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GREENHOUSE CHALLENGE FOR ENERGY STUDY – ABATEMENT TECHNOLOGIES ASSESMENT (FIRST PHASE)

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Appendix A: TECHNOLOGY ASSESSMENT TEMPLATE - CCS

CARBON CAPTURE AND SEQUESTRATION (CCS)

INTRODUCTION

The capture and long-term storage of CO2 from fossil fuel combustion is a highly promising but, as yet, generally unproven greenhouse abatement option. Current evidence suggests that Victoria may have opportunities to sequester emissions from its coal-fired generation in relatively near off-shore geological reservoirs. Carbon capture and sequestration (CCS) technologies are therefore a key component of the *Greenhouse Challenge for Energy* Abatement Technologies Assessment.

The current status of CCS does, however, raise some major challenges for such a technology assessment. In comparison with most other energy supply and end-use technologies to be considered, CCS is:

- ***Largely unproven at this time:*** The large-scale application of integrated electricity generation, CO2 capture and sequestration in geological reservoirs has not yet been demonstrated. Although most of the key component technologies would seem to be commercially available, or at least demonstrated at some scale, they need to be successfully integrated and scaled-up. Also, there are still some major uncertainties concerning the risks of re-release of CO2 from geological storage into the atmosphere. In contrast, most of the other abatement technologies to be assessed are in use at some scale, and far better understood. Also, it seems likely that considerable expenditure will be required before we can properly understand the abatement potential of CCS.

- ***Still poorly characterised:*** While there is general agreement that at least some CCS is technically feasible, its potential specific application in Victoria is not yet well understood. The State's most promising geological reservoirs for sequestration appear to be deep saline aquifers – the least understood of the different types of reservoirs potentially available.[1] There are also some challenges given the State's dependence on brown coal generation – most efforts to develop CO2 capture technologies worldwide have focussed on black coal generation technologies.
- ***Closely integrated with some other key technologies in the assessment:*** CO2 capture and sequestration technologies have to be integrated with major point source emissions. By far the most important of these are coal-fired electricity generation plant. Furthermore, it seems likely that cost-effective CO2 capture from coal-fired generators will require the use of advanced, high capital cost and commercially unproven generation technologies. This would exacerbate the risks and capital-intensive nature of coal-fired power stations with CCS, which is likely to create problems in introducing the technology. There is also the potential to capture and sequester emissions from gas-fired and biomass generating plant, as well as some industrial processes.

This creates difficulties in the technology assessment when attempting to:

- quantify technology costs and abatement potential (and their associated uncertainties) with CCS, given important existing uncertainties in its technical feasibility and environmental effectiveness,
- describe the interactions between CCS and electricity generation options, given their very close relationship in respect of CO2 capture, and
- outline the barriers to adoption, and hence appropriate policy options to encourage greater use of CCS technology, given its very different technical status compared with most of the other abatement options.

[1] Note that we are not referring to CO2 disposal in deep ocean waters, termed ocean sequestration. This report considers only geological sequestration options.

This report attempts to address these aspects of CCS for the *Greenhouse Challenge for Energy* Abatement Technologies Assessment. It draws upon published Australian and International literature, and conversations with some relevant Australian experts. These contacts are detailed in the reference list at the end of the report.

Given the possibly very large abatement potential of CCS, we require a means to deal with the present uncertainties in the technology's specific feasibility in Victoria, and its possible costs and scale of abatement should feasibility be established. We propose the use of scenario analysis for this. Three relevant scenarios might be for CCS to be respectively proven:

- feasible and environmentally safe, teamed with advanced brown coal generation technologies at a moderate cost increase, and used to sequester the great majority of emissions from electricity generation in the State,
- of only very limited abatement potential in the Victorian and Australian context due to inappropriate geological reservoirs, and
- feasible and environmentally safe for moderate abatement within the electricity sector at a significant cost increase.

The rest of this report follows the general structure of the Technology Assessment template provided by Allen Consulting for this first phase of the abatement technology assessment within the *Greenhouse Challenge for Energy* Study.

- A – Option summary
- B – technical change evaluation
- C – Financial evaluation
- D – Interaction with other technology options
- E – uncertainty assessment
- F – Key Barriers to Adoption
- G – Preferred Policy Options to Encourage
- References, and acknowledgements

A – OPTION SUMMARY

OPTION

Carbon Capture and Sequestration.

LOCATION OF IMPACT

Assessed for both Victoria and, more generally, the Eastern Australian States.

ACTIONS DRIVING ABATEMENT

Introduction of CCS technologies to Victorian and NEM electricity generation technologies, and select industrial sources.

OPTION IS 'LEAST COST' REPRESENTATIVE OF GROUP OF TECHNOLOGICAL POSSIBILITIES

We focus on CCS offering the most likely feasibility, lowest estimated costs and highest abatement potential for:

- Victoria – CO2 capture from Latrobe Valley brown-coal electricity generators with sequestration in nearby off-shore deep saline aquifers 800 metres or more beneath the sea bed, and
- Australia with a focus on the other Eastern States – for example, on-shore sequestration of Queensland black coal generation.

There are potential niche opportunities for capture from industrial plants, and CO2 sequestration in depleted oil and gas reservoirs (perhaps delivering Enhanced Oil Recovery or EOR although this is considered rather unlikely with present Australian oil reservoirs), or in deep unminable coal (perhaps delivering Enhanced Coal Bed Methane or ECBM). However, large-scale abatement of Victorian emissions seems certain to require CO2 capture from electricity generators, and sequestration in deep saline aquifers.

POTENTIAL FOR STEP CHANGE IMPROVEMENT

CCS for coal-fired electricity generation and deep saline aquifers is currently unproven at commercial scale, although there is general agreement that at least some applications will prove feasible. A first potential step change is through a large-scale demonstration project in Victoria or another Eastern State that confirms the feasibility of the technology. If this is, in fact, successful, a second potential step change is widespread application of CCS in the Victorian or wider Eastern State electricity sector.

THRESHOLD PRICE FOR STEP CHANGE

Should available sequestration reservoirs be proven feasible and environmentally safe, and technology costs and risks are reduced through government supported R&D and demonstration programs, it seems likely that carbon prices of around US$40-50/tCO2 might see wide-scale deployment as costs fall with experience, and electricity generation stock is turned over.

B – TECHNICAL CHANGE EVALUATION

The key technical steps for CCS are capturing CO2 emissions from electricity generation plants, transporting them to a suitable sequestration site, and then injecting the CO2 into a stable geological reservoir for long-term storage.

- *CO2 capture:* There are well-established technologies used in the oil and chemical industries for capturing CO2 from gas streams. However, flue gases from conventional (pulverised fuel or PF) coal plants pose some technical challenges. Most experience has been with chemically reducing rather than oxidising streams such as flue gases, and SOx and NOx can adversely impact solvent scrubbing technologies. More importantly, there is the relatively low concentration of CO2 (typically 10-15%) and very large flue gas volumes involved – perhaps 20,000 tonnes/day for a 1000MW plant (MacGill, 2003). There are significant cost concerns with present technologies and conventional PF plant, and active R&D efforts underway into large-scale low CO2 capture through better solvents, membranes and absorbents. One promising but as yet unproven technology for simplifying CO2 capture is to increase its concentration in the flue gases through Oxygen blown combustion. This might be retrofitted to existing plants but would involve additional cost and conversion efficiency penalties.

Perhaps the most promising technology option is Integrated Gasification Combined Cycle (IGCC) with shift conversion, where concentrated CO2 can be captured prior to combustion. However, while these technologies have been successfully demonstrated, their capital costs need to be reduced, and their reliability and operating flexibility improved to make them widely competitive in the electricity market (IEA, 2001).

For brown coal, there are possible Integrated Drying Gasification Combined Cycle (IDGCC) and Mechanical Thermal Expression MTE-IGCC technologies, although these have not yet been demonstrated at scale. CO2 capture from a brown coal IGCC plant has been demonstrated in the US, although the gasification technology used is now probably obsolete.

- *CO2 transportation:* There would seem to be few technical problems in transporting CO2 by pipeline. Such pipelines are already in operation in the US and elsewhere, and the gas is relatively easy to handle (IEA, 2001).
- *CO2 sequestration in geological formations:* The main options for storing CO2 underground over the thousands of years required to provide effective greenhouse emissions abatement are depleted oil and gas reservoirs, unminable coal beds and deep saline aquifers. There is some knowledge and experience in CO2 sequestration in depleted on-shore oil and gas reservoirs. There is some limited experience with injecting CO2 into unminable coal seams. Deep saline aquifers potentially offer by far the largest geological storage capacity, and lage-scale emissions abatement from the electricity sector will almost certainly require their use in Australia. Unfortunately, this type of reservoir is also the least understood in terms of distribution and geology and, therefore, possible long term risks when used for sequestration.

Preliminary work by the GEODISC program suggests that Victoria may have some potential niche opportunities for sequestration in depleted oil and gas reservoirs, and potentially very large deep saline aquifers offshore in the Gippsland Basin (note that these aquifers are many hundreds of metres below the seabed). However, much more site-specific work is required to properly assess the sequestration potential, and its probable associated costs, for these reservoirs.

IMPROVEMENT IN OUTPUT/UNIT OF INPUT

It is not clear what efficiency (output/input) measure, if any, is appropriate for CCS. Furthermore, there is only a limited understanding of what technologies might actually be used for wide-scale deployment, let alone how they might improve over time under *market (BAU)* and *technical potential* scenarios.

CO2 CAPTURE

Operating plant efficiencies: CO2 capture will certainly reduce generating plant efficiencies. Some recent IEA estimates including improvement over the period 2010 to 2020 through the introduction of new capture technologies, are: (Gielen, 2003)

Technology (Black coal)	Efficiency	Efficiency with CO2 capture
Conventional coal PF – 2010	43	31
Conventional coal PF – 2020	44	36
Coal IGCC – 2010	46	38
Coal IGCC – 2020	46	40
Gas CCGT – 2005	56	47
Gas CCGT – 2015	59	51

Effective greenhouse emissions abatement: The IEA (2001) estimates that CO2 capture at the power plant will likely reduce emissions per unit of generated electricity (tCO2/MWh) by around 80%. This reflects both the physical limitations of capture technologies, and the increased fossil fuel consumption required due to efficiency losses as outlined above. This might be expected to improve with technical development over time, particularly with regard to these falling efficiency losses. Nevertheless, CO_2 capture is almost certain to always involve a significant efficiency penalty for electricity generating plant.

CO_2 TRANSPORT AND SEQUESTRATION

Some studies suggest that the energy, and hence emissions, required for CO_2 transport and sequestration (mainly compression of the gas) might effectively reduce the amount of CO_2 effectively sequestered by around 10% (Allinson, 2003). This will be site specific. There may also be limited opportunities to improve this over time. The energy required for compression is proportional to gas volumes. Also the emissions intensity of the power source for compression is clearly important in determining the effective emissions abatement possible with CCS.

More generally, our understanding of how effective particular sequestration reservoirs are in providing secure long-term storage of emissions can be expected to develop with R&D and demonstration programs. It is difficult, however, to quantify such possible improvements at this time.

ABATEMENT CALCULATIONS

The abatement potential of CCS is difficult to estimate because of the many remaining uncertainties in general technical feasibility of large-scale capture, and the specific suitability of sequestration reservoirs - particularly in terms of environmental safety and effectiveness.

CO_2 CAPTURE:

Large point source emissions are almost certain to be required for cost-effective capture, and there are many technical uncertainties that will have to be resolved. *For Victoria* at present, these are largely the coal generation plants in the Latrobe Valley, although there may be some suitable industrial sites as well. The GEODISC program identified 6 sources in the Latrobe Valley totalling around 55MtCO_2/yr, and 4 Melbourne sources totalling around 4MtCO_2/yr (Bradshaw, 2002).

CCS of one large conventional coal-fired generator (1000MW) in the Latrobe Valley at an overall CO_2 capture rate of 80% would represent abatement of over 7.5 $MtCO_2$/yr.

At one extreme, if all of the Latrobe Valley sources could be effectively sequestered at an overall CO_2 capture rate of 80%, this represents abatement of 44$MtCO_2$/year at present emissions. This is perhaps 40% of present State emissions. Such sequestration might be expected to represent an even greater proportion of State emissions into the future given the rapid growth of electricity related emissions in comparison with other sectors.

For Australia, preliminary estimates of the GEODISC program suggest that perhaps 50-70% of stationary energy sector emissions (around 25-35% of total emissions) might feasibly be sequestered. It must be stressed, however, that these are very preliminary estimates.

Advanced generation technologies seem likely to be required for cost-effective capture. Victoria would therefore seem to face some particular challenges given its reliance on brown coal for electricity generation, while most worldwide efforts in such advanced generation technologies are for black coal plant. For Australia, NSW and Queensland would therefore seem better placed to benefit from international efforts in CCS given their use of black coal for electricity generation.

The potential timing of such abatement will be constrained by the process of technical development required to prove up the technologies. For example, establishing a demonstration plant might take until 2010. The commercial introduction of CCS might therefore be very limited before 2020. The US DOE Roadmap, IEA modelling (Gielen, 2003) and Batelle (2003) CCS scenario work all support this view that large-scale abatement through CCS is unlikely before 2030 or beyond. Given the likely requirement for advanced coal generation technologies for cost-effective CCS, its widespread introduction may also depend on retirement of existing plant, and trends in electricity demand.

For Victoria, an average 50 year plant life for existing coal fired generation, would see Loy Yang A (2000MW) retired around 2035, Hazelwood (1600MW) around 2015, Yallourn W (1450MW) around 2028 and Loy Yang B (1000MW) around 2045. Plant refurbishment may, of course, greatly impact on the timing of such retirements.

CO2 SEQUESTRATION IN GEOLOGICAL RESERVOIRS

The greatest uncertainties with CCS lie in the sequestration of CO2 into geological reservoirs. Of the three types of reservoirs that show promise, there is considerable knowledge and experience in the technical characteristics of depleted oil and gas reservoirs, and CO2 sequestration has actually been applied for EOR. There is some limited experience with injecting CO2 into unminable coal seams, including a demonstration project for ECBM collection in the US. Deep saline aquifers potentially offer by far the largest geological storage capacity. 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. There is currently one commercial project injecting CO2 from natural gas production into a saline aquifer in Norway.

Environmental risks and abatement effectiveness: The key questions are whether reservoirs are environmentally safe, and able to store the CO2 for the hundreds to thousands of years required if they are to represent effective emissions abatement. These issues seem likely to be very site-specific, and will therefore require detailed work in order to be resolved. Such efforts to date have been very limited. Environmental risks would seem to include (MacGill, 2003):

Risk	*Possible consequences*
Slow, long-term escape of CO_2 to atmosphere	Global warming
Sudden large-scale escape of CO_2 to atmosphere	Asphyxiation of humans, animals and plants; global warming
Escape of CO_2 to shallow ground waters	Water acidification, mobilised toxic metals, leached nutrients; global warming
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 risk factors include the (Bradshaw, 2002):

- appropriate matching of neighbouring CO2 sources with reservoir storage capacity,
- ease with which CO2 can be injected into the reservoir,
- likelihood of containment for sufficient time to achieve effective abatement, and
- chance that other natural resources in the site may be compromised.

It has been argued by UK DTI (2003) that it is currently impossible to quantify with any confidence the likelihood of accidental release from CO2 sequestration sites, and particularly deep saline aquifers. This results from the lack of detailed research and field trials, and the site-specific nature of such estimates. Also, there are possible tradeoffs with these risk factors – for example, high injectivity may point to problems with containment.

Victoria: The GEODISC program has made some preliminary estimates of potential sequestration sites in Victoria, and their match to appropriate emission sources (Bradshaw, 2002; Allinson, 2003). The results that have been published suggest that Victoria has possible niche opportunities for sequestration in depleted oil and gas fields. The Otway Basin represents one such opportunity. By far the greatest potential sequestration, however, appears to be in deep saline aquifers.

The Gippsland Basin formation offshore is seen as particularly promising. It is relatively close (less than 100km) to the major emission sources of the Latrobe Valley, and may be of sufficient capacity to store decades to hundreds years of these emissions. Initial studies suggest potentially cost-effective abatement because of high emission volumes, short transport distances and good injectivity. More detailed work is clearly required, particularly in terms of likely containment of the CO2 given possibly high CO2 transport within the reservoirs. The onshore Gippsland basin seems likely to be far less suitable.

Australia: The GEODISC program estimates that Australia, overall, has some niche opportunities for sequestration in depleted oil and gas reservoirs including possible EOR sites. These are limited by capacity and availability. There are also some niche opportunities for sequestration in unminable coal seams with possible ECBM. These appear limited by low CBM production rates and lack of infrastructure. By far the largest potential, however, is again with deep saline aquifers (Cook, 2003).

Sequestration reservoirs	*Sequestration potential (years of total Australian emissions)*
Deep Saline aquifers	>1600
Depleted fields (future)	9
ECBM (future)	3
EOR	0.4
Depleted fields (current)	0.4

Preliminary GEODISC work did not identify suitable large-scale sequestration sites adjacent to the major NSW emission regions of Newcastle-Sydney-Wollongong. There is now work underway to establish the potential of the offshore Sydney basin. South Australia's major emission area of Port Augusta-Adelaide also seems to lack good sequestration options. Queensland appears to have moderate sequestration opportunities for its two major emission nodes.

Nevertheless, GEODISC findings to date suggest that Australia might potentially be able to annually sequester 50-70% of stationary point source emissions[2] (Allinson, 2003).

C – FINANCIAL EVALUATION

There are many challenges and uncertainties in making cost estimates for CCS. One difficulty, of course, is that no large-scale CCS applications for electricity generation have yet been demonstrated. Another is the likely project-specific nature of such costs. Furthermore, there would seem to be good opportunities for cost reductions over time.

Costs are incurred at each of the three steps for CCS (IEA, 2003):

- CO2 capture from the electricity generation plant – there are cost tradeoffs given easier, hence lower cost, capture from more advanced, yet expensive, generating technologies such as IGCC. Typically, capture is estimated to represent 70-80% of total costs,
- CO2 transport from the plant to the sequestration site – largely volume and distance dependent and estimated to represent typically 10% of overall costs, and
- CO2 injection into the sequestration reservoir – generally quite site specific yet typically estimated to be responsible for only 10-15% of overall costs. CO2 volumes are a significant cost determinant. Offshore injection has particular cost issues. The required depth for injection is also relevant. Sequestration projects linked with EOR or ECBM can create additional value through increased oil and natural gas production. Finally, there may be significant ongoing monitoring costs involved in ensuring that long-term storage is actually being achieved.

[2] This calculation was done by matching potential reservoirs, and their estimated capacities, to nearby point emission sources. Reservoirs had to be potentially capable of sequestering 50 years or more of these emissions.

CO_2 CAPTURE

Widely varying cost estimates are available. Some recent IEA estimates for CO2 capture assuming a number of step changes in technologies are given in (Gielen, 2003). They are presented here as additional % costs with respect to costs for the standard plant. CO2 capture is an estimated 85% in all cases.

Technology	2010	2020
CO2 Capture added to conventional black coal PF plant		
Capital costs	+70%	+70%
Operating costs	+250%	+140%
Fuel costs	+40%	+22%
CO2 capture added to black coal IGCC		
Capital costs	+45%	+30%
Operating costs	+60%	+43%
Fuel costs	+21%	+15%
CO2 capture added to Natural Gas CCGT (2005 and 2015)		
Capital costs	+100%	+100%
Operating costs	+105%	+135%
Fuel costs	+19%	+16%

Victoria: No specific cost estimates for CO2 capture appear to be publicly available for brown coal plant, and associated advanced coal generation technologies.

Australia: There are some Australian specific costing studies available, such as Dave (2000). This study assumed CO2 capture retrofitted to existing black coal fired plant, and was therefore rather project specific. There are challenges in converting international cost studies performed in US$ to Australian dollars. A simple conversion at the exchange rate of the day (from A$1 = US$0.50-0.80 over the last 10 years) is clearly problematic.

CO_2 TRANSPORT AND SEQUESTRATION

IEA cost estimates for CO_2 transport over moderate distances are US$1-3/t$CO_2$. Similarly, estimated injection costs for CO_2 are around US$1-3/t$CO_2$ for good projects (IEA, 2001).

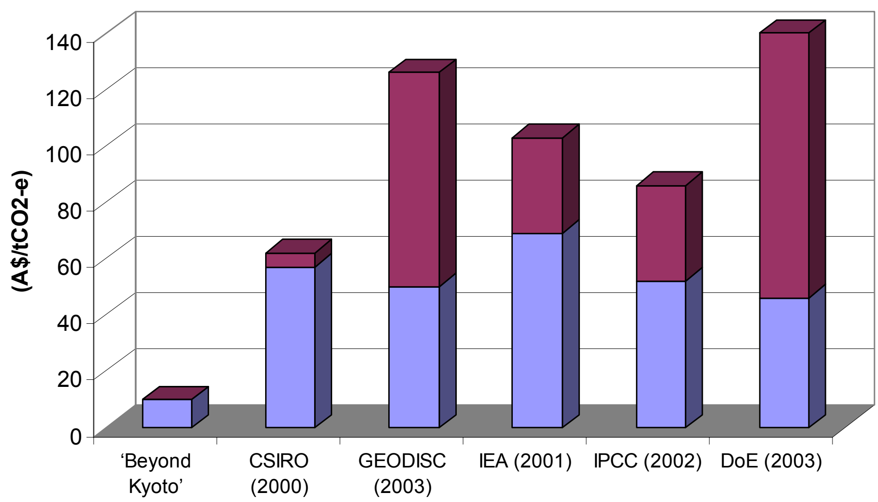
Annual operating expenses for CO_2 transport and injection are estimated to be generally of the order of 10-20% of capital expenditure.

Victoria: Preliminary estimates of the GEODISC program suggest that very large-scale abatement of Latrobe Valley emissions in the off-shore Gippsland Basin might achieve transport and injection costs of around US$5/t$CO_2$ emissions avoided. Note that such large-scale sequestration does require very high capital expenditure on associated infrastructure – the trade-off is potentially low per unit sequestration costs.

Australia: Preliminary estimates of the GEODISC program suggest generally higher abatement costs for source-sink matches elsewhere Australia – typically in the US$5-15 range. Costs for NSW would be expected to be higher than this given likely poor sequestration opportunities. Queensland would seem to face moderate sequestration costs.

OVERALL ABATEMENT COSTS

International studies of CCS costs per tCO2 avoided can vary greatly for methodological and project specific reasons as outlined in MacGill (2003). This paper also surveys recent cost estimates, with associated uncertainty ranges:



Victoria: Cost estimates from the GEODISC program suggest that large-scale CCS within Victoria may be possible at a cost of US$30-45/tCO2 – depending on capture costs estimated to range within US$25-40.

Recent estimates of the CRC for Clean Power from Lignite suggest a target cost of A$80/MWh for coal-fired generation with sequestration – equivalent to perhaps A$80/tCO2 avoided compared to conventional brown coal plant given some remaining CO2 emissions (CRC Association, 2003)[3].

Australia: GEODISC program results suggest that widespread CCS might be cost effective within the US$35-55/tCO2 range – again depending on capture costs estimated to range between US$25-40. This would seem to include sequestration of NSW and Queensland coal generation emissions.

[3] This rough estimate is based on a modern brown coal plant of emissions intensity 1.2tCO2/MWh being replaced by brown coal CCS with effective emissions of 0.2tCO2/MWh.

FUTURE COST REDUCTIONS

There would also seem to be good potential for cost reductions over time through:

- Technology improvements – perhaps novel R&D breakthroughs or steady progress,
- Economies of scale with larger plants and projects, and
- Technology learning associated with growing deployment.

However, it is difficult to put numbers to these possible cost reductions, particularly before a technology has been successfully demonstrated. At present, regardless, the cost uncertainties far outweigh possible learning effects with time and experience (Gielen, 2003).

D INTERACTION WITH OTHER TECHNICAL OPTIONS

CCS technologies have to be integrated with major point source emissions and by far the most important of these are electricity generation plant. Furthermore, CO2 capture costs seem likely to be highly dependent on the types of generation technologies in use. These costs represent some 70-80% of total CCS costs. In the longer-term, there are possible opportunities for CCS to play a key role in the development of H2 infrastructure and associated industrial processes.

CONVENTIONAL BLACK AND BROWN COAL GENERATION TECHNOLOGIES

At present, it is widely held that post-combustion CO2 capture from conventional PF plants may prove considerably more expensive than capture from advanced IGCC generation technologies. The most important reasons appears to be relatively low concentration of CO2 (typically 10-15%), low flue gas pressures and very large flue gas volumes that would need to be processed. Furthermore, energy losses with such capture can reduce plant efficiency by 30% or more.

Retrofitting CCS to existing plants may pose additional expenses given that their sites were not designed with CCS in mind. There are also less years of remaining operating life over which to recoup the equipment costs of CO2 capture. Note however that the US DOE amongst others believes that retrofitting may be potentially feasible in the future in some circumstances (CO2CRC, 2003).

Nevertheless, the evidence suggests that retrofitting CCS to Australia's existing coal-fired generation, or new conventional PF plants may not be possible.

OXYGEN-BLOWN COMBUSTION

Oxygen combustion can greatly increase the concentration of CO2 in the flue gases of conventional PF plant. This technology has not yet been demonstrated, but might provide a viable CO2 capture option for existing capacity, as well as a 'sequestration ready' option for new capacity of conventional plant. The major challenge to overcome is cost-effective production of O2 for the process (Coal 21, 2003).

ADVANCED COAL GENERATION TECHNOLOGIES

IGCC technologies are widely held to have the greatest potential for cost effective CO2 capture. The technology has been successfully demonstrated at commercial scale; however, challenges remain including long-term reliability and availability. The addition of a back-end shift reaction to facilitate CO2 capture has not yet been demonstrated on a commercial basis, and H2 gas turbines also need to be proved up (Coal 21, 2003). Such plants do promise significantly easier CO2 capture from the highly concentrated waste gas stream, and a far lower plant efficiency penalty (perhaps 20% or less) associated with this.

For Victorian Brown coal generation, the three prospective options at this stage for improving CO2 capture prospects appear to be IDGCC, MTE-IGCC and Integrated coal gasification, and integrated coal-to-oil and power generation. Brown coal's higher reactivity and moisture content than black coal may offer some important advantages for gasification, although international work including Holt (2004) has highlighted the particular challenges of low rank coals for IGCC .

The proposed IDGCC process would integrate the drying and gasification processes of wet brown coal. The hot fuel gas produced in the gasifier would be used to dry the incoming coal under pressure in a direct contact entrained flow dryer. The process can potentially reduce the cost of drying the coal, eliminate the need for heat exchanges to cool the gas and increase the power produced by the gas turbine. Oxygen blown IDGCC seems likely to be required to facilitate CO2 capture.

Mechanical Thermal Expression (MTE) offers the potential to significantly reduce the moisture content of brown coal and hence improve the efficiency of brown coal PF plants by up to 20%. This technology might be retrofitted to existing Latrobe Valley power stations. This technology also appears suitable to prepare fuel for standard IGCC plants.

Australian Power and Energy (APEL) have proposed a project to use brown coal to produce electricity in conjunction with low-sulphur liquid fuels, mainly diesel. The proposed process uses coal drying, gasification, gas to liquids and gas to electricity conversion, combined with the use of geosequestration.

While these three technologies show promise, none have yet been demonstrated at scale and are still at a relatively early stage of development.

GAS-FIRED CCGT

CO2 capture can be retrofitted to existing Combined Cycle Gas Turbine (CCGT) plant. Challenges include the very low (4%) CO2 concentration in the flue gases, although flue gas volumes are a half or less of conventional coal plant per MWh of generated electricity. The efficiency penalty with CO2 capture seems likely to be less than 20%.

There are widely varying cost estimates for CO2 capture with CCGT, however, they may be considerably higher than coal IGCC technologies (Gielen, 2003).

BIOMASS ELECTRICITY GENERATION

There are some interesting possible synergies between CCS and electricity generation from biomass. Sequestration of CO2 emissions from generating plant fuelled by carbon-neutral biomass fuels would actively remove CO2 from the atmosphere while delivering CO2 neutral energy. There are also possible synergies between technology developments in IGCC driven by coal research needs, and the potential of this technology for biomass fuels.

The generally small scale of biomass plants would seem likely to have significant cost implications for CCS unless they can share CO2 transport and injection infrastructure with other generation projects.

INDUSTRIAL 'PROCESS INTEGRATION'

In the longer-term, CCS may play a key role in the development of H2 infrastructure, and moves towards a H2 economy. The integration of IGCC technologies producing H2 for both electricity generation and a range of industrial processes can be envisaged.

E – UNCERTAINTY ASSESSMENT

Present uncertainties for CCS are dominated by the fact that large-scale application of CCS has not yet been demonstrated. Most of the key component technologies have been demonstrated. However, they must still be successfully integrated and scaled up. Also, we need to greatly improve our knowledge about deep saline aquifers, particularly in terms of environmental risks and their effectiveness in providing long-term abatement. Site-specific investigations are certain to be required. In contrast, most of the other abatement technologies to be assessed are in use, and far better understood.

Clearly, overall feasibility in the Victorian and Australian context will need to be established before uncertainties in technical change, costs and potential scale of abatement can be addressed. For the purposes of this study, then, a scenario approach may be most appropriate.

The three suggested scenarios are:

- CCS is shown to be feasible and environmentally safe, teamed with advanced brown coal generation technologies at only a moderate cost increase (eg an average 50% greater than existing new entrant costs), steadily introduced from around 2015 onwards for all new generating plant, and therefore used to sequester the great majority of emissions from electricity generation in the State by 2050. Victoria might also be sequestering emissions transported down from NSW generators,
- CCS proves to be of only very limited abatement potential in the Victorian and Australian context due to inappropriate geological reservoirs, and unexpectedly high costs in comparison with alternative technologies, and
- CCS achieves some moderate success in the post 2020 period, limited by the availability of suitable reservoirs, moderate costs (eg more than double present new entrant plant) and the high capital expenditure to develop infrastructure. Penetration by 2040 might be around 20-50% of total electricity generation.

F – BARRIERS TO ADOPTION

At this early stage of CCS development, barriers to adoption are dominated by the many uncertainties, and hence risks associated with the technology. Once these are resolved, the likely significant cost increase over conventional generation plant remains a key barrier. As often occurs with the introduction of novel, 'disruptive' technologies, the present regulatory framework is also likely to require significant change.

PRESENT UNCERTAINTIES, AND HENCE RISKS

The key uncertainties for CCS would seem to lie in its:

- environmental safety
- ability to deliver effective greenhouse abatement through long-term storage
- remaining questions on the likely technical and economic feasibility of different technologies for large-scale CO2 capture

For Victoria, there are particular issues regarding the suitability of brown coal generation technologies for CCS. The most prospective geological sequestration option for large-scale abatement is deep saline aquifer – the most poorly understood type of reservoir. Site-specific investigations will be required to address the question of environmental safety and long-term CO2 containment, as well as potential cost effectiveness (Allinson, 2003).

RELATIVELY HIGH COSTS

There is no doubt that CCS will add to the cost of carbon-based electricity generation options. Its value lies in its ability to sequester CO2 emissions. CCS therefore requires an effective 'price' on greenhouse emissions within the economy, and the expectation that this price will continue for the foreseeable future. It also requires a technology cost structure that allows it to be cost-effective at such a price for emissions, and that is able to effectively compete against other possible abatement options.

Other important cost issues are the additional costs and risks of first-of-a-kind projects. Also, CCS at any significant scale will require extremely capital-intensive infrastructure development (Coal 21, 2003). This capital intensity and 'lumpiness' of CCS on top of already capital intensive and lumpy coal-fired power station investments is a major barrier to deployment.

For Victoria, a 'price' within the economy for greenhouse emissions will be greatly impacted by international and national developments. The most prospective CCS option for the State appears to offer potentially moderate and highly cost-competitive abatement per tCO2 through very significant CO2 volumes, but will require very large capital expenditure for the infrastructure required (Allinson, 2003). There will be considerable risks associated with such expenditure as well.

INADEQUATE REGULATORY FRAMEWORK

The present Victorian and National regulatory framework may pose some significant barriers. Particular issues include how CO2 emissions are classified (eg waste) and planning frameworks for CO2 transport and the development of sequestration sites

(Tyndall Centre, 2004a). Liability is also a very important issue (WA Greenhouse Taskforce, 2003).

PUBLIC ACCEPTANCE OF CCS

Public acceptance of CCS as an appropriate emissions abatement technology is a key requirement for its successful wide-spread deployment. This acceptance should not be assumed, and is likely to be subject to clear demonstration that the technology is safe, effective and necessary, given the other available, publicly attractive, abatement technologies that might be pursued (CSIRO, 2003; Tyndall Centre, 2004b).

G – PREFERRED POLICY OPTIONS TO ENCOURAGE

All the barriers noted above would seem to require policy development by government.

Present uncertainties, and hence risks

R&D and Demonstration Programs: would seem to be a key need for CCS development in the electricity sector, in order to determine, and hopefully prove, the technical and economic feasibility of the approach. It is extremely unlikely that private industry would fully fund such efforts given the high risks and 'public good' aspects of the work.

The US DOE identifies public funding for R&D, cost-sharing by the Federal Government in first-of-a-kind demonstration of new technologies, and tax incentives to encourage widespread deployment of these demonstration technologies as the three most important aspects of Federal support (Coal 21, 2003).

The costs of such demonstration programs, and the level of public support required, are both likely to be very high. For example, the US DOE *FutureGen* project envisages the construction of a 275 MW advanced coal-fired generation plant with CCS at a overall cost of US$1billion, with as much as 80% of this funding coming from government (DOE, 2003).

Such large demonstration projects also carry high risks. For example, the US DOE 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 to date (MacGill, 2003).

Lower cost approaches to demonstration are available. For example, an Early Opportunities for CCS study by the IEA (Gale, 2002) has focussed on matching existing high purity CO2 sources (hence low capture costs) with nearby enhanced recovery projects through EOR and ECBM that offer the potential to offset at least some storage costs.

R&D has very high risks but generally low costs associated with failure and a range of wider benefits for the community.

In the Australian context, there is a need to balance our possible contributions to the international effort and first-mover advantages, with the likelihood that Australia will be a technology 'taker' for significant elements of CCS. Some R&D and most demonstration projects will have site-specific, and hence Australian focussed, elements. Local demonstrations build expertise while assessing performance under Australian conditions. Some public-private consortia efforts with associated demonstration programs have been developed here, for example CRCs. However, the sheer scale of investment required to demonstrate large-scale advanced power generation and CCS technologies is beyond anything seen to date (Coal 21, 2003). Australia has proven research expertise in coal utilisation and related areas, but only very limited experience with advanced generation technologies in comparison to the US, Japan and Europe. Lower-cost demonstration opportunities are also unlikely to lie with coal-fired electricity generation.

For Victoria, a number of advanced brown coal generation technologies are under development. The costs and risks of publicly funding commercial-scale demonstration plants for these technologies, however, is likely to be high. In terms of sequestration sites, there would seem to be very good reasons to further investigate the likely

characteristics of the offshore Gippsland Basin, and possible niche opportunities to demonstrate sequestration in oil and gas reservoirs.
In all cases, carefully targeted and well designed R&D and demonstration programs with a strong focus on managing the inherent risks of these types of activities will be required.

The management of environmental and long-term storage risks is, in the end, a political and social decision, not a technical choice. It has been argued that a comprehensive qualitative and quantitative risk assessment framework will be required, and that this is best managed through a participatory framework (CSIRO, 2003). For the community, the key issues for CCS appear to be – "is it safe, is it ethical, and is there a better way?" (CO2CRC, 2003). Governments will play a key role in addressing these community concerns.

For industry, the potential for CO2 leakage during collection, transportation or injection poses possible immediate health and environmental hazards. Leakage from sequestration reservoirs over the longer term would have important implications for the effectiveness of CCS for emissions abatement.

Liability for any such leakage is a key issue. Long-term leakage, in particular, may occur over time periods far longer than those normal when imposing end-of-life responsibilities on resource development companies for mines and petroleum projects (WA Greenhouse Task Force, 2003; WA Government, 2003). It seems inevitable that such potential legacies will eventually fall on governments to manage.

Given a future price for carbon emissions, short-term leakage from CCS infrastructure could be monitored and offset at the time of operation. Longer-term leakage is far more difficult to manage. Taking the example of ecosystem sequestration, it seems likely that the holder of carbon certificates obtained from such sources will ultimately be responsible for maintaining the sink. Certificates will also have limited validity – either 20 or 30 years (Pew Centre, 2003). Arrangements for geosequestration may require similar approaches, although it is important to note that conventional 'cap and trade' emissions trading schemes would allow the owners of CCS facilities to avoid permit requirements, rather than providing carbon certificates. The latter, however, may feature in emissions reductions trading schemes, or if project based CCS activities are included through special arrangements such as those in place for ecosystem sequestration.

One policy option is to charge producers a levy at the time of injection. This would be used to create a fund for long-term monitoring and, if required, remediation of the storage site and offset emission reductions for escaped CO2 (WA Greenhouse Task Force, 2003).

RELATIVELY HIGH COSTS

A price for greenhouse emissions within the economy: Large-scale CCS will certainly require a policy framework that creates a 'price' for greenhouse emissions within the economy. The actual price required in the longer-term is not yet clear, but seems likely to be reasonably significant given current cost estimates for CCS of around US$40-50/tCO2 avoided.

Monitoring and verification of emissions abatement, and a policy framework that recognises and rewards such abatement will be necessary.

Costs and risks of first-of-a-kind projects: While the use of market-based instruments can drive technical progress and innovation for near commercial technologies, they are alone unlikely to drive development of technologies at the demonstration phase (Coal 21, 2003; MacGill, 2003).

Capital-intensive infrastructure: The development of major infrastructure such as that required for large-scale CCS deployment may be difficult to achieve through private funding alone. CCS will exacerbate the already capital-intensive nature of the electricity industry. Financial support, or a planning framework that directs such infrastructure development while spreading costs and risks over a number of private players, seems likely to be required.

INADEQUATE REGULATORY FRAMEWORK

The present International, Australian and Victorian regulatory framework for CCS is inadequate.

As with many novel and disruptive technologies, present regulatory arrangements will need to be modified to meet these new circumstances. In particular, existing classifications (eg CO2 as waste, hazardous waste or a resource) and associated legislation and rules are almost certainly inappropriate. The major areas that appear to need addressing are:

- environmental and health risks of CCS
- questions of effective longer-term CO2 storage (and potential liabilities associated with this)
- environmental health and safety issues with CCS capture, transport and injection
- licensing of available sequestration resources, infrastructure development for CO2 transport and injection
- regional planning frameworks so that participants can potentially share infrastructure and sequestration resources (eg emission hubs)
- territorial boundary issues (for example, State emissions being injected into Federal waters)
- intellectual property arising from R&D and demonstration programs

Given present uncertainties and likely rapid technological and scientific advance, such legislation will probably have to be modified on an ongoing basis. Unfortunately, this adds a further dimension of uncertainty and therefore risk for CCS participants.

A PARTICIPATORY PROCESS

A transparent and equitable process for wide stakeholder participation in the development of CCS will be required before it can be accepted as safe, secure, appropriate and affordable (Victorian Government, 2004).

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- Guy Allinson, Andy Rigg and Greg Lyman of the CRC for Greenhouse Gas Technologies (CO2CRC)
- David Lea, APEL
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They are, of course, not responsible for any errors in this report.

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APPENDIX A

TECHNOLOGY ASSESSMENT TEMPLATE - CCS