have been one of our major electricity generation technologies for more than 50 years. Some 85% of Australian electricity supply comes from such plant. The 'near zero emission' concept for coal-fired generation involves capturing the CO_2 emissions arising from coal combustion and sequestering it in geological reservoirs.

The key technical steps are capturing CO_2 emissions from the power plant, transporting them to a suitable sequestration site, and then injecting the CO_2 into a stable geological reservoir for long-term storage.

CO_2 Capture:

There are well-established technologies used in the oil and chemical industries for capturing CO_2 from gas streams. Power plant flue gases, however, pose some technical challenges. Most practical experience with CO_2 capture has been from chemically reducing gas streams rather than oxidising flue gases (IEA, 2001).[11] Furthermore, there are the enormous volumes of CO_2 emitted by large coal fired plant – some 20,000 tonnes/day for a 1000MW plant. Small-scale CO_2 capture from conventional power stations has been demonstrated. Large-scale capture, has not, and there are significant cost concerns with present technologies.

R&D efforts are therefore underway in other technical options for large-scale, low cost CO_2 capture – for example, better solvents, membranes and solid adsorbents. Oxygen-blown combustion might also be feasible (IEA, 2001).

[11] There may be particular problems for existing Australian generating plant – our less stringent SOx and NOx emission standards than Europe and the US can adversely impact present solvent scrubbing technologies (Dave, 2000).

Integrated Gasification Combined Cycle (IGCC)

CO_2 capture is far easier with coal-fired IGCC plant. In these plants, the coal is reacted with oxygen and steam to produce a fuel gas. This can then be burned in a Combined Cycle Gas Turbine. Most CO_2 can be captured prior to combustion from the concentrated gas stream.

There is considerable international experience with gasification in the oil and chemical industries, and a number of coal-fired IGCC demonstration plants in operation worldwide. According to the IEA (2001) "IGCC has been successfully demonstrated but the capital cost needs to be reduced and the reliability and operating flexibility needs to be improved to make it widely competitive in the electricity market" (IEA, 2001). 'H_2 rich' gas turbine technologies also have to be proved up.

CO_2 capture from IGCC will certainly be easier than with conventional coal-fired plant. The PMSEIC *Beyond Kyoto* report argues that IGCC shows the greatest potential for cost-effective electricity generation with CO_2 capture.

CO_2 transportation:

There would seem to be few technical problems in transporting CO_2 by pipeline. Such pipelines are already in operation in the US and elsewhere, and the gas is relatively easy to handle (IEA, 2001). Transporting CO_2 long distances does, however, have important cost implications (Allinson, 2003).

Geosequestration:

The main options for storing CO_2 underground over the hundreds of years required for effective emissions abatement are shown in Figure 1.

There is considerable knowledge and experience with CO_2 sequestration in depleted oil and gas reservoirs. Such sequestration is in wide use for Enhanced Oil Recovery (EOR) where it actually provides a net financial benefit. Furthermore, these types of reservoirs are proven traps and have well known geologies. The capture of CO_2 from a lignite (brown coal) IGCC plant and its use for EOR is being demonstrated by the Weyburn project in the US (IEA, 2001).

There is only limited experience with injecting CO_2 into unminable coal seams. The CO_2 is permanently locked up in the coal. Even better, this can release methane bound to the coal and enhance recovery for Coal Seam Bed Methane operations (ECBM) – a growing source of natural gas in countries including Australia. At this time, however, there is only one project using CO_2 sequestration for ECBM recovery, located in the US (IEA, 2001).

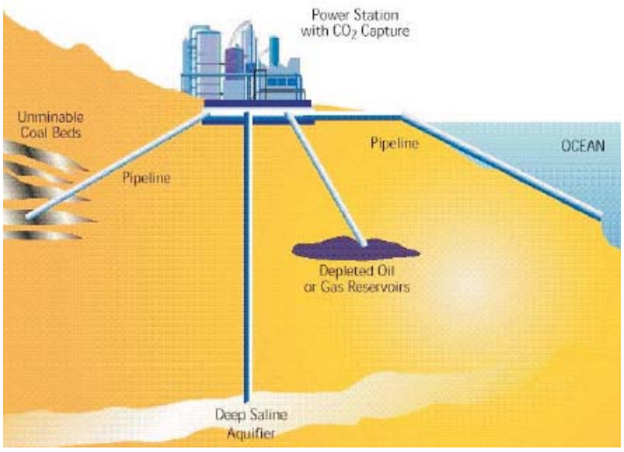

Figure 1: Options for CO_2 sequestration (taken from IEA, 2001).

CO_2 injection into deep saline aquifers potentially offers by far the largest geological storage capacity for geosequestration. Large-scale emissions abatement from the electricity sector will almost certainly require their use. Unfortunately, this type of reservoir is also the least understood in terms of distribution and geology; primarily because they have not had any commercial value until now. Considerable research is still required and there are significant uncertainties and hence risks. There is currently one demonstration project sequestering CO_2 extracted from a natural gas project into a saline aquifer – Sleipner Vest in Norway (IEA, 2001).

In conclusion, the large-scale application of CO_2 capture and geosequestration from coal-fired electricity generating plant has not yet been demonstrated. Most of the key technologies would seem to be commercially available or at least demonstrated at some scale. They have not, however, been integrated and scaled up in a commercial-size demonstration plant. Also, there are still significant uncertainties concerning the risks of re-release of CO_2 from geological storage into the atmosphere. Nevertheless, there is general agreement that at least some geosequestration of coal-fired electricity generation is technically feasible.

Delivered energy services (benefits):

Coal-fired generating plant is the key baseload technology in many electricity industries and offers low-cost, relatively reliable and dispatchable electricity. These plants also create very significant CO_2 emissions – perhaps 6 million tCO_2/year for a typical 1000MW plant.

The ability to add CO_2 capture and sequestration to existing plants would seem to offer very significant emissions abatement yet not require major changes to present electricity infrastructure or operating practice. Much would depend on whether IGCC plant is necessary for cost-effective CO_2 capture, and the availability of geological storage near existing generating regions. If generation must be moved, this could greatly impact on network investment and costs.

Adding CO_2 capture and geosequestration to coal-fired plant will add to costs, so the benefit of the technology in reducing emissions is a primary driver. Although the term 'zero emissions coal' is sometimes used, there will still be significant emissions. This is because of the energy and cost trade-off in how much CO_2 is captured, and the energy required to transport and pump the CO_2 underground.

The IEA (2001) estimates that coal-fired IGCC plant with geosequestration will still emit around 150 $kgCO_2$/MWh in its operation. This is some 40% of existing natural gas-fired CCGT plant, as shown in Figure 2.

There are also upstream greenhouse emissions from coal extraction to consider.[12] These emissions can range from zero to 20% of direct power plant emissions (Gielen, 2003). These overall emission estimates, assume, of course, that the sequestered CO_2 actually remains effectively stored for some hundreds of years.

Costs:

There are many challenges and uncertainties in making cost estimates for coal-fired electricity generation with geosequestration (Freund, 2002; Gielen, 2003). One difficulty, of course, is that no such plants have yet been built. Also, there would seem to be good potential for technical breakthroughs in key steps of the process and, undoubtedly, learning from scale and experience that could reduce costs in the longer-term.

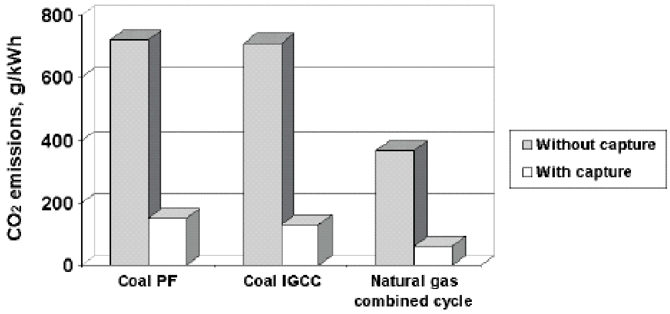

Figure 2: CO_2 emissions from different fossil fuel generation options with, and without, CO_2 capture (taken from IEA, 2001).

Three types of costing studies have generally been undertaken (Gielen, 2003):

- engineering assessments focusing on specific technologies and projects,
- comparative studies that combine different engineering studies, and
- modelling assessments using 'technology learning' concepts and engineering software tools. These are of key importance with novel, unproven technologies.

Engineering assessments offer the highest certainty, yet the least general applicability in terms of future technology development. Such project-specific studies require criteria to be defined including chosen technologies, plant size, fuel costs, CO_2 transport distances, geological reservoir characteristics, project lifetime and financing (Freund, 2002).

More generally, some methodological choices are also critical to cost estimates: (Gielen, 2003)

- the choice of discount rate and use of Net Present or levelised costs (Freund, 2002),
- presentation of results in terms of capital costs ($/MW), electricity costs ($/MWh) or CO_2 abatement ($/$tCO_2$ avoided),
- selection of reference technology against which the plant is compared – for example, the same plant without capture, existing conventional plant or 'best practice' plant,
- energy system boundary – for example, operating or full life-cycle emissions, and
- economic life cycle boundary – for example, including R&D and demonstration costs.

[12] Note,however, that there are also potentially significant upstream CO_2 emissions from natural gas extraction.

Sequestration projects linked with EOR or ECBM can create additional value – potentially sufficient to offset the sequestration costs. Such opportunities are limited however. If significant abatement is to be sought, it can be assumed that most electricity generation projects will not earn such benefits – the value of geosequestration will lie in their 'avoided' emissions. Because CO_2 capture and sequestration is an 'add-on' to generating plant, this abatement will have costs.

Studies to date have differed in type, defined project criteria and methodology, and this makes comparison difficult.[13] With this proviso, we present the cost estimates (with uncertainty ranges) for a number of Australian and International studies in Figure 3.

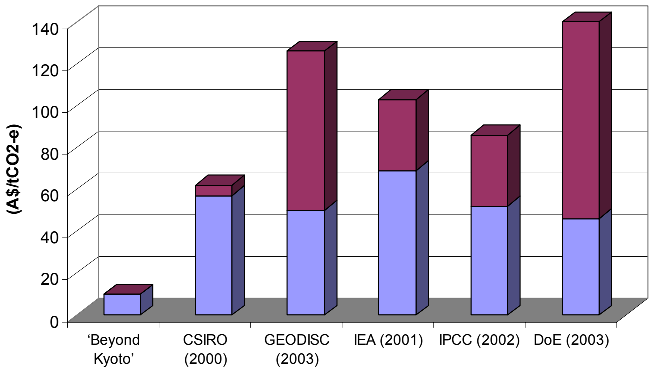

Figure 3: Estimated emission abatement costs[14] (and their uncertainty range) from different Australian and International studies for coal-fired electricity generation with geosequestration.[15]

The cost estimate quoted in the PMSEIC Beyond Kyoto report is drawn from unpublished data by Roam Consulting, so the chosen criteria and methodology in its calculation are unknown. Nevertheless, it is some four to five times less than these other published estimates, which all suggest significant abatement costs.

Possible future costs:

There are opportunities to reduce these costs with time, and experience via: (Freund, 2002)

- technology improvements – perhaps novel R&D breakthroughs or steady progress,
- economies of scale with larger plants, and
- technology learning associated with growing deployment. This is generally described through the use of experience curves.

It is difficult, however, to put numbers to these possible cost reductions, particularly before a technology has been successfully demonstrated.[16] At present, regardless, the cost uncertainties outlined above far outweigh possible learning effects (Gielen, 2003).

Potential scale of abatement:

Global:

Studies to date have confirmed that there is potentially a very large worldwide storage resource. Some theoretical global estimates from the IEA (Gale, 2002) are shown in Table 1. These were derived using general assumptions – actual or realisable storage potential will require regional studies and analysis. Such research is underway worldwide, including Australia. [17]

Table 1: Theoretical global storage potential.

Storage option	Gt CO_2 (% est. global CO_2 emissions to 2050)
Depleted Oil + Gas fields	920 (45%)
Unminable coal beds	40 (2%)
Deep Saline Aquifers	400-10,000 (20-500%)

[13] There are also difficulties in converting US$ estimates to A$. The currency exchange rate has varied over the approximate range A$1 = US$0.50–0.80 over the last ten years. Also, it appears that the capital costs of coal-fired plant in Australia are lower than typical US plant costs – other factors are clearly relevant in making cost conversions.

[14] These results are presented in terms of $/t$CO_2$ emissions avoided. In our view, this is the more relevant for making greenhouse abatement technology comparisons than electricity ($/MWh) costs given the different greenhouse intensities of various low-emission generation options.

[15] The CSIRO study considered two hypothetical projects – a coastal plant using ocean sequestration, and an inland plant sequestering into a depleted gas field. GEODISC base their capture costs on international estimates of US$25-40/t$CO_2$.

[16] Both engineering assessments and experience curve analysis can play a role in estimating possible future costs. Coal-fired electricity generation with CO_2 capture and sequestration has not yet been deployed so experience curves cannot be directly applied. However, some of the likely key components are in use, and can be separately analysed. The mature and widely deployed technology components may not offer great cost reduction opportunities. Nevertheless, there can be considerable 'learning' when integrating such existing technologies (IEA, 2000).

ABARE (2003) comments that "Speculating about renewables costs beyond 2010 is just that – speculation." This is even more applicable to an unproven technology.

[17] See, for example, Bradshaw (2002) "Broad brush style estimates of CO_2 storage potential at the global and continent scale are probably of limited value for future research programmes, and more sophisticated storage capacity estimates are required that integrate economics, source to sink matching and technical viability."

Clearly, the greatest resource potential is that of deep saline aquifers. However, these are also the least understood and potentially expensive type of reservoir. The proximity of suitable storage near large point emission sources is also a critical determinant of the potential storage resource given the costs that would be involved in transporting CO_2 large distances.

Australia:

Australia's GEODISC[18] program has made some preliminary regional estimates of national storage potential (Bradshaw, 2002; Allinson, 2003). This work suggests that Australia's storage potential may be very large – 1600 years or more of present emission levels. However, some 95% of the identified resource is deep saline aquifer and there would seem to be only very limited opportunities for high value EOR and ECBM sequestration.[19]

The great majority of Australia's identified storage potential is located in North Western Australia – an impractical distance from existing coal-fired generation on the east coast.[20] GEODISC results to date suggest that Victoria's brown coal plant may have good sequestration options, Queensland's black coal plant moderate sequestration potential while NSW's black coal generators likely have poor opportunities.

Nevertheless, GEODISC's findings to date suggest that Australia might potentially be able to annually sequester 50-70% of stationary point source emissions (Allinson, 2003).

Other societal factors:

A range of other societal factors and impacts also need to be considered when considering sustainable energy options. These include:

Direct environmental risks:

Geosequestration involves a range of environmental risks that are only poorly understood. Some of the major risks are outlined in Table 2 (adapted from Tarlo, 2003).

Table 2: Environmental risks with geosequestration

Risk	Possible consequences
Slow, long-term escape of CO_2 to atmosphere[21]	Global warming
Sudden large-scale escape of CO_2 to atmosphere[22]	Asphyxiation of humans, animals and plants
Escape of CO_2 to shallow ground waters	Water acidification, mobilised toxic metals, leached nutrients (Bruant,2002)
Displacement of deep brine upward	Contamination of potable water sources
Escape of other captured hazardous flue gases (eg. SOx, NOx)	Range of possible environmental harms

Other environmental impacts:

Coal-fired electricity has a range of adverse environmental impacts other than climate change. These include regional air pollution, water usage and significant land use impacts.

Wider economic impacts:

The coal industry makes an important contribution to the Australian economy and, in particular, national exports. Technologies that allow continued use of coal while meeting Australian and International climate protection objectives might protect this contribution.

There are other wider economic factors to consider as well. For example, the present Australian coal mining, processing, and electricity generation sector is a relatively poor creator of jobs per dollar of investment – largely due to its capital intensity and reliance on imported technologies (MacGill, 2002).

[18] This program commenced in the Australian Petroleum CRC, and now continues in the CRC for GHG Technologies.

[19] The IEA (Gale, 2002) notes that GEODISC work to date has concluded "opportunities for CO_2 EOR and CO_2 storage in deep unminable coal seams are limited and only niche opportunities may occur. Also, due to the immaturity of oil and gas production in Australia, storage of CO_2 in depleted gas fields is not a near term opportunity. CO_2 storage in deep saline aquifers is, therefore, likely to be the most likely route for storing large volumes of CO_2 in Australia."

[20] The IEA (Gale, 2002) highlights the "clear dichotomy between Eastern Australia (where there are larger CO_2 sources and reservoirs with low storage capacity) and Western Australia (where there are smaller CO_2 sources and larger storage potential)".

[21] This is particularly relevant to deep saline aquifers because of our present poor understanding of their geologies.

[22] Such a release might result from seismic activity, and there is some suggestion that sequestration activities might cause geomechanical changes of this type.

Energy security:

Australia has very substantial coal reserves – perhaps 300 years or more at present rates of consumption. If secure long-term greenhouse abatement is possible, these coal reserves offer considerable energy supply security.

Comparing abatement options

A range of emission abatement approaches and associated technologies might contribute to longer-term abatement in the electricity sector. These approaches include:

- end-use energy efficiency in appliances, equipment, the built environment and industrial processes,
- lower-emission fossil fuel technologies including CCGT plant and distributed gas-fired generation options like cogeneration,
- renewable generation sources such as PV, wind power and biomass, *as well as*
- ecological or geological sequestration.

While it is beyond the scope of this paper to make a full technical assessment of how these options compare, we will briefly consider the key factors for such comparison.

Technical feasibility:

There are many proven and commercially available energy efficiency, high-efficiency fossil fuel and renewable energy technologies. Some of these technologies are already widely deployed in some regions of the world.

For example, high efficiency household appliances are increasingly available to consumers, highly efficient CCGT is now the preferred electricity plant in many parts of the world while wind power is the fastest growing electricity source in the world.

There are also speculative and as yet unproven technology developments in these fields as well. Nevertheless, the deployed technologies clearly pose far less technical risk than currently unproven approaches including coal-fired generation with geosequestration.

Delivered energy services (benefits):

The different abatement technologies offer different energy services and benefits. Energy efficiency effectively 'delivers' saved energy right where it is required – at the end-user. Distributed renewables and other small-scale generation can also deliver power where it is consumed. This avoids network losses and can potentially defer network upgrades.

For larger-scale generation, CCGT plant has advantageous investment and operational (dispatchability) characteristics compared with coal-fired plant. Some important renewable energy sources, however, have varied and somewhat unpredictable generation and this may impose additional costs on industry operation.

In terms of greenhouse abatement, energy efficiency offers abatement equivalent to the emissions of the electricity supply that is displaced. CCGT has emissions less than half of conventional coal-plant while most renewables have no emissions from operation. Lifecycle emissions can, however, be significant for some renewables – for example, some biomass and PV. In comparison, coal-fired generation with geosequestration seems likely to have emissions some 40% of CCGT, and an order of magnitude greater than promising renewables like wind.

Costs:

The difficulty in cost estimates, and hence comparisons, has been noted above. The costs of proven and commercially available technologies are reasonably well understood, but can vary greatly depending on application specific and methodological factors.

Certainly, end-use energy efficiency offers some of the most cost-effective greenhouse gas emissions reductions available – many energy efficiency options have negative abatement costs (IPCC, 2001). The cost of CCGT generated electricity depends greatly on the fuel cost. In regions with plentiful low cost gas, these plants can offer lower cost generation than coal-fired units. This is not, however, currently the case in much of Australia given very low coal costs. Renewable energy sources generally have higher direct costs than fossil fuel generation. Recent wind power and biomass projects in Australia have generation costs perhaps double coal-fired plant (CoAG, 2002) while PV is an order of magnitude more expensive.

It is difficult to make comparisons between these commercially available and increasingly deployed technology options against coal-fired generation with geosequestration. With this proviso, we present some approximate estimates of their respective abatement costs in Figure 4.

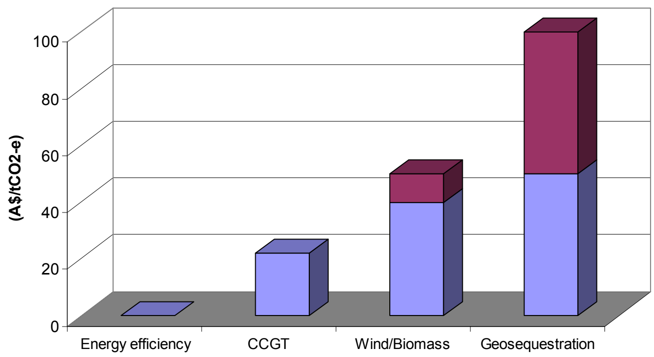

Figure 4: Approximate estimated abatement costs for different options in comparison to conventional Australian coal generation.[23]

These costs are somewhat project dependent, particularly those for wind and biomass projects. CCGT generation costs are very dependent on gas prices and availability at particular locations. Nevertheless, it is clear that coal-fired electricity with geosequestration likely faces severe cost-competition in terms of delivering abatement.

These costs may change markedly with the scale of abatement sought, as discussed in the next section. There is also potential for the costs of all these options to fall with technical progress and greater deployment. For example, the costs of wind power have fallen some 20% in the last five years (EWEA, 2002). The cost of coal-fired electricity with geosequestration is dominated by present uncertainties but could also be expected to fall with R&D, demonstration and eventually large-scale deployment.

Potential scale of abatement:

All the identified abatement options would seem to offer potentially significant abatement opportunities. The IPCC (2001) estimates that global emissions from buildings and industry could be more than halved by 2020, with most of this abatement at net negative direct costs. The UK DTI (2003) *White Paper* estimates that half of the emissions reductions required in the UK by 2020 can come from energy efficiency.

CCGT plant already makes a very significant contribution to electricity supply in some countries. For example, CCGT in the UK now supplies almost the same amount of electricity as conventional thermal plant. In Australia, however, CCGT currently represents less than 5% of installed capacity. Significant expansion will require gas supply and network development but is certainly achievable (CoAG, 2002). This does, however, raise questions about the likely scale of low-cost Australian gas reserves.

The potential scale of renewable energy deployment varies according to technology. Biomass 'fuel' resources from waste streams and agricultural crop residues are necessarily limited. The use of energy crops expands fuel availability but at a cost, and with eventual limitations from agricultural land use.

Australia has a very large potential wind resource. Most of this is in the south of the continent and land-use conflicts may arise for some of this resource. Costs may also rise as the better sites are taken up. There are also questions of how much wind can be accommodated within present electricity networks without imposing substantial costs. Nevertheless, Denmark now gets 20% of its electricity from wind and Germany almost 5% (MacGill, 2003). Many European countries and some US states have set very ambitious renewable energy targets (BCSE, 2003).

In comparison, geosequestration offers a very large but currently uncertain abatement potential. The main limitations would currently seem to lie in storage options for NSW, South Australia and, to a lesser extent, Queensland regions with high emissions.

Other societal factors:

The various abatement options pose varied environmental risks and impacts. Energy efficiency has generally low risks and no additional impacts. CCGT plant causes lower air, water and solid waste environmental harms than coal-fired generation. Some renewable technologies can have regional pollutant impacts – for example, biomass plants. They can also have potentially significant land-use impacts.

[23] Many energy efficiency options have low or even negative abatement costs (IPCC, 2001). Abatement costs for CCGT and wind/biomass projects are calculated from CoAG (2002) estimates of $/MWh costs. Geosequestration costs are averaged from published studies. Costs for all technologies will, of course, change with technical progress and increasing scales of deployment.

Geosequestration poses some rather different environmental risks from CO_2 leakage. In particular, it can never be as safe an abatement as leaving the coal in the ground.

With regard to wider economic impacts, energy efficiency and renewables offer some potentially advantageous investment and job creation opportunities (Greene, 2003; MacGill, 2002).

The energy security impacts of these abatement options also vary. Reducing energy use is one of the best energy security options available. Renewable generation can also offer longer-term energy security advantages through the use of natural renewable energy flows, although short-term variations in their availability can raise short-term energy security challenges.

Some geosequestration scenarios

There are great challenges in determining possible emission abatement futures in the longer-term given the range of present and possible future abatement technologies, and their potential technical feasibility, cost, abatement scale and other impacts. Nevertheless, scenario analysis can be a useful tool for exploring possible futures and guiding policy making.

Australian scenarios:

The PMSEIC *Beyond Kyoto* report presented some electricity sector emission scenarios as shown in Figure 5. From these, it concluded that "although these are extreme scenarios the chart indicates that within the foreseeable future, only carbon capture and geosequestration has the potential to radically reduce Australia's greenhouse signature."

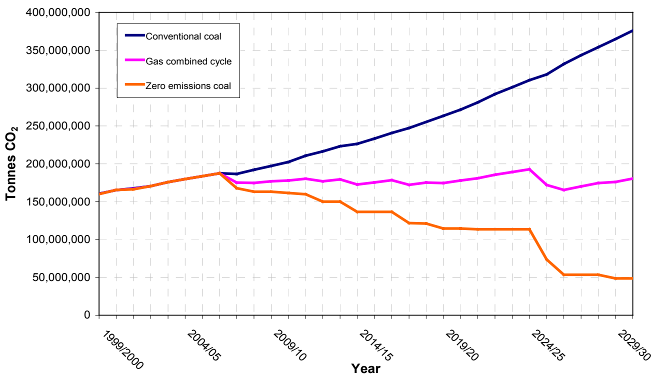

Figure 5: Abatement potential of electricity technology options (taken from PMSEIC, 2002).

It is not clear how such a conclusion was reached. The report's sequestration scenario would seem to assume that electricity use can increase some 130% over the next 30 years while all electricity generation by then comes from 'zero emission coal' Geosequestration starts to contribute to emission reductions in around 2006.

GEODISC scenarios suggest that up to 70% of present stationary sector emissions (the electricity sector presents 70% of this) might be sequestered (Allinson, 2003). Passey (2003) has explored other possible geosequestration scenarios with different assumptions of electricity demand growth and sequestration potential. These suggest generally more modest abatement potential because of the difficulties in matching suitable storage to some regions with high emissions, and likely rates of introduction.

More generally, no PMSEIC scenarios combining the range of available abatement technologies - energy efficiency, high efficiency fossil fuel generation and renewables – are presented for comparison.[24] Furthermore, there is no discussion of the very different risk profiles presented by the different scenarios.

Global scenarios:

Some preliminary global scenario work by the IEA (Gielen, 2003) using their Energy Technology Perspective (ETP) model is showing very different outcomes to those of PMSEIC, as shown in Figure 6. In particular, geosequestration plays almost no role in 2020 and only a minor role in 2040 – renewables make over twice its contribution. Other scenario results also suggest a major decline in global coal-fired electricity whether geosequestration is available or not. There are important caveats with this (and all) scenario modelling. Nevertheless, it suggests other possible technology futures where geosequestration might play a useful but far from dominant role.

There is a broad international consensus including (IPCC, 2001; UNDP, 2002 and UK DTI, 2003) that approaches combining energy efficiency, distributed cogeneration, renewable

[24] See, for example, work by CSIRO (Graham, 2003) modelling Australian energy scenarios with conventional and renewable energy sources.

energy and low-emission fossil fuelled generation hold the greatest potential for large scale emission reductions.

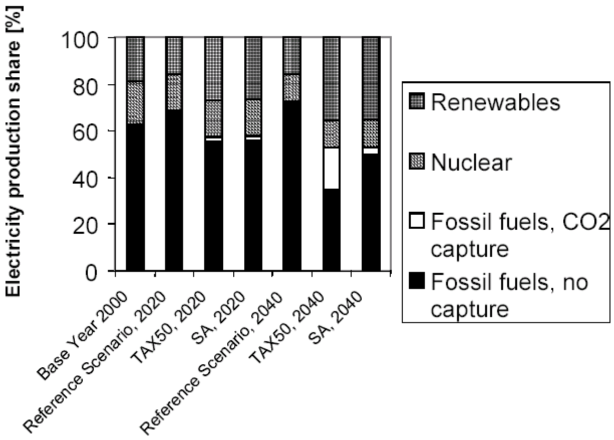

Figure 6: Electricity production from different generation options – some preliminary results from IEA ETP modelling (taken from Gielen, 2003). Note that the reference scenario assumes no CO_2 policies, TAX50 assumes an emission penalty of US\$50/tCO_2-e from 2010, and a sensitivity analysis (SA) assumes TAX50 yet excluding Solid-Oxide Fuel Cell breakthroughs (which reduce geosequestration costs).

Innovation policy implications

An important question is whether present Australian innovation policy for sustainable energy reflects both:

- the urgent need to drive major innovation in abatement technologies, and
- a risk-based technology assessment of the different abatement options in order to focus R&D and commercialisation (deployment) efforts effectively.

This answer is almost certainly no, with only modest levels of government funding support for R&D and inadequate demand-pull (market development) measures. There is also growing concern that the government is trying to pick winners with its support for geosequestration.

Geosequestration:

The Government's "principal source of independent advice on issues in science, engineering and innovation", PMSEIC, has made only two specific policy recommendations for driving innovation in emission abatement technologies. These are the establishment of a national 'near zero emissions coal generation' development and demonstration program, and the need for market instruments to drive deployment of low emission generation.

We would certainly agree with the IEA (2001) that "In view of the many uncertainties about the course of climate change, further development of CO_2 capture and storage technologies is a prudent precautionary action."

However, considerable uncertainties remain with the technical and economic feasibility of the technology. At the same time, there will be very significant financial risks in large-scale demonstration projects.

For example, 'FutureGen' is a US government led ten-year research project to build the world's first coal-fuel plant to produce electricity and H_2 with zero emissions (DoE, 2003). The capital cost of this 275MW plant and sequestration infrastructure is estimated to be around A\$1.3 billion – some four times greater (\$/MW) than conventional coal plant. The US government expects the private sector will fund only 20% of this.

There has been very limited success with large-scale demonstration programs of this type. The US Clean Coal Technology program spent around A\$1.8 billion of public funds over more than a decade to develop advanced power generation technologies. There has, however, been no commercial uptake of these technologies by US companies (Watson, 2000).

Australia has far less capability in advanced coal-fired generation and geosequestration technologies than the US, and therefore faces an even greater challenge in undertaking such demonstration projects.

There are lower risk approaches. For example, the IEA's Early Opportunities Study is focussing on existing high CO_2 purity emission sources and well understood, high value, EOR and ECBM storage reservoirs (Gale, 2002). Unfortunately, such opportunities are not likely to be available to the Australian Electricity Industry.

There are also important questions on the time required for large-scale demonstration projects to be undertaken, and then, if successful, for wide scale deployment to begin. It is difficult to envisage geosequestration entering such deployment before 2015 even with successful demonstration efforts. Market-based deployment programs only really have a role once technologies are proven and demonstrated.

Some useful innovation policy directions:

While this question lies beyond the scope of this paper, there are some useful guidelines for policy development to consider.

Local deployment delivers local abatement. Also, near commercial abatement technologies have a 'value chain' that goes from manufactured equipment through system integration, project development, installation, operation all the way to on-going maintenance. Even with imported hardware, local deployment programs can deliver local earned value, knowledge ('software') and institutional capacity ('orgware') through most of this chain. Deployment also supports local manufacturing opportunities.

R&D efforts in local technology 'software' and 'orgware' for internationally available 'hardware' can greatly support sustainable local competitive advantage. R&D efforts in novel hardware, however, generally face far greater international competition.

Innovation policy for abatement technologies:

Energy efficiency technologies have important R&D and Demonstration needs. For the many existing technologies, however, the main challenge is to drive wide deployment. This largely requires regulatory, and perhaps targeted market-based, mechanisms given that there are many highly cost-effective options that are still not being adopted by energy users.

CCGT and gas-fired distributed generation options in Australia are highly reliant on the development of gas infrastructure, and governments have an important role in this. Along with regulatory and possible incentive arrangements, there are market-based mechanisms such as the Queensland 13% Gas Scheme, or National Emissions Trading that might be used. Distributed generation also faces a range of barriers from NEM arrangements.

Renewable energy has vital R&D and Demonstration needs to seek novel technologies and breakthroughs. Commercially available renewables, however, mainly require wide scale deployment to drive down costs. MRET is a useful market-based driver for this, but is likely to require an expanded target in order to be effective. Other barriers including present NEM regulatory arrangements also need addressing.

Geosequestration requires R&D efforts. Early demonstration projects are high risk and best based on 'easier' and lower-cost opportunities with high purity CO_2 emission sources (to reduce capture costs) and well-understood sequestration reservoirs (to reduce storage risks). These opportunities are unlikely to lie in Australia's electricity sector.

Conclusions

This paper began with the question of what role geosequestration can play in greenhouse abatement in the Australian electricity industry. The answer is that we don't yet know, and we need to find out as part of a process that:

- reduces risks and maximises our emission reduction opportunities through a portfolio of technology options for abatement, that are
- supported by a coherent innovation strategy, which is
- carefully integrated within a wider energy and climate policy framework.

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