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AN EVALUATION OF THE POTENTIAL ROLE FOR CO_2 CAPTURE AND STORAGE IN AUSTRALIA'S FUTURE ENERGY MIX

TECHNOLOGY ASSESSMENT REPORT 30

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Executive Summary

CCSD's Research Program on Future Scenarios and Options undertook in 2001/2002 to evaluate, through simulation techniques, the potential role of CO_2 capture and sequestration technology in meeting Australia's electricity generation needs to 2050.

There are four principle factors which will determine the extent to which CO_2 capture and sequestration will play a role in future efforts to reduce greenhouse gas emissions from electricity generation in Australia. These four factors are:

1. The future emission reduction burden of the Australian electricity generation sector.
2. Australia's national electricity demand growth rate.
3. The cost of alternative options to reduce greenhouse gas emissions in electricity generation.
4. The cost of CO_2 capture and sequestration.

These factors form the basis of scenarios which were developed in the report and around which sensitivity analysis revealed the following key results:

- Neither gas nor renewables alone appear to be cost-effective in meeting the required reductions in greenhouse gas emissions.

- CO_2 capture and sequestration technology is adopted under all three emission target scenarios with the main difference being the timing of the initial uptake which varied in the scenarios presented from 2010 at the earliest to 2045 in the latest instance.

- Black coal based IGCC and CO_2 capture and sequestration technology tended to complement one another so that the greater the uptake of CO_2 capture and sequestration, the greater the share of black coal based IGCC.

Overall, providing a medium to long term view is taken, there are several possible futures in which CO_2 capture and sequestration can be expected to play a significant role in future electricity generation.

It is recommended that the CCSD maintain a watching brief on the development of CO_2 capture and sequestration technology and the other identified factors. As new information becomes available, the remaining uncertainties can be slowly reduced and the future role of the technology predicted with increasing confidence.

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1.0 Introduction

A single solution to energy-related greenhouse abatement does not exist. Despite policy interventions designed to increase the opportunities for greater use of methane and renewables within the supply mix, it is unlikely that coal-based technologies can be wholly replaced within the framework of a carbon-constrained world. While process and efficiency improvements will continue to be pursued by the coal industry, serious consideration will have to be given to the CO_2 capture and sequestration option if greenhouse gas emissions from the utilization of coal are to be significantly reduced. At this stage there has been relatively little attention paid to the contributions that different technologies will make to reducing greenhouse gas emissions. It is uncertain whether CO_2 capture and sequestration technologies will play a niche role within energy systems of the future or whether such technologies will underpin the energy system.

Objective 2(ii) of the 2001/2002 program for Project 4.2 has been designed to partially fill this information gap by evaluating, through simulation techniques, the potential role of CO_2 capture and sequestration technology in meeting Australia's electricity generation needs to 2050. This will provide for CCSD participants insight into the potential role that these technologies may play in the future and as a result, to develop an appropriate research strategy.

As a first step the study develops a set of future energy scenarios for Australia. Then, by applying CSIRO Energy Technology's Electricity Market Model, the study determines the extent to which CO2 capture and sequestration can be expected to play a role in each of the scenarios. In those scenarios where CO_2 capture and sequestration does not appear to be cost-effective, the reduction in costs that would be required in order to improve the uptake of the technology is calculated.

Below we first discuss how the scenarios were developed and quantified. Following that we briefly discuss the modelling framework before presenting the results in the following section. Concluding comments and recommendations are presented in the final section.

2.0 Scenario development

In determining how to develop an appropriate set of future energy scenarios the project team first considered what existing information could be obtained from two Intergovernmental Panel on Climate Change (IPCC) reports – the *Special Report on Emission Scenarios (SRES)* and the *Climate Change 2001: Mitigation* report. In the *SRES* report, the IPCC presents several base line scenarios for world greenhouse gas emissions to the year 2100. The scenarios are developed by considering some competing assumptions regarding how the world's social, political and economic environment will evolve over the next century.

For example the *SRES* report considered the degree of political dominance between values which favor the economy versus the environment and globalization versus isolationism. They then developed a further set of themes that would be affected by which political values dominated including the degree of local versus international environmental action, the speed of technological transfer and rates of technological change. From these broad themes they were able to develop scenarios of economic growth, energy demand, environmental policy and consumer preferences. By parameterizing these scenarios and using various models, they were then able to forecast greenhouse gas emissions. The scenarios of world greenhouse gas emissions vary considerably, predicting annual emissions falling to less than 1990 emissions or, at the other extreme, increasing to around 6 times that level by 2100.

While the *SRES* report assumes that governments do not enact any specific greenhouse gas mitigation policies, the *Mitigation* report provides scenarios of how countries, through government intervention, could achieve specific emission targets. The scenarios presented in the *SRES* and *Mitigation* reports are very informative at a world level. However, there are few conclusions that can be drawn for Australia. The IPCC researchers modelled Australia as part of an aggregated OECD region. Consequently, there are no specific results reported for Australia. That is, although one scenario in the *Mitigation* report might suggest that CO_2 capture and sequestration is a good option for some part of the OECD, this does not necessarily hold true for Australia.

Despite this shortcoming, the IPCC reports provide a helpful guide as to what factors need to be considered when examining greenhouse gas issues over long time frames. This information was used to form the basis of an Australia-specific scenario analysis. By drawing on the IPCC reports, it was determined that the principle factors that need to be considered in order to examine the potential for alternative greenhouse gas reduction technologies for electricity generation are:

1. The future emission reduction burden of the Australian electricity generation sector.
2. Australia's national electricity demand growth rate.
3. The cost of alternative options to reduce greenhouse gas emissions in electricity generation.
4. The cost of CO_2 capture and sequestration.

These four factors are examined and quantified below.

2.1 The future emission reduction burden of the Australian electricity generation sector

The IPCC's *Climate Change 2001: Mitigation* report reviewed over one hundred studies which modelled the process of climate change mitigation. A summary of their findings is presented in Box 1. Paraphrasing, they found that there is no consistent framework for modelling climate change mitigation. One can set targets based on either stabilization of atmospheric concentrations, stabilization of annual emissions, stabilization of average temperatures or maximization of net benefits from emission reduction.

In some ways the emission concentration and emission level target approaches are much the same. There is only disagreement about the level of emissions required and the particular time-path. Some of the differences are simply due to the use of different climate models. However, in general, the IPCC conclude that stabilization at 450 ppmv will require emission reductions in Annex I countries after 2012 that go significantly beyond their Kyoto Protocol commitments. However, it would not be necessary to go much beyond the Kyoto commitments for Annex I by 2020 for achieving stabilization at 550 ppmv or higher.

Box 1: Review of emissions scenarios from the IPCC's *Climate Change 2001: Mitigation* report

Based on the type of mitigation, the scenarios can be classified into four categories: concentration stabilization scenarios, emission stabilization scenarios, safe emission corridor (tolerable windows/safe landing) scenarios, and other mitigation scenarios.

Scenarios for concentration stabilization account for a large proportion of the mitigation scenarios, with 47 of the 126 mitigation scenarios being classified into this type. Many scenarios of this type were quantified in the process of the EMF comparison (Weyant and Hill, 1999) where a systematic guideline was prepared for stabilization quantification. Of the 47 scenarios, two-thirds are intended to stabilize atmospheric concentrations of CO_2 at 550ppmv. The concentration of 550ppmv was used as a benchmark for stabilization in the previous studies on mitigation scenarios. This number may be related to the frequent references made to it in political discussions. The adoption by the European Union of a maximum increase in global average temperature of 2°C above pre-industrial levels is roughly equivalent to a stabilization level of 550ppmv CO_2 equivalent or 450ppmv CO_2. It does not imply an agreed-upon desirability of stabilization at this level. In fact, environmental groups have argued for desirable levels well below 550ppmv, while other interest groups and some countries have questioned the necessity and/or feasibility of achieving 550ppmv. Scenarios with levels of concentration stabilization other than 550ppmv are contained in IPCC (1990), Manne *et al.* (1995), Alcamo and Kreileman (1996), Ha-Duong *et al.* (1997), Manne and Richels (1997), and Fujii and Yamaji (1998).

The emission stabilization scenarios account for 20 of the 126 mitigation scenarios. Most scenarios of this type are intended to stabilize at 1990 emission levels in Annex I or the Organization for Economic Co-operation and Development (OECD) countries. Some scenarios have emissions stabilizing at other levels, for example, the emissions stabilization scenario of DICE (Nordhaus, 1994) aims at a level of 8GtC/yr of CO_2 and chlorinated fluorocarbons (CFCs) by 2100. Other stabilization scenarios, namely the "Safe Emissions Corridor" or "Tolerable Windows" (WBGU, 1995; Alcamo and Kreileman, 1996; Matsuoka *et al.*, 1996) and "Climate Stabilization" (Nordhaus, 1994) scenarios, determine the upper limit of emissions based on a constraint of some natural threshold, such as global mean temperature increase rate. Only a few studies are based on such scenarios.

Other scenarios based on DICE (Nordhaus, 1994), MERGE (Manne and Richels, 1997) and MARIA (Mori and Takahashi, 1998) determine the level of emission reduction based on net benefit maximization, which is estimated as the benefit produced by climatic policy minus the policy implementation cost.

450ppmv and 550ppmv are two widely modelled targets. Targets in this range are roughly the level needed to prevent a rise in average global temperatures of above 2°C, a target which has been adopted by the European Union. However, there is no international agreement on acceptable changes in average global temperatures.

It would seem reasonable to assume that the international community will eventually undertake concerted action to reduce emissions to somewhere in this target area sometime in the next 50 years. Indeed, the process could accelerate rapidly if within the next decade we begin to see harder evidence of faster than expected change in average global temperatures. Thus, although the Kyoto Protocol process has stalled, it must be expected that, even if it takes to 2020 or even 2040, there would be substantial international pressure on all counties to begin substantive climate change mitigation actions by the middle of the century.

The position taken by Australia's current government is to prepare for such an eventuality rather than to immediately commit to any targets. Currently there are a variety of government policies aimed at repositioning the electricity sector to be less greenhouse gas emission intensive (e.g. GGAP, Generator Efficiency Standards). Only a few of these, however, will ever have a large enough impact to bring about significant structural change in the electricity generation sector. Currently, the four most important of these greenhouse gas emission reduction policies are:

- The Federal government's mandatory 2 percent renewables target Act (MRET).
- The as yet un-ratified Kyoto Protocol.
- The Queensland government's Cleaner Energy Strategy which requires Queensland retailers to source 13% of their electricity supply from gas from 2005.
- The New South Wales government's proposal for enforceable per capita emission reduction targets for electricity retailers (following the failure of a voluntary scheme which operated from 1997 to 2000).

Together these policies insure against the eventuality that at some point in the period from now to 2050 there will be a requirement for Australia's electricity generation industry to significantly restrain or reduce greenhouse gas emissions and, in doing so, make a large scale shift to alternative technologies. Even if the Kyoto Protocol fails to come into force, an alternative scheme may replace it by 2050. Indeed, if the SRES scenarios are to be believed, eventually, a more stringent emission reduction scheme must be brought into place at the international level if the risk of significant global warming is to be avoided.

Assuming some sort of enforceable emission target is eventually enacted in Australia, the key remaining questions that have to be answered in order to determine what the electricity industry's emission reduction burden will be are:

- How much of the emission reduction target will be met by sectors other than electricity generation (e.g. forestry sector)? Will some sectors be exempt? (e.g. livestock sector)
- Will Australia be able to avoid undertaking all of its emission reduction domestically by taking part in various flexibility mechanisms such as Joint Implementation, international emissions trading and the Clean Development Mechanism? The Clean Development Mechanism allows Annex B parties which comprise of most developed countries to obtain certified emission reduction credits through financing emission reduction projects in non-Annex B countries. Joint implementation is very similar except that it allows the transfer of emission reduction credits between Annex B countries only. Emissions trading allows any credits an Annex B country gains either through domestic greenhouse reduction activities or through the Joint Implementation and Clean Development Mechanisms to be traded.
- Will some electricity generation companies, technologies or fuels receive special treatment or will the market be left to decide?

With these considerations in mind 'soft', 'moderate' and 'hard' electricity generation sector emission reduction targets were developed to show what appears to be the most likely scenarios and to better understand the apparent uncertainties. Various story lines were developed in order to quantify them. The scenario story lines are as follows:

- *A 'soft' emission target:*
  - Australia does not ratify the Kyoto Protocol and annual emissions continue to increase
  - In the scheme that replaces the Kyoto Protocol, Australia is successful in negotiating a relatively weaker country specific target
  - The targets are phased-in slowly and do not begin for some time
  - Australia takes part in emission trading and other flexibility mechanisms which reduce the degree to which it has to carry out emissions reduction domestically
  - Of the emission reduction that is carried out directly in Australia, the electricity sector, at worst bears an equitable burden of its emissions with forestry, transport and other sectors doing equal or more than their fair share
  - Overall, the emission target for the electricity sector in this scenario is to stabilize annual emissions to around the 2000 level by 2050 with targets phased in from 2025

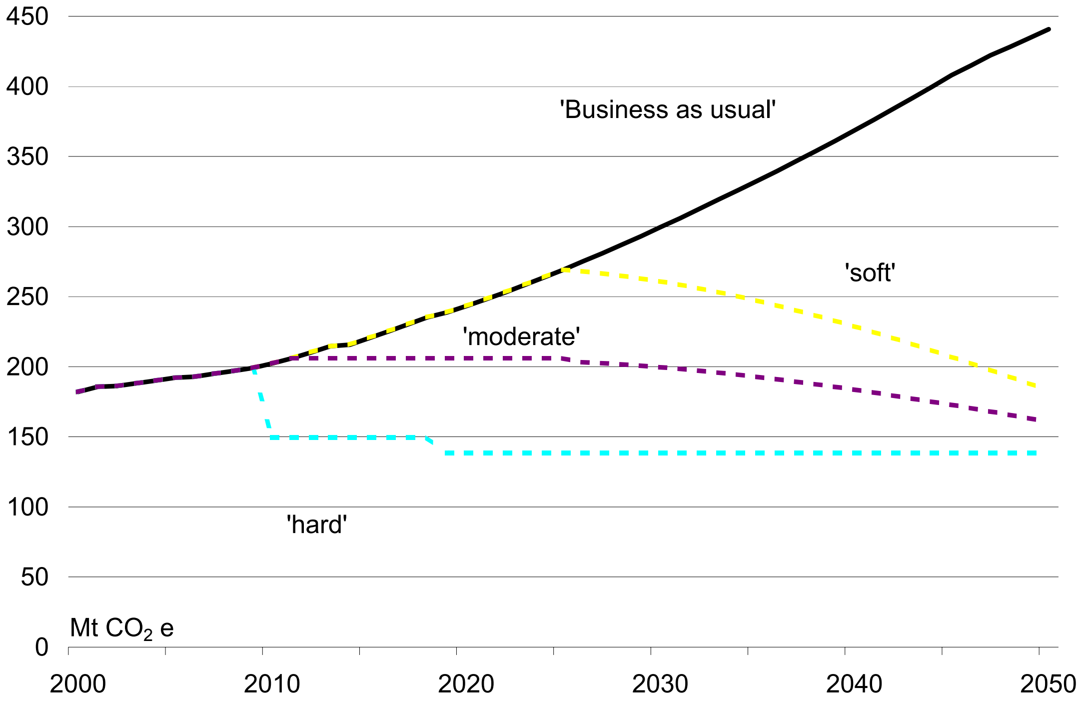
- *A 'moderate' emission target:*
  - Australia does not ratify the Kyoto Protocol but enacts its own target to stabilize (but not reduce) annual emissions beginning at around the same time as the 2008-12 commitment period but allowing more time for the cost of abatement to fall
  - In the next international emission reduction scheme Australia does choose to participate
  - The new targets are phased-in slowly and do not begin for some time
  - Australia takes part in emission trading and other flexibility mechanisms which reduce the degree to which it has to carry out emissions reduction domestically
  - The electricity sector bears an equitable share of the emission reduction burden
  - Overall, the emission target for the electricity sector in this scenario is to stabilize annual emissions to around the 2012 level and then reduce emissions to around mid-1990's levels by 2050 with this reduction target being phased in from 2025

- *A 'hard' emission target:*
  - Australia ratifies the Kyoto Protocol
  - In the scheme that follows the Kyoto Protocol, Australia is partially successful in negotiating a relatively weaker country specific target
  - The targets are phased-in a decade later
  - Australia mostly takes domestic action to meet its target as various interest groups in Australia successfully lobby for all abatement spending to take place in Australia on the basis that Australia needs to continue to nurture its growing greenhouse abatement industry
  - The electricity sector bears an equitable share of the emission reduction burden

- Overall, the emission target for the electricity sector in this scenario is to reduce greenhouse gas emissions to 108% of 1990 levels in the 2008-2012 Kyoto commitment period with a further 8% reduction required by 2020.

These three scenarios are demonstrated in Figure 1. Note, at the furthest point the ‘soft’ and ‘hard’ emission reduction targets are around 45 Mt CO_2e apart, which is about 25% of current emission levels in the electricity sector. The business as usual scenario assumes no government enforced emission target apart from those policies that are already in place (i.e. MRET, Queensland 13% gas).

Figure 1: Electricity sector specific emission reduction target scenarios versus business as usual



2.2 National electricity demand growth to 2050

Forecasts of growth in Australia’s national electricity demand are available from organizations such as the Australian Bureau of Agricultural and Resource Economics (ABARE), the National Electricity Market Management Company (NEMMCO) and the Electricity Supply Association of Australia (ESAA). Forecasts from these organizations, as well as consideration of some other factors, form the basis for national electricity demand scenarios. Growth in electricity demand reflects a variety of influences including:

- national and world economic growth rates (Australia is reliant on exports for a significant proportion of national income),
- exposure to electricity price volatility,
- changes in electrical equipment prices and the average efficiency of plant in use,

- changes in the uptake of distributed energy and cogeneration plant,
- technological change, and
- changes in consumer preferences.

Figure 2: Future growth in electricity demand: industry forecasts and scenario assumptions

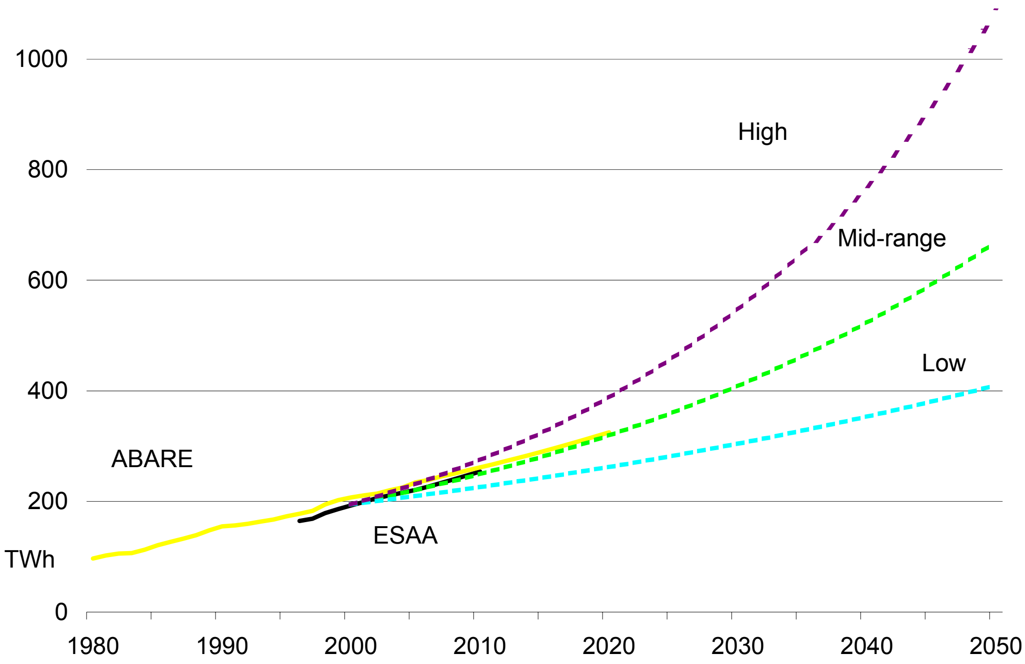


Figure 2 shows the current electricity demand historical data and forecasts from ABARE (Dickson, Thorpe, Harman, Donaldson and Tedesco, 2001) up to the year 2020 and Electricity Supply Association of Australia Limited (2001) up to 2010. The two sources differ somewhat because ABARE includes some non-grid generation that ESAA does not. Also ABARE's projection period is longer. Disregarding these differences it would seem safe to conclude that the likely mid-point for growth in electricity demand over the coming decades will be between 2.2 and 2.8 per cent. Taking this information and the discussion above into account the following three scenario story lines were developed:

- *Low demand growth:*
  - World and domestic conditions are generally unfavorable leading to slower economic growth in Australia (e.g. poor outcomes at future World trade negotiations, drought/salinity, aging society, society values gradually steer away from growth, Japanese economic collapse)
  - Electricity consumers are increasingly exposed to electricity price volatility encouraging them to engage in more off-peak generation reducing transmission losses, greater uptake of electricity storage amongst businesses

  - The uptake of distributed energy including cogeneration and direct use of gas increases substantially reducing transmission losses, providing some efficiency gains and directly displacing electricity consumption
  - Consumers increase their preference for more efficient electrical appliances and significant reductions in costs of those items are readily achieved by manufacturers
  - Overall, electricity demand growth reduces to 1.5 per cent per annum

- *Mid-range demand growth:*
  - World and domestic conditions remain similar to today with economic growth in Australia continuing at around the 3 to 4 % level, on average.
  - Electricity consumers are not significantly exposed to electricity market volatility
  - The uptake of distributed energy including cogeneration and direct use of gas is moderate to slow with minimal reductions in transmission losses, moderate efficiency gains and minor displacement of electricity consumption
  - Consumers increase their preference for more efficient electrical appliances only when it becomes abundantly clear that rapid cost savings are possible and such cost reductions are rare
  - Overall, electricity demand growth is 2.5 per cent per annum, much the same as the present

- *High demand growth:*
  - World and domestic conditions improve with economic growth in Australia increasing by 1-2 percentage points (e.g. Lifting of trade barriers on most commodities, Japanese economic recovery, society values geared towards growth and ‘consumerism’)
  - Electricity consumers are not exposed to electricity market volatility at all
  - The uptake of distributed energy including cogeneration and direct use of gas is slow with minimal reductions in transmission losses, small efficiency gains and minor displacement of electricity consumption
  - Consumers (including businesses) increase their preference for power and convenience over efficiency in their electrical appliance purchases (e.g. more powerful vacuums, refrigeration units with more electrical features, more outdoor lighting, more powerful space cooling and heating appliances used more often, greater automation and electrification of all household and business appliances)
  - Overall, electricity demand growth increases to 3.5 per cent per annum

In all three scenarios it is assumed that the elasticity of demand is -0.3. This is a behavioural characteristic which says that when the price of electricity changes, consumers will change their use of electricity in the opposite direction by around a third of the percentage by which the price changed. For example, when we model a scenario which has a deep emission reduction requirement this will increase electricity prices. Although the options are limited (e.g. substitution to gas, cogeneration, purchase more efficient capital equipment) we would generally expect a reduction in demand from the base line. In order to model this we typically form an assumption about how much demand is expected to change for a given change in the electricity price.

Unfortunately, history provides no real indication of how consumers would react to substantial price changes since electricity prices have been stable for some decades. However, -0.3 is a parameter which has been estimated by other economists as being reasonable, reflecting the difficulty which consumers would expect to have in modifying their electricity consumption behaviour. A recent notable reference is the National Institute of Economics and Industry Research (2000) which estimated demand price elasticities in the range of 0.2–0.5 for the NEM.

2.3 The cost of alternative options to reduce greenhouse gas emissions in electricity generation

Besides CO_2 capture and sequestration the options for reducing greenhouse gas emissions in the electricity generation sector include using less greenhouse gas intensive fuels (e.g. gas, renewables, co-firing), more efficient generating plant (e.g. combined cycle plant) and greater use of waste heat (i.e. cogeneration). One can think of these options as existing on a cost curve which increases the greater the emission reduction that is required. In order to know which technologies will be employed we need to know at what point each of these options lie on the curve and at what rate the curve rises.

For the purposes of this study it was not appropriate to devote significant research time to a detailed study of all the various technological options available that are not at all related to coal utilization. However, in order to determine whether CO_2 capture and sequestration will be able to compete, it was necessary to form a reasonable position on:

- The general level of costs of utilizing alternative greenhouse gas emissions reduction technologies
- The emission reductions that can be achieved
- The availability of energy resources required by each of the technologies including the evolution of fuel prices as their resources come under increasing pressure

Estimates of electricity generation costs and other considerations have been drawn from CSIRO in-house data and various literature, some of which has been generated by previous CCSD work. Nevertheless, there remains a high degree of uncertainty in this area. Again, three scenarios were developed to explore those uncertainties. The principle data uncertainties are in relation to plant cost, fuel efficiency and capacity factor and low, high and mid-range estimates of these data are reported in Table 1.

Besides assuming the technology cost and performance data in Table 1, the low, high and mid-range scenarios also assume the following:

- *Low cost alternatives path:*
  - Gas and biomass resources and suitable renewable energy sites are more readily available than expected over the proceeding five decades

Table 1: Low, high and mid-range cost scenario data for selected plant attributes in 2050

	2000	**Low cost** 2050	**Mid-range cost** 2050	**High cost** 2050
Plant cost (US$/kW)				
Brown coal-fired	1300	1000	1100	1200
Black coal pf	1100	950	1000	1050
IGCC - black coal	1500	710	950	1190
Gas simple cycle	350	200	250	300
CCGT	750	530	600	670
Solar photovoltaics	5500	1290	2500	3710
Solar thermal	2700	600	1200	1800
Fuel cell - methane	2160	400	900	1400
Wind	1000	630	750	870
Hydro	2500	2500	2500	2500
Biomass single cycle	1590	1020	1200	1380
Fuel efficiency HHV (rate)[a]				
Brown coal-fired	0.28	0.34	0.33	0.31
Black coal pf	0.36	0.47	0.45	0.42
IGCC - black coal	0.43	0.60	0.57	0.53
Gas simple cycle	0.30	0.38	0.35	0.32
CCGT	0.48	0.75	0.66	0.57
Solar photovoltaics	1	1	1	1
Solar thermal	1	1	1	1
Fuel cell - methane	0.6	0.8	0.8	0.7
Wind	1	1	1	1
Hydro	1	1	1	1
Biomass single cycle	0.30	0.45	0.40	0.35
Capacity factor (rate)[b]				
Brown coal-fired	0.87	0.92	0.90	0.88
Black coal pf	0.73	0.91	0.85	0.79
IGCC - black coal	0.70	0.93	0.85	0.77
Gas simple cycle	0.26	0.32	0.30	0.28
CCGT	0.76	0.98	0.92	0.85
Solar photovoltaics	0.19	0.31	0.27	0.23
Solar thermal	0.24	0.36	0.32	0.28
Fuel cell - methane	0.60	0.95	0.85	0.74
Wind	0.29	0.43	0.38	0.33
Hydro	0.31	0.31	0.31	0.31
Biomass single cycle	0.75	0.98	0.90	0.82

a Total plant efficiencies in terms of energy sent out per fuel energy consumed are assumed to be lower shown here due to auxiliary power consumption needs of around 5 percent.

b Refers to the likely average national demonstrable use of installed rated capacity rather than ideal or achievable performance levels. Actual estimates used in the model differ on a State basis. 2000 estimates for brown coal-fired, black coal pf, gas simple cycle, CCGT and hydro are based directly on State capacity and output data for 1999-200 reported in *Electricity Australia 2001*, published by Electricity Supply Association of Australia Limited (2001). See Appendix A and Table 4 for further details.

- *Mid-range or expected cost path:*
  - Gas and biomass resources and suitable renewable energy sites are limited such that costs of securing resources and sites of equal quality would be expected to rise gradually in the future.

- *High cost alternatives path:*
  - Gas and biomass resources and suitable renewable energy sites are not as readily available as expected over the proceeding five decades and as a result the costs of such resources or sites increases substantially with increasing use.

2.4 The cost of utilizing CO_2 capture and sequestration

CO_2 capture and sequestration will be considered as a fairly generic technology in this report. It is available at a certain cost per tonne that takes into account all use of materials, parasitic power demand, loss of plant efficiency and permanent sequestration of CO_2. Its cost varies according to the type of plant to which it is applied. Costs also vary according to how much CO_2 is required to be sequestered as suitable sequestration sites could become limited. As in the previous scenario driver there is significant uncertainty as to the future level of costs of this technology.

Table 2: Low, high and mid-range estimates for the cost of CO_2 capture and sequestration (\$A/t CO_2e)

	2000	**Low cost** 2050	**Mid-range cost** 2050	**High cost** 2050
Brown coal-fired[a]	44	36	39	41
Black coal pf	44	36	39	41
IGCC - black coal	35	20	25	30
Gas simple cycle	75	46	55	64
CCGT	75	46	55	64

a Brown coal capture technology assumed to achieve the same performance as black coal.

The following three scenarios were developed to reflect these uncertainties:

- *Low cost CO_2 capture and sequestration:*
  - The costs of CO_2 capture and sequestration decreases to the amounts shown in the low cost column of Table 2 by 2050.
  - CO_2 sequestration sites are found to be abundant and therefore the costs of sequestering CO_2 are not inflated by competition to secure such sites.

- *Mid-range or expected cost path for CO_2 capture and sequestration:*
  - The costs of CO_2 capture and sequestration decreases to the amounts shown in the mid-range cost column of Table 2 by 2050.
  - CO_2 sequestration sites are limited so that the costs of sequestering CO_2 increase by \$A0.50 per tonne for every additional 10 million tonnes of CO_2 sequestered per annum.

- *High cost CO_2 capture and sequestration:*

  - The costs of CO_2 capture and sequestration decreases to the amounts shown in the high cost column of Table 2 by 2050.
  - CO_2 sequestration sites are limited so that the costs of sequestering CO_2 increase by $A1.00 per tonne for every additional 10 million tonnes of CO_2 sequestered per annum.

3.0 CSIRO Energy Technology's Electricity Market Model

All of the scenarios developed were simulated to the period 2050 using CSIRO Energy Technology's Electricity Market Model. The model broadly conforms to most Australian and international 'bottom up' partial equilibrium optimization driven modelling approaches but was developed internally using CSIRO Energy Technology's scientific, engineering and economic expertise. Before we turn to the results, the following dot points explain some important features of the model:

- The model utilizes 'bottom up' non-linear programming techniques to mirror real world plant investment decisions by simultaneously taking into account:
  - The requirement to earn a reasonable return on investment over the life of a plant
  - That the actions of one plant effects the profitability of all other plants simultaneously and dynamically
  - That consumers react to electricity price signals
  - That the consumption of energy resources by one plant effects the price and availability of that resource for other plants and the overall cost of electricity generated
  - Electricity market policies and regulations

- The model only evaluates uptake on the basis of cost effectiveness but at the same time takes into account the key constraints with regard to the operation of electricity markets such as requirements for peak plant, current renewable energy and gas legislation, existing plant in each State and lead times in construction of new plant. It does not take into account:
  - Community acceptance
  - Environmental impacts of solvents, water usage and non-greenhouse related emissions
  - Plant siting issues other than cost
  - Location of plant within a State
  - Specific location of CO_2 sequestration sites

A short mathematical description of the model equations is available on request from Paul Graham (Paul.Graham@csiro.au).

4.0 Simulation results

Four principle factors were identified which will determine the future role of CO_2 capture and sequestration. However, the results are analyzed in the context of the first factor - the future emission reduction burden of the Australian electricity generation sector. This methodological choice reflects the fact that early results indicated that this factor was the most important, both in terms of the *timing* of the uptake of CO_2 capture and the *depth* or extent to which CO_2 capture and sequestration is adopted.

4.1 Three emission target scenarios

Initially the three alternative emission targets – 'soft', 'moderate' and 'hard'- were simulated using the mid-range data for each of the other three driving factors. The principle results are presented in Figures 3 to 5 and Table 3. The results are characterized by the following common features:

- CO_2 capture and sequestration is installed primarily at IGCC plants. Only in the 'hard' greenhouse gas emission reduction target scenario do we see significant application of the technology at black coal pf and brown coal based electricity generation, as a short term measure. This reflects the fact that, under this scenario, emission targets must be met before substantial IGCC capacity can be installed. CO_2 capture and sequestration is not utilized at any gas based electricity generation plants in any scenarios.
- New IGCC power plants, in some cases with CO_2 capture and sequestration installed, begin to be commissioned in the 2010-2020 period and by 2050 provide approximately 60 percent of electricity consumed.
- The impact of emission reduction measures is an increase of up to 65 per cent in wholesale electricity generation costs in the short term. This translates to a 25 percent increase in real retail electricity prices, decreasing to 10 per cent by 2050. Overall, the rise in electricity prices induces a subsequent 5 per cent decline in electricity demand by 2050 relative to what would have been the case with no emission limit.
- The share of gas and renewables increases to make up the remaining portion of electricity generation at the expense of brown coal.

These results reflect the fact that neither gas nor renewables alone appear to be cost-effective in meeting the required reductions in greenhouse gas emissions. Gas based electricity generation is limited by available gas resources with the model estimating that the expected doubling of share of gas-based electricity generation is accompanied by a near doubling of the price of gas-fuel to around $5.5 per GJ. Similarly, despite an expectation of rising capacity factors and falling capital costs, the potential for renewables is limited by the availability of suitable sites and resources.

The main difference between the results is in the timing of impacts. In the 'hard' emission target scenario, which assumes Kyoto ratification, CO_2 capture and sequestration is adopted as early as 2008 as an initial means of meeting the target. Around 14 percent or 25 million tonnes of coal related CO_2 emissions are captured and sequestered beginning shortly after 2008. This implies retrofitting of the technology to existing coal plants (some of which are brown coal plants). The capture rate then remains constant for around 4 years and then accelerates to an over 60 per cent rate of capture as new IGCC plants are fitted with the technology.

In the ‘soft’ greenhouse gas emission target scenario which assumes a delayed and less stringent emission abatement measure, CO_2 capture and sequestration technology is not taken up until around 2030 but increases rapidly after that point. In the ‘moderate’ emission target scenario CO_2 capture and sequestration begins to be adopted a decade earlier in 2020.

Figure 3: Characterisitcs of the 'hard' emission reduction target scenario

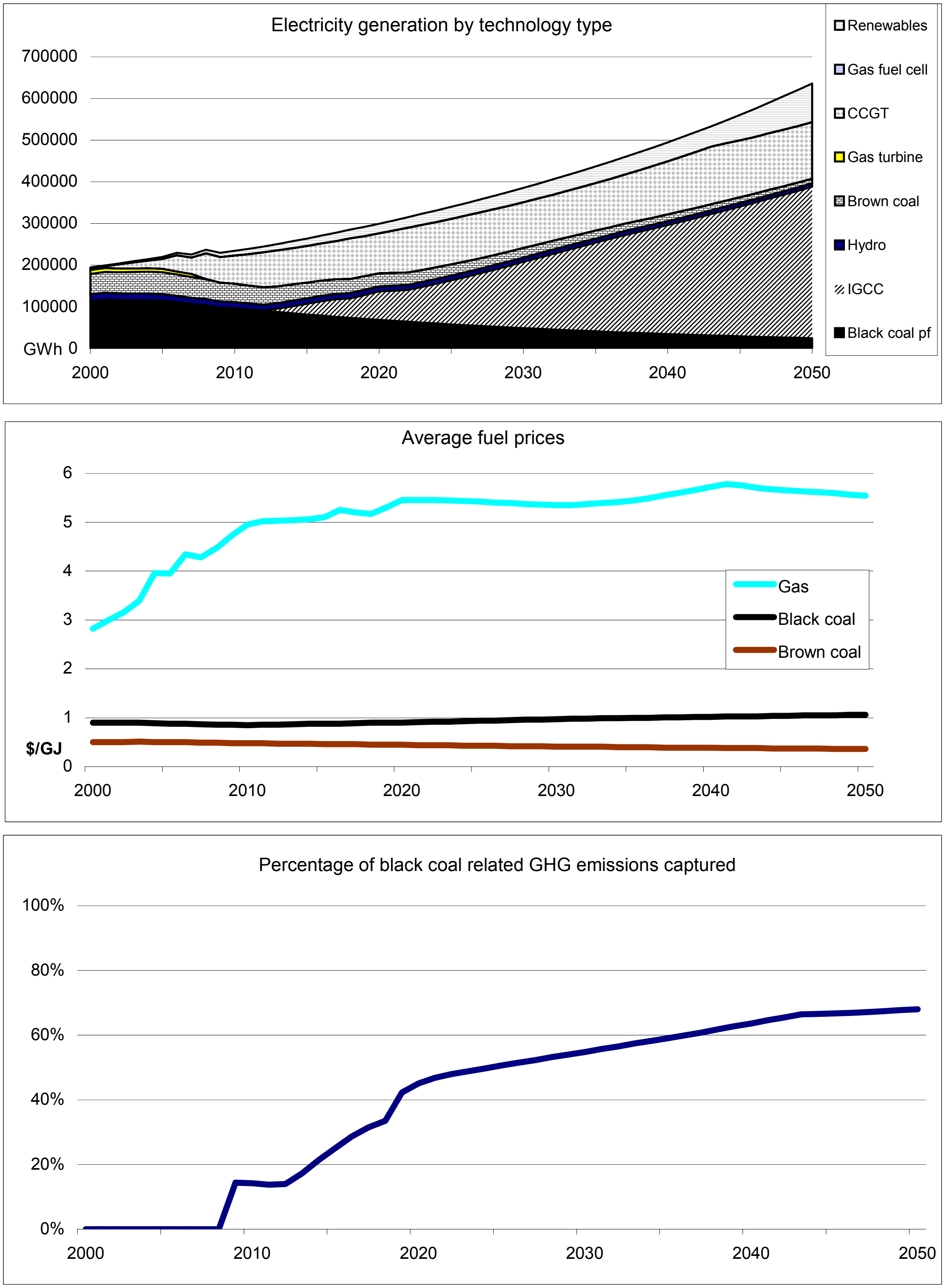


Figure 4: Characterisitcs of the 'moderate' emission reduction target scenario

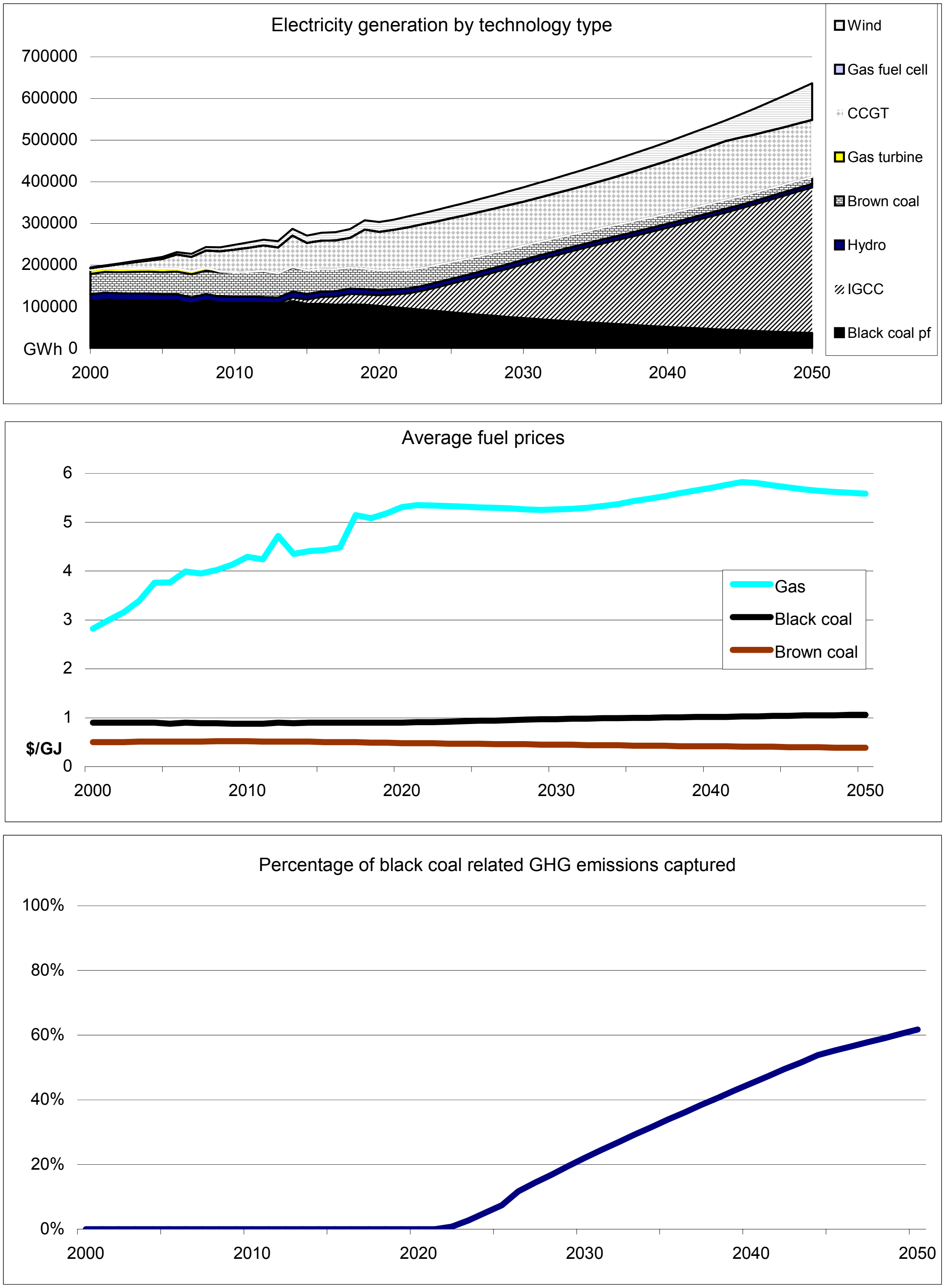
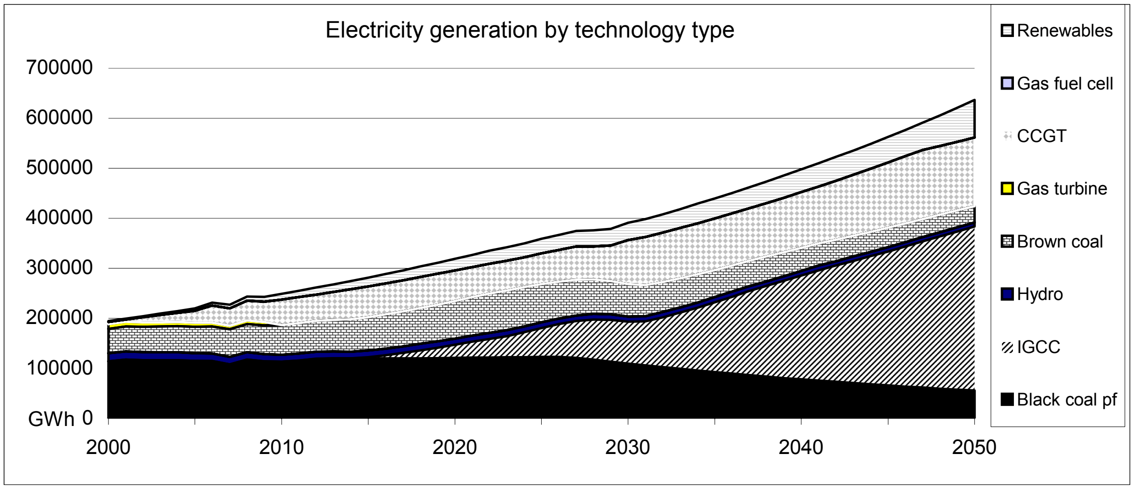
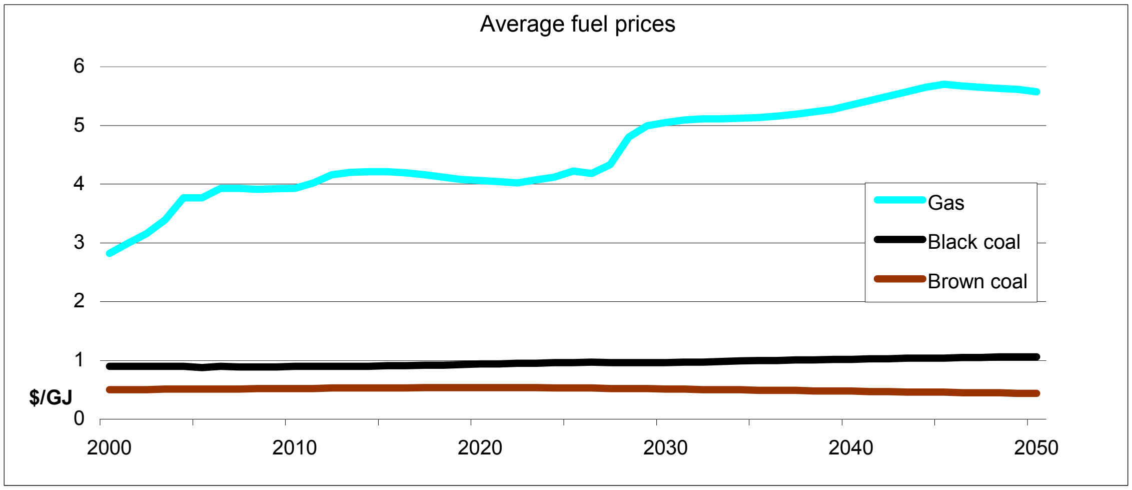


Figure 5: Characterisitcs of the 'soft' emission reduction target scenario





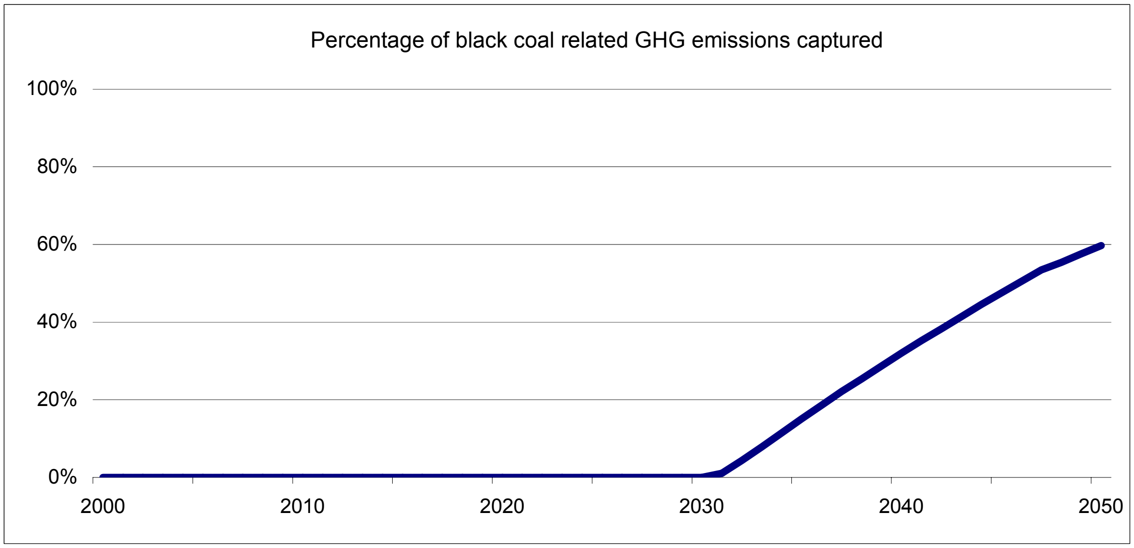


Table 3: Principals results of the 'Mid-range' data under three emission target: 'soft, 'moderate' and 'hard'.

'Soft' electricity sector greenhouse gas emission target results

		2000	2010	2020	2030	2040	2050
Average retail electricity prices	index	100.0	102.1	100.6	113.8	112.3	110.0
Net GHG emissions	Mt CO2e	182.0	200.8	242.3	261.0	229.0	183.4
CO_2 capture and sequestration	Mt CO2	0	0	0	0	63.9	147.4
CO_2 emission permit price	$A/t CO2e	0	0	0	26.2	28.2	28.1
Share of generation							
Black coal	%	58.7	45.4	46.2	49.4	57.4	60.3
Brown coal	%	25.1	23.7	23.6	16.5	9.2	5.1
Gas	%	7.2	20.6	19.1	22.5	22.4	21.6
Renewables	%	9.1	10.4	11.2	11.6	11.0	13.0
Total generation	TWh	194.6	249.1	318.9	390.8	497.3	636.3
Demand response	%	0	0	0	-4.3	-4.8	-4.9

'Moderate' electricity sector greenhouse gas emission target results

		2000	2010	2020	2030	2040	2050
Average retail electricity prices	index	100.0	102.9	117.5	116.4	113.1	110.0
Net GHG emissions	Mt CO2e	182.0	199.2	206.0	199.7	183.7	160.9
CO_2 capture and sequestration	Mt CO2	0	0	0	33.5	89.5	151.6
CO_2 emission permit price	$A/t CO2e	0	0	23.3	28.2	28.2	28.1
Share of generation							
Black coal	%	58.7	44.2	42.1	52.2	58.5	60.7
Brown coal	%	25.1	23.7	15.7	8.8	4.9	2.7
Gas	%	7.2	21.8	30.4	27.3	25.6	21.5
Renewables	%	9.1	10.4	11.8	11.7	11.0	15.1
Total generation	TWh	194.6	248.9	303.6	386.9	495.9	636.1
Demand response	%	0.0	-0.1	-4.8	-5.2	-5.1	-4.9

'Hard' electricity sector greenhouse gas emission target results

		2000	2010	2020	2030	2040	2050
Average retail electricity prices	index	100.0	125.6	122.5	117.3	113.1	110.0
Net GHG emissions	Mt CO2e	182.0	149.6	138.5	138.5	138.5	138.5
CO_2 capture and sequestration	Mt CO2	0	25.6	50.9	83.2	127.3	166.4
CO_2 emission permit price	$A/t CO2e	0	39.9	34.5	30.2	30.4	32.8
Share of generation							
Black coal	%	58.7	41.4	45.6	53.9	59.9	61.0
Brown coal	%	25.1	18.9	10.6	5.8	3.2	1.8
Gas	%	7.2	28.6	31.9	28.6	25.8	21.3
Renewables	%	9.1	11.0	11.9	11.7	11.1	15.9
Total generation	TWh	194.6	234.4	299.6	385.6	494.8	635.7
Demand response	%	0.0	-5.9	-6.1	-5.6	-5.3	-5.0

4.2 Sensitivity analysis

The three emission reduction scenarios above assumed that mid-range data estimates for the remaining driving factors would prevail. Those remaining driving factors are:

- Australia's national electricity demand growth rate
- The cost of alternative options to reduce greenhouse gas emissions in electricity generation
- The cost of CO_2 capture and sequestration

The figures on the following three pages (Figures 6 to 8) show how sensitive the trend in the uptake of CO_2 capture and sequestration technology is to changes in these three remaining driving factors. The mid-range results still correspond to the three scenarios discussed in the previous section. However, in Figures 6 to 8 we have placed them in the context of their more extreme possibilities – the high and low data assumptions. The high and low data assumptions are extreme relative to today's expectations, however, each of these assumptions is accompanied by a mildly plausible story line which was developed in section 2. For the sake of brevity, in the figures and in the discussion below, we refer to them by their shorter titles – low and high – rather than their story lines.

Figure 6 shows the results for the 'hard' emission target scenario. Here, utilization of CO_2 capture and sequestration begins in all scenarios by 2015 at the latest. As expected the increase in the uptake of CO_2 capture and sequestration proceeds most rapidly when the growth in demand for electricity is high, the cost of CO_2 capture and sequestration is low and the cost of alternative GHG reduction options in electricity generation is high.

In fact, the only scenarios which have a significant limiting effect on the uptake of CO_2 capture and sequestration is when electricity demand growth is low and the cost of CO_2 capture and sequestration is high. In the latter case the utilization of CO_2 capture and sequestration plateaus in 2035 at around 90 million tonnes of CO_2 per annum because it has become too difficult to find further low cost CO_2 capture and sequestration sites.

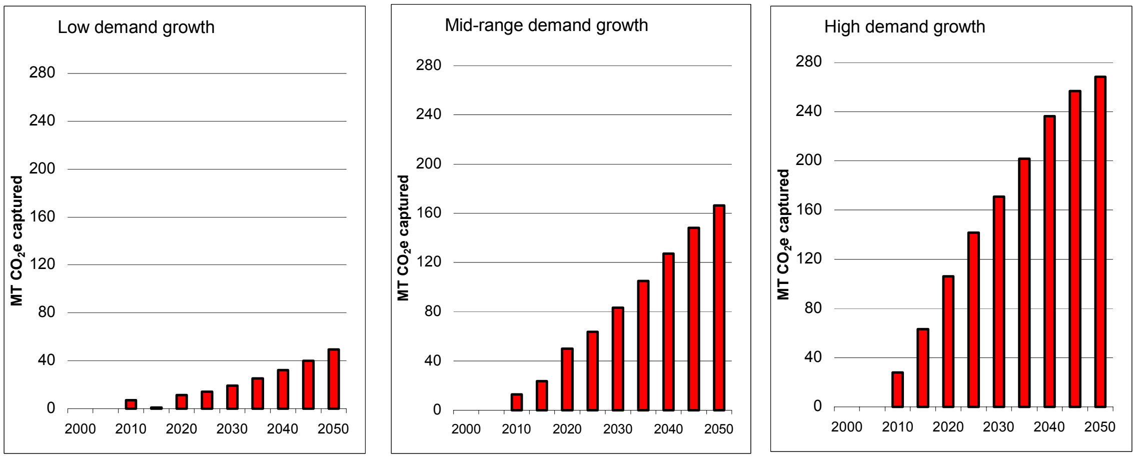
Figure 7 shows the sensitivity results for the 'moderate' emission target scenario. In this figure adoption rates are significantly less than those of the 'hard' emission target scenario. The main exception is again high demand growth. In the high demand growth scenario, adoption of CO_2 capture and sequestration technology as a greenhouse gas mitigation solution is almost as great as that in the 'hard' emission target scenario at 260 million tonnes by 2050. Jumping forward to the 'soft' emission target results in Figure 8 the effect of high growth in electricity demand is the same. Thus the rate of growth in electricity demand appears to be a very important factor regardless of the emission target.

Returning to the 'moderate' emission target scenario results we again observe that where we have a high cost of CO_2 capture and sequestration, the absolute level of CO_2 capture and sequestration is limited. The alternative assumptions regarding the cost of alternative greenhouse gas emission reduction options show that the timing of the introduction of CO_2 capture and sequestration can be affected by up to 15 years if we contrast the high and low cost cases. That is, electricity generators will tend to utilize lower cost alternatives such as some renewables and gas while they remain low cost. However, as the cost of finding additional renewable generation sites and gas resources becomes too high CO_2 capture and sequestration is adopted.

The sensitivity analysis of the 'soft' emission reduction target reveals the possibility of slow and very low uptake of CO_2 capture and sequestration technology. The slowest and lowest uptake would appear to be when demand growth is low or the cost of CO_2 capture and sequestration is high. The earliest uptake in this scenario is around 2025.

Figure 6: Scenario analysis of CO_2 capture and sequestration under the 'hard' electricity sector specific greenhouse gas emission reduction target scenario

Electricity demand growth scenarios

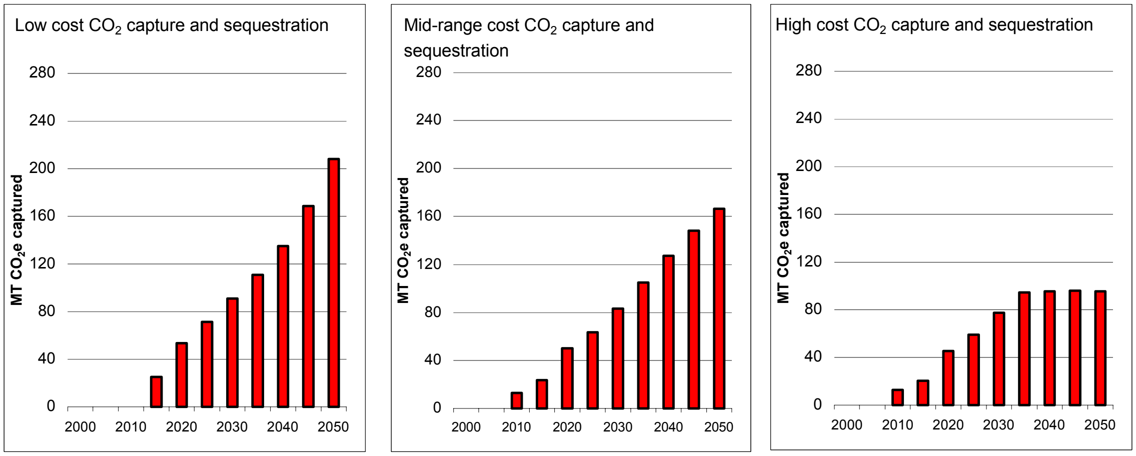


Low demand growth

Mid-range demand growth

High demand growth

Cost of capture and sequestration scenarios

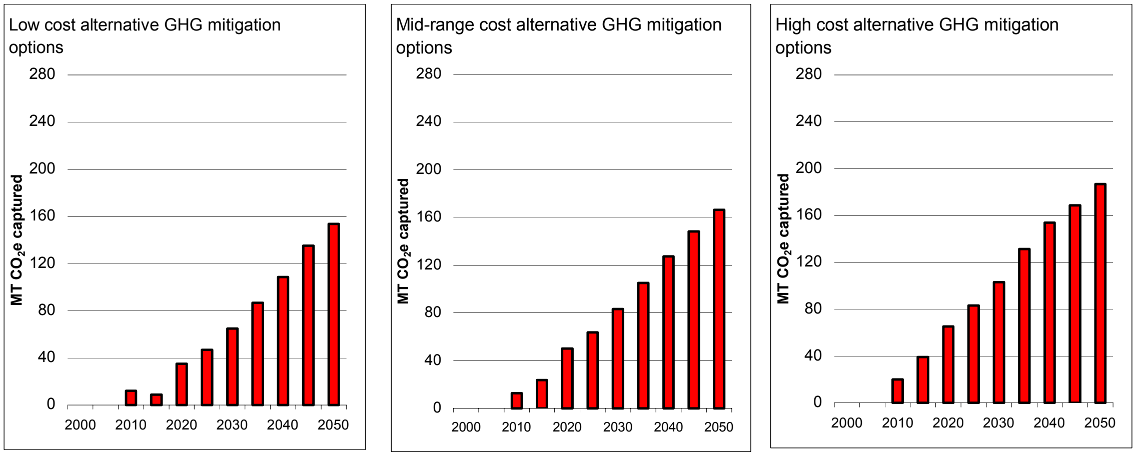


Low cost CO_2 capture and sequestration

Mid-range cost CO_2 capture and sequestration

High cost CO_2 capture and sequestration

Cost of alternative greenhouse gas mitigation options scenarios



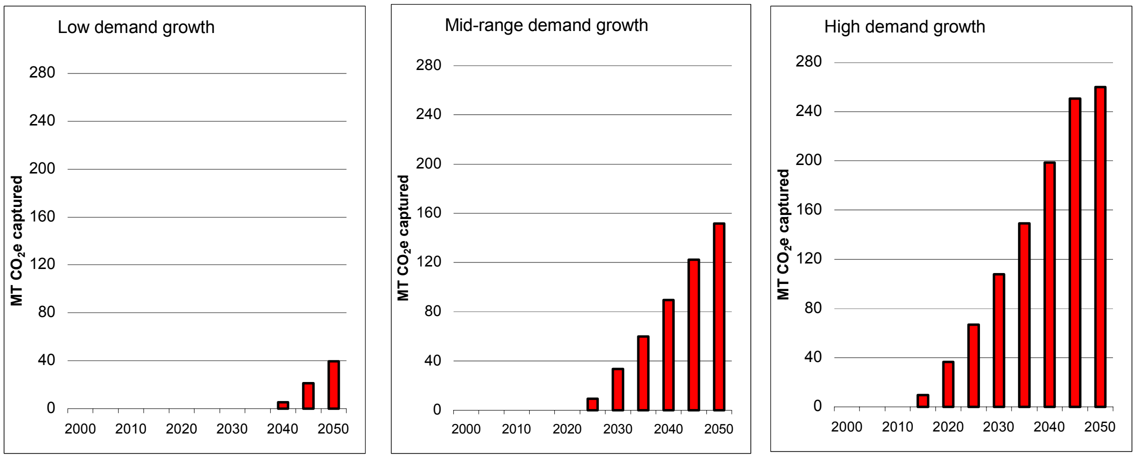
Low cost alternative GHG mitigation options

Mid-range cost alternative GHG mitigation options

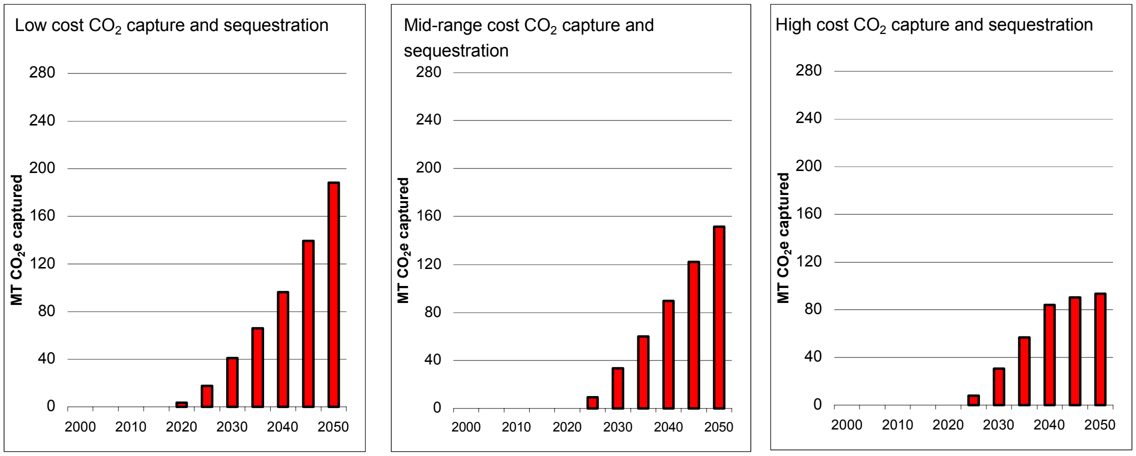
High cost alternative GHG mitigation options

Figure 7: Scenario analysis of CO_2 capture and sequestration under the 'moderate' electricity sector specific greenhouse gas emission reduction target scenario

Electricity demand growth scenarios



Cost of capture and sequestration scenarios



Cost of alternative greenhouse gas mitigation options scenarios

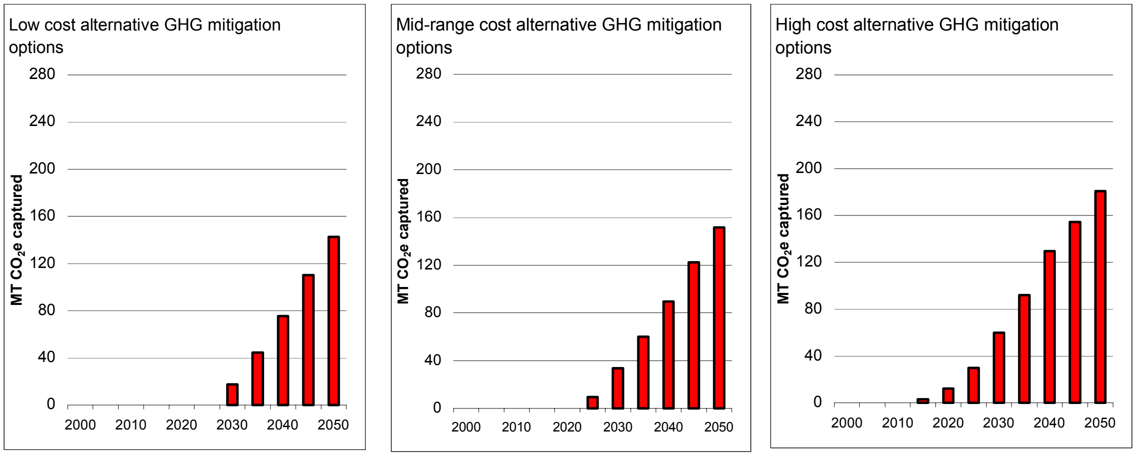
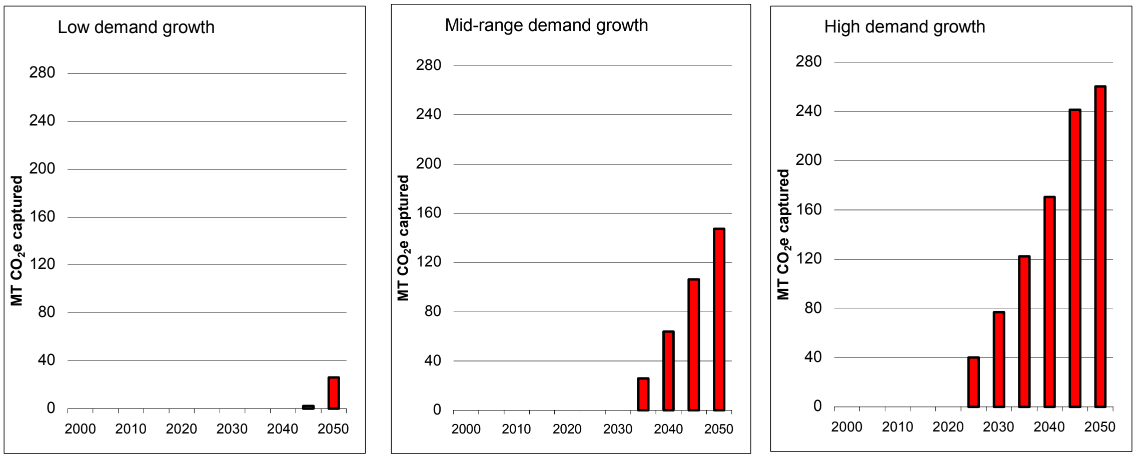
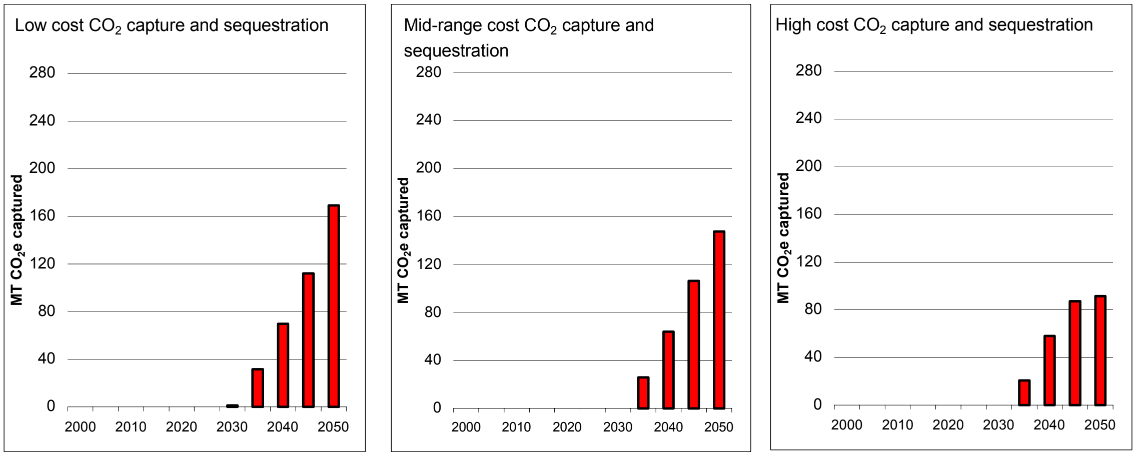


Figure 8: Scenario analysis of CO_2 capture and sequestration under the 'soft' electricity sector specific greenhouse gas emission reduction target scenario

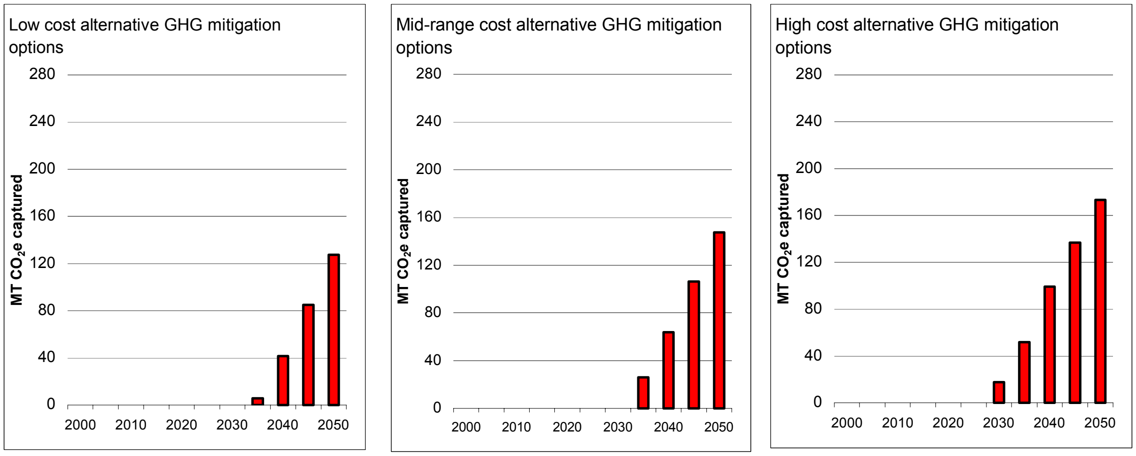
Electricity demand growth scenarios



Cost of capture and sequestration scenarios



Cost of alternative greenhouse gas mitigation options scenarios



Taking all of the sensitivity results into account the following additional observations can be made about the simulations that were carried out:

- The slowest and lowest uptake of CO_2 capture and sequestration was that the technology was not adopted until 2045 and amounted to less than 30 million tonnes per annum.
- The fastest and highest uptake of CO_2 capture and sequestration was around 30 million tonnes CO_2 as early as 2010
- The maximum sequestration space required was just over 270 million tonnes CO_2 per annum.
- In the cases where CO_2 capture and sequestration did not feature strongly, the CO_2 mitigation cost of alternative mitigation options were around $A20 per tonne CO_2 or lower and so in order for CO_2 capture and sequestration to play a larger role in these scenarios, its costs would need to be below this level.

Caution should be taken in interpreting these observations. The observations only apply to the simulations carried out which varied each of the three remaining principle factors one at a time against the three emission targets. To reduce the number of scenarios to a manageable level, it was unfortunately not possible to model all possible combinations of factors. Some combinations of factors could potentially produce more extreme results. For example, the uptake of CO_2 capture and sequestration would be at its absolute lowest and slowest if one combined assumptions of low demand growth with, a soft emission reduction target, high cost CO_2 capture and sequestration and low cost alternative greenhouse gas mitigation options *all at once*. In such a scenario CO_2 capture and sequestration may not feature at all before 2050.

5.0 Conclusions and recommendations

This study identified four principle factors which will determine the extent to which CO_2 capture and sequestration will play a role in future efforts to reduce greenhouse gas emissions from electricity generation in Australia. These four factors are:

1. The future emission reduction burden of the Australian electricity generation sector.
2. Australia's national electricity demand growth rate.
3. The cost of alternative options to reduce greenhouse gas emissions in electricity generation.
4. The cost of CO_2 capture and sequestration.

The study then developed a set of story lines which defined the upper, middle and lower bounds of our expectations about how these factors will evolve over the next 50 years. Developing these story lines has two purposes. One is to better understand the degree of uncertainty. A less plausible story line means an event is less likely. The second and primary reason for the story lines is to assist in quantifying the scenarios.

Once the scenarios were quantified, three emission target reduction scenarios were simulated – 'soft', 'moderate' and 'hard'. Each of these scenarios took as given that there would be some requirement to reduce emission in the electricity generation sector by

2050. However, they differed in terms of how soon those reductions had to be made and the ultimate level of stabilization of annual emissions required by 2050. The key results of the simulations were:

- Neither gas nor renewables alone appear to be cost-effective in meeting the required reductions in greenhouse gas emissions
- CO_2 capture and sequestration technology is adopted under all three emission target scenarios with the main difference being the timing of the initial uptake.
- Black coal based IGCC and CO_2 capture and sequestration technology tended to complement one another so that the greater the uptake of CO_2 capture and sequestration, the greater the share of black coal based IGCC.
- When emission targets are 'soft' to 'moderate', growth in electricity demand and the costs of technological alternatives to CO_2 capture and sequestration are also crucial in determining the timing of the uptake of CO_2 capture and sequestration.

Sensitivity analysis revealed these additional observations:

- The adoption of CO_2 capture and sequestration technology may plateau as increasing difficulties in finding sequestration sites erode its competitive position.
- High growth in electricity demand ensured a strong role for CO_2 capture and sequestration regardless of the emission target scenario
- CO_2 sequestration space required was between 30 and 280 million tonnes CO_2 per annum by 2050.
- The cost of CO_2 capture and sequestration would need to fall below $A20 per tonne CO_2 to improve the uptake of the technology in the scenarios where the technology did not appear to be a significant part of the overall mitigation response.

Overall, providing a medium to long term view is taken, there are several possible futures in which CO_2 capture and sequestration can be expected to play a significant role in future electricity generation. As new information arrives about the various factors discussed above, the remaining uncertainties can be slowly reduced and the future role of the technology more accurately predicted. In closing, the results of this report support the following two recommendations:

Recommendation 1**:** That the CCSD continue to maintain a watching brief on the development of CO_2 capture and sequestration technology.

Recommendation 2**:** That the CCSD continue to conduct scenario analysis as means of understanding the role of various technologies of interest and monitoring those factors which are most important in shaping the structure of a sustainable electricity and coal utilization industry.

5.1 Issues for further research

The following issues were identified as areas where current knowledge is lacking and more information would improve our knowledge of the market prospects for CO_2 capture and sequestration technology:

- Evaluation of the optimal economic scale for CO_2 capture and sequestration technology (e.g. 90% versus 30% CO_2 capture).
- Comparing the location and size of sequestration space with the location of desirable capture sites.
- Evaluation of the optimal CO_2 capture and sequestration partner technology.

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Appendix A

Table 4 sets out annual capacity factors by State and electricity generation plant type. The data is based on Electricity Supply Association of Australia Limited (2001) and was calculated as the reported energy delivered divided by the reported installed capacity when multiplied by the number of hours in a year.

Table 4: Annual capacity factors for 1999-2000

	NSW	VIC	QLD	SA	WA[a]	TAS	NT	Snowy[b]	States average
Hydro	0.31	0.13	0.68	-	0.37	0.50	-	0.17	0.31
Steam	0.60	0.82	0.71	0.42	0.54	0.00	-	-	0.66
Coal	0.60	0.87	0.72	0.65	0.54	-	-	-	0.70
Gas	-	0.20	-	0.29	0.54	-	-	-	0.26
Oil	-	-	-	-	-	0.00	-	-	0.00
Multi-fuel	-	-	-	-	0.54	-	-	-	0.54
Internal combustion	-	-	-	-	0.24	0.29	0.38	-	0.31
Gas turbine	0.00	0.05	0.04	0.05	0.15	-	0.16	-	0.08
Gas	-	0.05	0.22	0.05	0.15	-	0.14	-	0.10
Oil	0.00	-	0.01	-	0.15	-	0.24	-	0.02
Multi-fuel	-	-	-	-	0.15	-	-	-	0.15
Combined cycle	0.71	-	0.69	0.86	-	-	0.78	-	0.76
Gas	0.71	-	0.69	0.86	-	-	0.78	-	0.76
Coal	-	-	-	-	-	-	-	-	-

a Not enough information was available to separate with confidence Western Australian plant capacity factors on a fuel basis.

b Based on 3006 MW of installed hydro plant whilst hydro capacity factors in New South Wales and Victoria relates to 25 and 453 MW of installed plant respectively.