CENTRE FOR
LOW EMISSION
TECHNOLOGY

Low emission technologies with geosequestration in the context of a transformed energy infrastructure to mitigate global climate change

Centre for Low Emission Technology

Position Paper

The Centre for Low Emission Technology (cLET) is an unincorporated joint venture (UJV) partnership of the State of Queensland through the Department of State Development Trade and Innovation, CSIRO through its division of Energy Technology and the Energy Technology Flagship Program, Australian Coal Research Limited, Stanwell Corporation Ltd, Tarong Energy Corporation Ltd and the University of Queensland.

The mission of the
Centre for Low Emission Technology is:

"Progressing the development of enabling technologies for the production of low emission electricity and hydrogen from coal"

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Foreword

This position paper by the Centre for Low Emission Technology (cLET) examines the role of low emission technologies with geosequestration in a future transformed energy infrastructure.

A future transformed energy infrastructure would be one that relies on the production and use of electricity and hydrogen energy vectors with near zero or no carbon emissions into the atmosphere. Such a system is essential to avoid dangerous human interference with the earth's climate.

The analysis presented in this paper begins with the consensus that fossil energy use is the main cause of the rising atmospheric concentration of carbon dioxide (CO_2) responsible for global climate change.

Despite the challenges posed by climate change, the International Energy Agency's (IEA) world energy outlook shows that over the next 25 years, fossil fuels will continue to dominate primary energy demand. Both fossil fuel use and CO_2 emissions are expected to increase in absolute terms by more than 50% from current levels.

The IEA outlook shows that efforts by nations to pursue energy efficiency, conservation and the increased use of alternative energy technologies (principally renewable energy), would only lead to a very modest reduction in fossil energy use and CO_2 emissions relative to the business as usual case. The reduction in emissions anticipated from aggressive adoption of these policy measures will not meet any climate stabilisation goal.

Moreover, the historical trend in the use of fossil fuels, the current situation presented by rising oil and gas prices and energy security concerns, suggests that coal will play a greater role in the future fossil energy mix.

Recognising the insatiable global demand for fossil fuels, this paper presents an analysis which argues that a transformation away from the current pattern of fossil energy production, distribution and end use, to a new energy system is needed. In order to address the climate challenge, the production and use of electricity and hydrogen vectors with near zero or no carbon emissions into the atmosphere would become essential elements of the transformed energy infrastructure.

Amongst the options available, low emission fossil fuel technologies together with other alternative energy options can be the source of production of these decarbonised electricity and hydrogen energy vectors. In producing these energy vectors, low emission technologies with CO_2 capture and storage (CCS) would achieve deep reductions in emissions. CCS technologies would also provide a transitional pathway without serious disruption of the existing global economy and energy infrastructure.

Ultimately, as the fossil fuel resource base is depleted, increasing deployment of renewable energy technologies would also serve as a source for the production of electricity and hydrogen. The future will require the pursuit of a strategy based on a balanced portfolio of energy technology options, which together with energy efficiency and conservation, will establish a climate sustainable energy infrastructure.

A review is presented in the paper of the current status of CCS technologies based on the special assessment report on CO_2 Capture and Storage recently published by the Intergovernmental Panel on Climate Change (IPCC).

It is apparent from this review that CCS technologies currently operate in niche applications in a mature market where the capture costs are low and where incentives exist for CO_2 utilisation. For such niche applications, a potential capacity to remove and store about 360 million tonnes per year (Mt/y) of CO_2 has been identified in the IPCC report.

However, challenges requiring technology development to reduce costs exist for applications of CCS in power generation, industrial and transport sectors. The implementation of CCS in these sectors that are predicted to account for more than 60% of the CO_2 emissions anticipated from energy use in 2030, could make a very significant contribution in meeting climate stabilisation goals. Moreover, sufficient global capacity exists to store several hundred years of emissions from these sectors in geological formations.

The IPCC report also notes that early deployment of CCS technologies in the power generation and industrial sectors would support ‘learning by doing’ to reduce the costs of carbon abatement by 20-30%. In the longer term, higher cost reductions are achievable with the implementation of break through concepts currently in the research and development (R&D) phase.

Lastly, against this back drop of the challenges and potential opportunities for low emission technologies with CCS, this paper provides context for the Centre for Low Emission Technology’s R&D program and its forward plans. These plans are elaborated in the paper. They have a clear focus aimed at facilitating the development of advanced Integrated Gasification Combined Cycle (IGCC) based clean coal technologies for decarbonised electricity and hydrogen production.

I am sure you would agree that cLET’s mission squarely tackles the challenges ahead for implementing a future climate sustainable energy infrastructure that builds on Australian assets and skills.

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Abbreviations

ABARE:	Australian Bureau of Agricultural and Resource Economics
ASU:	Air Separation Unit
BAU:	Business as usual
CCS:	CO_2 Capture and Storage
CFD:	Computational Fluid Dynamics
cLET:	Centre for Low Emission Technology
CO:	Carbon monoxide
CO_2:	Carbon dioxide
CSLF:	Carbon Sequestration Leadership Forum
ECBM:	Enhanced coal bed methane recovery
EGR:	Enhanced natural gas recovery
EOR:	Enhanced oil recovery
Gt/y:	Giga (billion) tonnes per year
GWe:	Giga (billion) watts electrical
H_2:	Hydrogen
H_2O:	Water
H_2S:	Hydrogen sulfide
IEA:	International Energy Agency
IEA GHG:	International Energy Agency Green House Gas R&D Program
IEA WEO:	International Energy Agency World Energy Outlook
IGCC:	Integrated Gasification Combined Cycle
IPCC:	Intergovernmental Panel on Climate Change
kg/h:	Kilograms per hour
LHV:	Lower heating value
LNG:	Liquified natural gas
Mt/y:	Mega (million) tonnes per year
N_2:	Nitrogen
NCRIS:	National Collaborative Research Infrastructure Strategy
NGCC:	Natural Gas Combined Cycle
Ni:	Nickel

NLEGTF: National Low Emissions Gasification Test Facility

O_2: Oxygen

OECD: Organisation of Economic Cooperation and Development

Pd: Palladium

PJ: Peta (quadrillion) Joules

ppmv: Parts per million by volume

S: Sulphur

SCR: Selective Catalytic Reduction

Executive Summary

CO_2 emissions into the atmosphere are continuing to rise and the main contributor to the rising atmospheric concentration is the use of fossil fuels.

Human economic activity is currently 90% dependent on fossil fuels and the International Energy Agency's World Energy Outlook (IEA WEO 2004) predicts that over the next 25 years, global primary energy demand will increase by over 50%, with 83% of the increase in the future energy demand being provided by fossil fuels. Over two-thirds of this increase in energy demand is also expected to come from developing countries, particularly as these countries raise their living standards. With the increasing use of fossil fuels, CO_2 emissions into the atmosphere are expected grow by over 50% from 24 to 37 billion tonnes per year (Gt/y) in 2030.

The corresponding data for Australia shows that by 2030, energy consumption will increase by more than 60%, with fossil fuels providing over 94% of our primary energy needs (ABARE, 2005). A significant increase in greenhouse gas emissions from this pattern of domestic energy use is also anticipated.

A transformation away from fossil fuel use in the current global economy to prevent climate change is not an easy task. It will require many decades of concerted national and global action to implement the use of a new energy system with near zero or no carbon emissions into the atmosphere. It is a process that has yet to begin to be collectively addressed by the global community as a serious need.

There are three recognised approaches to reduce CO_2 emissions from current and future energy use:

- Reducing energy use through conservation and energy efficiency measures;
- Deploying alternative energy technologies such as renewables and nuclear;
- Fuel switching to lower carbon fuels and deploying low emission fossil fuel technologies with CO_2 Capture and Storage (CCS).

The first and second options involve reducing fossil fuel consumption by reducing energy demand and by deploying renewable energy and nuclear fission technologies with low or no CO_2 emissions. The third option enables reductions in greenhouse gas emissions to be achieved with substitution of less carbon intensive fossil fuels, or by removing between 85-95% of CO_2 emissions otherwise released into the atmosphere through the capture and underground storage *(geosequestration)* of CO_2.

The IEA WEO 2004 has also evaluated an alternative energy scenario that examines the impact of aggressive policy measures promoting the increased use of renewable energy technologies, energy efficiency and conservation in reducing global primary energy demand. Whilst predicting a modest 10% reduction in fossil energy use and an overall reduction of 16% in global CO_2 emissions without any adverse impact on the global economy relative to the business as usual (BAU) case, the scenario does not meet any climate stabilisation goals.

Although low emission fossil fuel technologies with CCS were not evaluated as an option in the IEA BAU and alternative energy outlook scenarios, it is an emerging energy technology option being deployed commercially today in the Sliepner gas field in Norway, In Salah in Algeria, and in the Weyburn oil field in Canada. These commercial applications of CCS technology have been initiated to demonstrate the safe storage of CO_2 and remove about 3 million tonnes per year (Mt/y) for climate change mitigation purposes.

For the effective use of CCS technology for climate change mitigation, widespread implementation of infrastructure with trunk pipelines linking large stationary, point sources (with CO_2 capture) to storage sites with a capacity to retain several decades of emissions from these point sources, would be needed. A survey of the global storage capacity for CO_2 shows an ability to retain a significant proportion of several hundred years of CO_2 emissions from large point sources in the power generation and industrial sectors within depleted oil and gas fields, deep unmineable coal seams and underground saline reservoirs. Emissions from fossil fuel use in these sectors would represent over 60% of the anticipated global CO_2 emissions in 2030.

CO_2 storage in depleting oil and gas fields and unmineable coal seams can produce commercial benefits from enhanced oil recovery (EOR), enhanced natural gas recovery (EGR) or coal bed methane recovery (ECBM; or enhanced coal seam methane recovery). These benefits could partially offset the cost of deployment of CCS technology. However, a much larger option on a scale that could address the mitigation of global climate change is in the underground storage in saline reservoirs, but this option does not yield any commercial benefits to offset the cost of CCS.

Following the initial oil price shocks of 2-3 decades ago and concerns about the security of energy supply *(also acutely relevant currently)*, the global trend has been to rely on natural gas and coal as the leading fuel options for power generation and the production of hydrogen (H_2), chemicals, and more recently, liquid transportation fuels. However, the rising price of natural gas in several regions of the world coupled with higher demand, is expected to shift the balance towards the future use of coal in these sectors.

Coal, the most abundant global fossil energy resource with reserves that exceed the combined resources of oil and gas, is relatively well distributed and accessible in many regions of the world, and unlikely to face concerns about the cost and the security of energy supply that nations with a high dependency on oil and gas are likely to endure. As a result of concerns about the cost and security of energy supplies, it is highly likely that the near to mid-term diversification of the global energy mix towards coal *(and the continuing dominance of oil and gas in this diversified mix)*, would require the deployment of CCS technology to achieve deep reductions in CO_2 emissions to mitigate climate change.

In the longer term, transformation of the current global energy infrastructure to the comprehensive use of decarbonised electricity and hydrogen energy vectors across all sectors of the global economy would be necessary to achieve significant reductions in greenhouse gas emissions into the atmosphere. *The use of fossil fuel technologies with CCS that could remove 85-95% of* CO_2 *emissions otherwise released into the atmosphere, provides a low emissions option to mitigate climate change. An advantage of this option is* that *it has a significant potential to achieve very deep reductions in greenhouse emissions without serious disruption of the global economy and the existing energy infrastructure.*

In pursuing a strategy involving the initial implementation of low emission technologies to mitigate global climate change, there must be a realisation that the total global fossil fuel resource base is finite. Although it could take several decades if not centuries to reach this limit, *low emission fossil fuel technologies with CCS are therefore bridging technologies in the transformation to a future climate sustainable, energy infrastructure.*

Ultimately, the journey towards the above goal would have to incorporate renewable energy resources as the end source of supply of electricity and hydrogen energy vectors in a radically transformed energy system. *Thus, a balanced portfolio approach involving the development and deployment of all forms of energy technologies with low or no carbon emissions is required to avoid global climate change* and to assist the transformation to a new energy system. *Early action to achieve deep reductions in greenhouse gas emissions can be met with the deployment of low emission fossil fuel technologies with CCS.*

The Intergovernmental Panel on Climate Change (IPCC) has recently published a report evaluating CCS technologies and their potential contribution to mitigating global climate change. The IPCC report has noted that *in most scenarios for the stabilisation of global greenhouse gas (*CO_2*) concentrations at between 450-750 parts per million by volume using a least cost portfolio of options, the economic mitigation potential of CCS would amount to 220-2,200 Gt of* CO_2 *cumulatively. This would mean that CCS contributes between 15-55% to the cumulative mitigation effort worldwide until 2100, averaged over a range of baseline scenarios. In most scenario studies, the role of CCS in mitigation portfolios increases over the course of the century, and inclusion of CCS in the mitigation portfolio is found to reduce the costs of stabilising* CO_2 *concentrations in the atmosphere by 30% or more. CCS will begin to deploy at a significant level when* CO_2 *prices begin to reach approximately US $25-30 per tonne.*

The assessment by the IPCC further indicates that CCS technologies currently operate on a limited scale in a mature market with CO_2 capture in industrial applications and with pipelining and utilisation for EOR in depleting oil fields. Currently, close to 40 Mt/y of CO_2 from both natural formations and industrial sources are being used globally in EOR operations, but without CO_2 storage. Opportunities were also found to exist involving the low cost capture of about 360 Mt/y of relatively pure industrial CO_2 emissions for near term storage to meet climate stabilisation goals.

The application of capture technologies in other large sectors of the global economy such as power generation, steel production and cement manufacture with storage in depleted gas and oil fields and underground saline reservoirs are less mature - primarily due to more limited operating experience at large scale with these systems. Other applications of oxyfuel combustion for CCS, enhanced coal bed methane recovery (ECBM; or coal seam methane recovery), mineral carbonation or ocean storage are in the early demonstration or research phases of activity.

Analysis of data reviewed by the IPCC of the cost of electricity, hydrogen and the associated cost of carbon abatement in power generation and industrial plants, shows that the cost of decarbonised electricity or hydrogen increases by 34-49% and 17-144% respectively, being dependent on fuel and plant types and locally prevailing fuel prices and plant investment costs. The cost of decarbonised electricity and hydrogen is cheapest for natural gas plants, but this situation is dependent on the cost of natural gas relative to coal in different regions of the world. With a higher anticipated rate of increase in the price of natural gas, coal-based power and hydrogen plants with CCS are expected in future to have the lowest electricity, hydrogen production and CO_2 abatement costs.

Amongst the coal-fired power generation options, Integrated Gasification Combined Cycle (IGCC) plants based on coal gasification with CCS are expected to yield the lowest electricity and CO_2 abatement costs relative to combustion based options, with either post or oxyfuel combustion capture of CO_2. Unlike the coal combustion based CCS power plants, IGCC with CCS also permits applications with electricity production and the cogeneration of hydrogen, chemicals and/or liquid transportation fuels with the lowest carbon abatement costs.

Data additionally show that the cost of CO_2 abatement is lowest for the production of hydrogen as opposed to decarbonised electricity from both natural gas and coal. With the lowest CO_2 abatement costs for hydrogen production it can be expected that *as technologies evolve for the more efficient distribution, storage and use of hydrogen, it would emerge as the preferred energy vector compared to decarbonised electricity in a future carbon constrained world.*

The IPCC study notes that the cost of CCS with decarbonised electricity or hydrogen production is 9-27% and 10-32% cheaper respectively when combined with EOR, and could provide economic incentives for the early application of CCS in some regions of the world.

In the longer term, *increased deployment of CCS on a larger scale in power generation and industrial plants, through 'learning by doing', can be expected to reduce the costs of CCS by 20-30% within a period of less than a decade.* However, much higher cost reductions are anticipated from improvements to the thermal efficiencies of power plant technologies, and with the deployment of new breakthrough concepts for CO_2 capture that are currently in the research and development phase. Moreover, energy use penalties and capital costs for CO_2 capture represent the largest cost component in any CCS system.

In recognition of the significant role that future coal-fired, IGCC plants could play in providing decarbonised electricity, hydrogen, liquid transportation fuels and chemicals at the lowest carbon abatement costs, the Centre for Low Emission Technology (cLET) has embarked on a research program to facilitate technology development and deployment. *The cLET R&D program focuses on improvements aimed primarily at the implementation of 2nd generation IGCC plants with CCS.* The work aims to achieve higher net cycle efficiencies, lower energy penalties for CO_2 capture via hydrogen separation, and the use of other improved enabling technologies for coal gasification, dry gas cleaning and gas processing optimised for plant operation with low water usage and the higher ambient temperature conditions of the Australian landscape.

The cLET initiative primarily addresses bench, pilot and demonstration scale initiatives for hardware development. When the situation becomes clearer for the implementation of early, large scale IGCC projects in Australia under the Commonwealth Government's Low Emission Technology Demonstration, the Queensland Clean Coal Projects and the Coal 21 funds, cLET will link its program initiatives to support these technology platforms and to achieve commercial outcomes. Additional funding of the cLET program would be required to address these latter outcomes.

In parallel with its technology based R&D initiatives, cLET is also undertaking work on promoting the public awareness and the social acceptance of low emission fossil fuel technologies. This activity is based on the premise that technology alone cannot change energy behaviour if it is not taken up by society. Work undertaken elsewhere in the world shows that the lay public has a very limited understanding of the pros and cons of these technologies and the role it could play in mitigating climate change.

cLET has conducted state wide public surveys in Queensland and New South Wales aimed at establishing the baseline attitudes of the public to low emission technologies. These have been followed by focus group workshops held with both the lay public and community leaders in several regions in Queensland, and recently in New South Wales. Preliminary analysis of the state wide surveys has confirmed that the general public has a very limited knowledge of CCS technologies, while the focus group workshops showed an increased interest and willingness to accept the use of low emissions technologies amongst a portfolio of solutions to mitigate global climate change.

The emerging message from this study is that a major education initiative on climate change and the range of options to mitigate greenhouse gas emissions is required in the near future. The cLET study has identified an approach that could be used in embarking on an initiative that should be national in its outreach.

1: Introduction

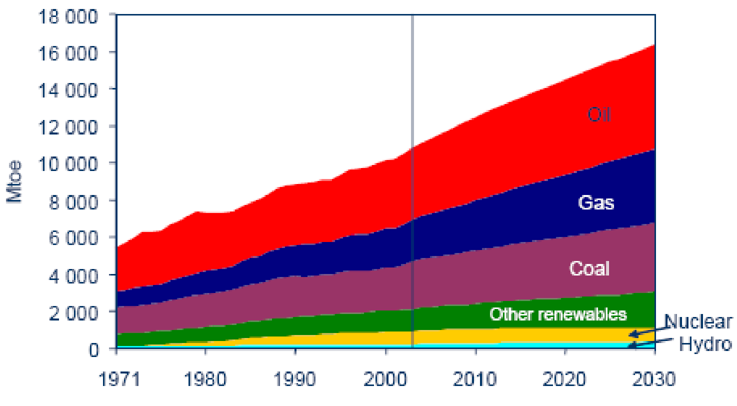
The global economy needs to follow a pathway of significantly reducing carbon emissions into the atmosphere from the use of energy. The rising concentration of carbon dioxide (CO_2) in the atmosphere from the use of fossil energy, is the main contributor to climate change. The global energy supply infrastructure is currently 90% dependent on coal, oil and gas with developments occurring since the dawn of industrialisation.

Transformation away from fossil fuel use in the current global energy infrastructure established over a period of several centuries is not an easy task. It will require many decades of concerted national and global action to implement the use of an alternative energy system with zero or carbon neutral emissions into the atmosphere. It is a process that has yet to begin in a serious and coordinated approach amongst nations.

This position paper by the Centre for Low Emission Technology (cLET) analyses the central role that low emission technologies with CO_2 Capture and Storage (CCS; in more loose terminology, *geosequestration*) could play in transforming the global energy infrastructure into an environmentally and climate sustainable system.

2: The nexus between energy and climate change

In the business as usual (BAU) scenario of the World Energy Outlook (WEO) published by the International Energy Agency (IEA) in 2004 (revised in 2005), fossil fuels are expected to continue dominating global energy supply. In 2030, the consumption of fossil fuels is expected to increase by around 50% in absolute terms over its use in 2003. As shown in Figure 1, fossil fuels are also expected to contribute about 83% to the growth in total energy demand to 2030, and remaining close to 85% of the primary energy mix.

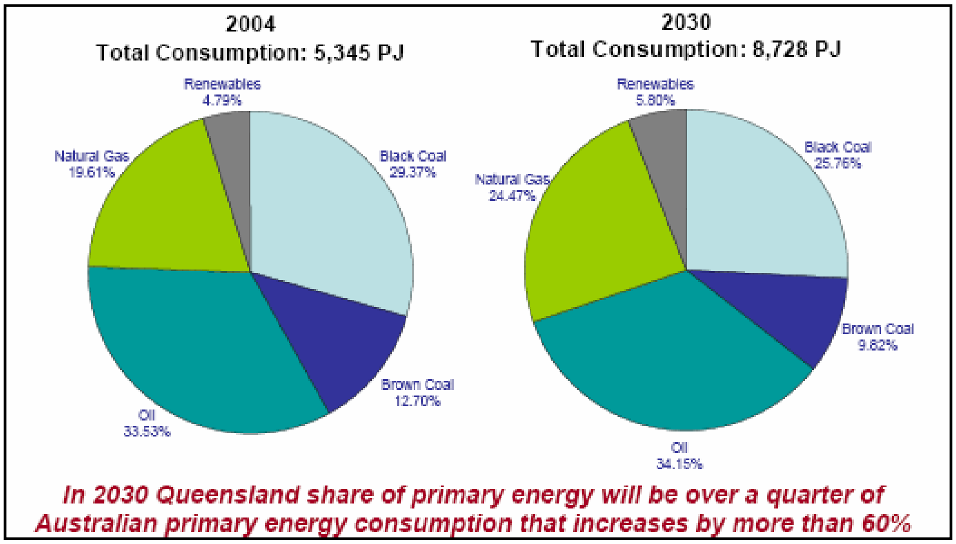


Oil, gas and coal together account for 83% of the growth in energy demand between now and 2030 in the Reference Scenario

Figure 1. World primary energy demand to 2030 (IEA World Energy Outlook [IEA WEO] 2004, revised in 2005).

The IEA's WEO also shows that by 2030, energy consumption in developing countries will exceed those of the developed countries. About 66% of the increase in world demand for energy is projected to come from developing countries as they improve their living standards. Despite this observation, the IEA WEO forecasts show low per capita energy use (per head of population) in developing countries that is significantly less than those in developed countries. Additionally, a persistent energy poverty issue is identified, with close to 1.4 billion people in these countries continuing to have no access to electricity in 2030.

Figure 2 shows data for primary energy use in Australia in 2004 and the BAU forecast to 2030 published by the Australian Bureau of Agricultural and Resource Economics (ABARE, 2005). Primary energy consumption is expected to increase over 60% from 5,345 to 8,728 peta (quadrillion) Joules (PJ) per annum in 2030. Fossil fuels are expected to dominate primary energy supply, remaining at around 94% in 2030. Relative to current energy use, modest increases in the share of gas from 19.6 to 24.5% and renewables from 4.8 to 5.8% is anticipated in this outlook. The increase in use of natural gas and renewables are expected to reduce the share of energy supply from coal from 42% in 2004 to about 36% in 2030, but with coal and oil remaining the largest sources of primary energy consumption in Australia throughout the forecasted period.



In 2030 Queensland share of primary energy will be over a quarter of Australian primary energy consumption that increases by more than 60%

Figure 2. Forecast growth in primary energy use in Australia (ABARE, 2005).

Figure 3 shows the increase in global CO_2 emissions associated with the increase in global energy use to 2030 reported in the IEA WEO. CO_2 emissions are expected to increase from 24 to 37 billion tonnes per year (Gt/y) in 2030. With the anticipated growth in energy use in developing countries, much of the increase in greenhouse gas (CO_2) emissions also comes from the developing countries.

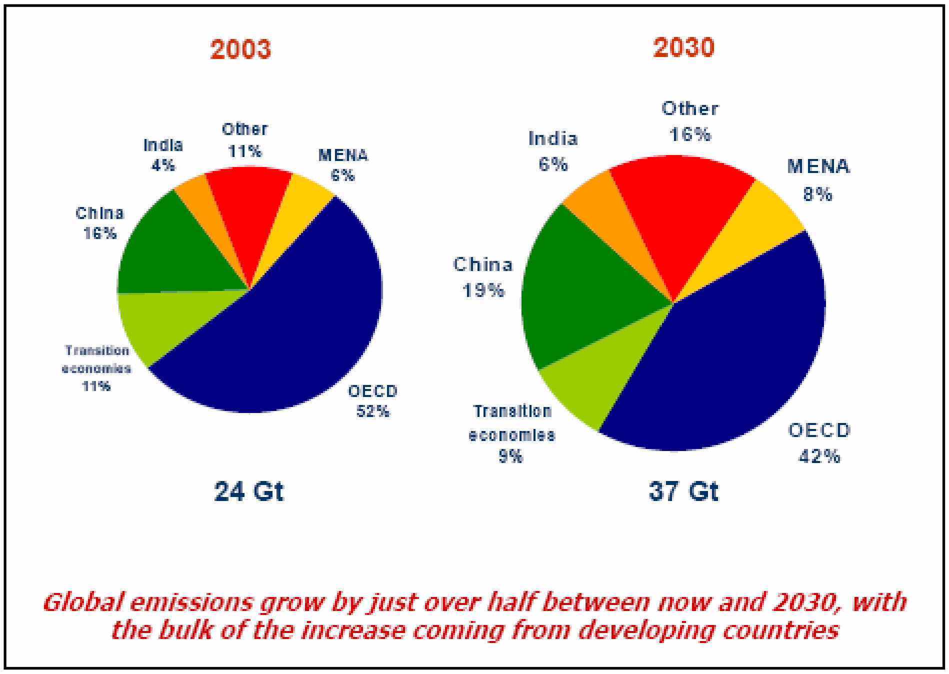


Figure 3. World CO_2 emissions to 2030 (IEA WEO 2004, revised in 2005).

The IEA WEO 2004 also evaluated the potential impact of an aggressive, alternative policy scenario aimed at the deployment of more renewable energy technologies and the faster deployment of more energy efficient technologies on future global energy use. In this scenario, primary energy demand was forecast to reduce by about 10% of the total BAU forecast for energy consumption of the reference scenario (Figure 1). CO_2 emissions with a reduction in fossil energy use were shown to be 16% lower than the BAU forecast of 37 Gt/y (Figure 3) anticipated in the reference scenario.

Clearly, the expected dominance of fossil fuels and increasing global greenhouse gas emissions in the both the BAU and alternative policy scenarios, are driven by an existing global energy infrastructure and the affordability and availability of both fossil energy resources and technologies to exploit them. Both scenarios of the IEA WEO 2004 fall considerably short of meeting any reasonable target required to mitigate global climate change.

For example, assuming that the global community is able to collectively agree on a 550 parts per million by volume (ppmv) (at twice the pre-industrial concentration of CO_2) policy measure to stabilise the concentration of CO_2 in the atmosphere, modeling of this stabilisation scenario suggests that the scale of reduction in CO_2 emissions that would be required to achieve this target by the turn of the century is of the order of 2600 billion tonnes of CO_2. This reduction in greenhouse gas emissions is equivalent to the need to remove over 100 years of the annual rate of global CO_2 emissions into the atmosphere produced from the current pattern of fossil energy use.

3: Technology options and the carbon constrained energy future

There are 3 main approaches to reduce global greenhouse gas emissions from energy use;

a) Reducing energy use through conservation and energy efficiency measures;
b) Deploying alternative energy technologies such as renewables and nuclear;
c) Fuel switching to lower carbon fuels and deploying low emission fossil fuel technologies with CCS.

These main approaches viewed in the context of an emerging carbon (emissions) neutral energy future are shown in Figure 4.

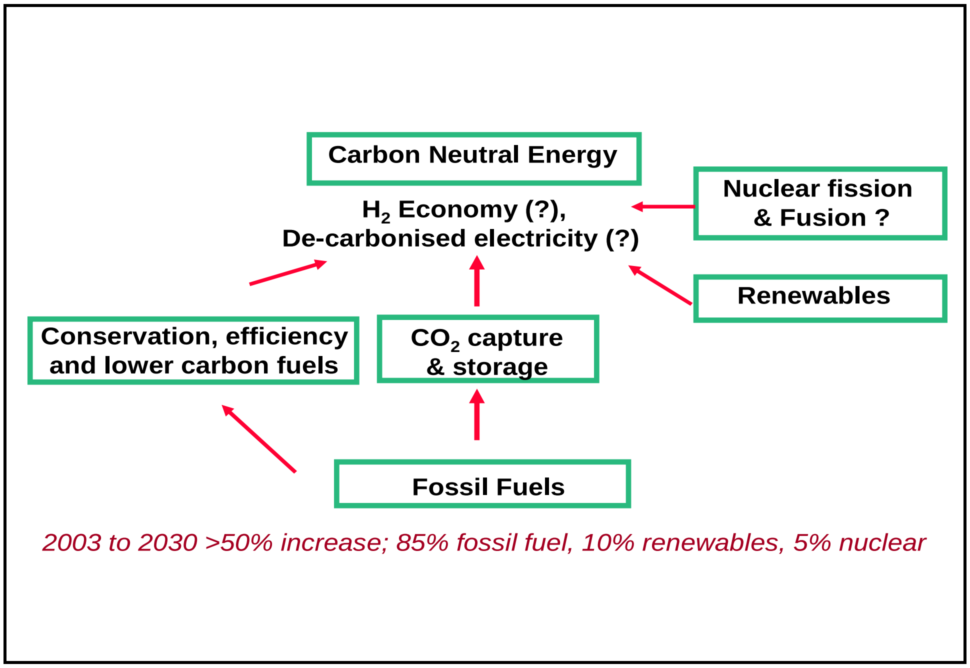


Figure 4. Energy technology options for a carbon constrained future (Thambimuthu, 2006).

The aim of energy conservation and improved energy production and end use efficiencies would be to reduce fossil fuel consumption from current and future use, whilst increased penetration of renewable and nuclear fission energy with low or zero CO_2 emissions where practical, would also displace the use of fossil fuels.

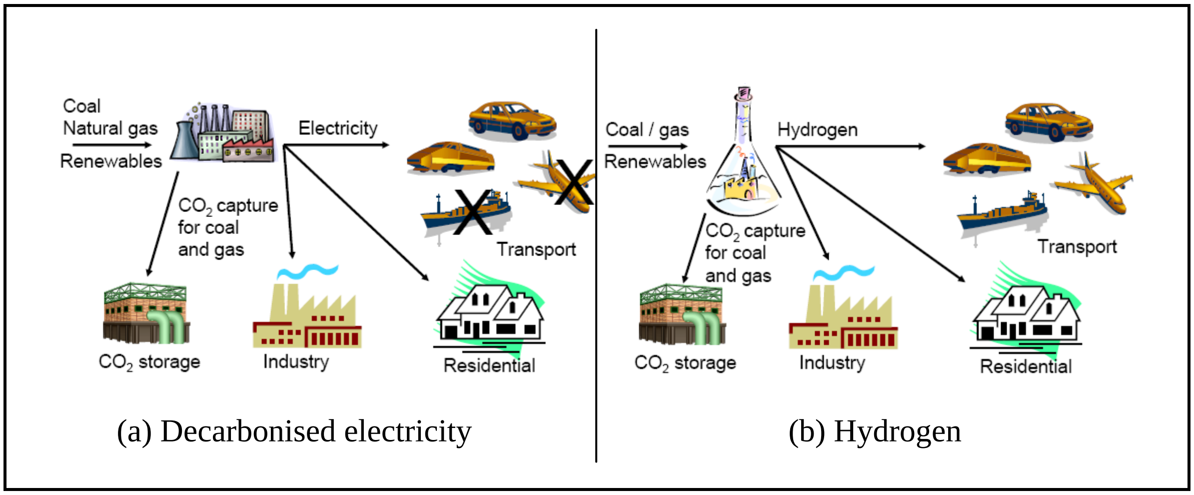
In an energy system predominately based on fossil fuels, the option of switching from higher carbon fuels such as coal to lower carbon fuels such a natural gas and oil could also slow the rate of greenhouse gas emissions into the atmosphere, whilst meeting a growing energy demand. However, the preferential shift from one fossil energy resource to another would have to consider the impact of fuel costs and energy supply and demand. Presently, both oil and gas are facing increasing concerns about the security of energy supply with rapidly rising prices and with global production mainly concentrated in the Middle East, North Africa (MENA) and Russia.

The use of fossil fuel technologies with CCS that could remove 85-95% of CO_2 *emissions otherwise released into the atmosphere, provides a low emissions option to mitigate climate change*. An advantage of this option is that *it has a significant potential to achieve very deep reductions in greenhouse emissions without serious disruption of the global economy and the existing energy infrastructure.*

In the longer term, the increasing use of energy vectors such as decarbonised electricity and hydrogen (H_2) produced from fossil fuels, renewable and nuclear energy would be required for the transportation and other distributed energy end use sectors – this being necessary to prevent the direct burning of carbon containing fuels so as to further reduce or maintain zero carbon (carbon neutral) emissions into the atmosphere with the expected growth in emissions from the use of traditional oil derived fuels in these sectors (see Figure 6).

The eventual shift to an energy system driven by the supply and distribution of decarbonised electricity and hydrogen as the main energy vectors (and without carbon emissions to the atmosphere from their production and end use), will achieve the goal of implementing a transformed, climate sustainable energy infrastructure.

The production of these energy vectors would also become ultimately reliant upon the more efficient recovery and use of renewable energy resources - as renewable energy technologies develop and reduce in cost, whilst enabling the continuous supply of large fluxes of energy to meet the growing global, energy demand. The role of decarbonised electricity and hydrogen in meeting energy use requirements in distributed end use applications is shown in Figure 5.



(a) Decarbonised electricity (b) Hydrogen

Figure 5. Role of (a) decarbonised electricity and (b) hydrogen is supplying distributed energy (Thambimuthu, 2006).

In the near term, the impact of these various energy technology options from considerations of both the cost and maturity of technology for applications in reducing greenhouse gas emissions can be examined within the context of the BAU and alternative policy scenario forecasts of the IEA reviewed previously in Section 2.

Both renewable and nuclear (fission) energy have been shown to have a modest contribution to primary energy supply to 2030. This is mainly due to the cost and availability of renewable energy technologies to meet demand, and the cost and public concerns about nuclear fission technologies retarding more widespread deployment.

With anticipated increased supply, inter-regional trade and demand, natural gas which is the lowest carbon fossil fuel is shown to have a greater share of the global primary energy in 2030 in both the IEA BAU and alternative policy scenarios. Much of this increase in gas consumption is expected to occur in the power generation sector alongside coal, but with coal remaining as the main source of fuel (at around 38%), as it is today, for electricity production.

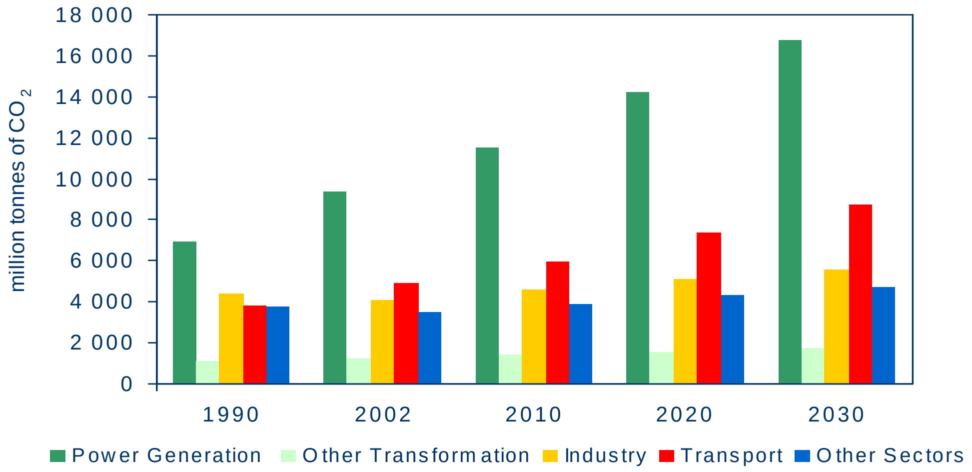
In the aggressive alternative policy scenario of the IEA WEO, the impact of a concerted action by governments in implementing energy conservation and efficiency measures together with the increased deployment of renewable energy technologies, are also shown to have a modest impact in meeting and reducing energy demand and CO_2 emissions in the global economy as noted previously in Section 2.

Although the subject of R&D interest worldwide, the technology potential of nuclear fusion as an energy option has yet to be realised. The technology once realised, could play a potential role as a preferred option to existing nuclear fission technologies which currently face public opposition about safety and the risks of global nuclear proliferation.

Low emission fossil fuel technologies with the capture and underground (geosequestration) storage of CO_2, is an emerging energy technology option that has not been evaluated in the IEA WEO. CCS technologies have achieved limited deployment in commercial applications in 3 major demonstration initiatives worldwide. About 3 million tonnes per year (Mt/y) of CO_2 is currently captured and stored in geological formations from natural gas production in the Sliepner field in Norway, In Salah in Algeria and in the Weyburn oil field in Canada. CO_2 used in the Weyburn oil field is also used to promote enhanced oil recovery (EOR), and is captured from a coal gasification plant located in North Dakota, USA. Significantly more CO_2, 9.7 Mt/y captured from chemical/industrial plants (Simbeck, 2005) and 30 Mt/y currently recovered from natural underground CO_2 formations, are used in EOR operations without CO_2 storage in the USA (Intergovernmental Panel on Climate Change [IPCC], 2005).

CCS is considered to be a low emission energy technology option that would need to be deployed on a large scale to realise the cost benefits of CO_2 emissions reduction for climate change mitigation. Capture applications are being targeted at large CO_2 point sources such as in power generation, and other industrial applications such as cement manufacture, minerals and metal processing, and petrochemical plants. As shown in

Figure 6, the power generation sector represents the largest source of energy related CO_2 emissions in world, followed by emissions from the transport sector as the second largest source of emissions. Emissions from power generation and transport are expected to increase significantly in the period to 2030 - the management of these emissions with CCS (see Section 4 for the reduction in emissions with CCS in the power generation and transport sectors), together with those from industrial sources would make a significant contribution towards climate change mitigation globally.



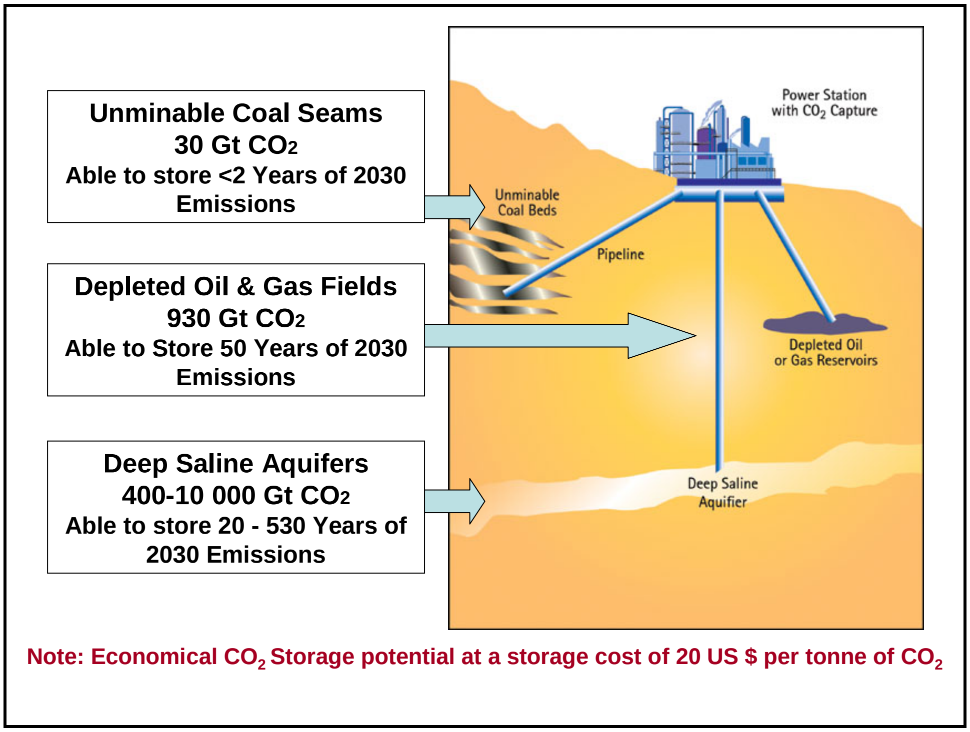
Large emissions growth in the power generation and transport sectors, large power generation and industrial plants represent over 60% of 2030 emissions

Figure 6. Global CO_2 emissions by sectors (IEA WEO, 2004).

To realise economies of scale in the transport of CO_2 to storage sites, trunk pipeline systems would be required linking several large point sources to a storage site with a capacity to retain several decades of emissions from these point sources.

Storage operations may initially combine with EOR, enhanced natural gas (EGR) or coal bed methane recovery (ECBM; or coal seam methane recovery) with commercial benefits (where opportunities exist) gained from the additional production of oil and natural gas that can partially offset the cost of CCS (see Section 5). These storage options in oil and gas fields and coal seams are seen to be of much more limited capacity globally as shown in Figure 7 relative to the capture potential of greenhouse gas emissions anticipated from large point sources in the power generation and industrial sectors in 2030.

However, as also shown in Figure 7, significantly larger CO_2 storage capacities exist in underground saline reservoirs, which at the upper limit of the range, have the ability to store several hundred years of the expected capture potential of greenhouse gas emissions in the power generation and industrial sectors anticipated in 2030. This larger storage capacity option, however, does not yield any commercial benefits (in comparison to storage with EOR and ECBM) for the application of CCS. In these circumstances the cost of CCS would be borne entirely for the purpose of mitigating climate change.



Note: Economical CO_2 Storage potential at a storage cost of 20 US $ per tonne of CO_2

Figure 7. Global geological storage capacities for CO_2 (IEA GHG, 2006).

4: Vision for low emission technologies in a transformed global energy infrastructure

Since the oil price shocks of the 1970s and 1980s, the use of oil for power generation in large centralised plants has been discouraged in policy directives adopted by the developed nations within the Organisation of Economic Cooperation and Development (OECD). As a result, and coupled with further rises in the price of oil in more recent times, the current global practice has been an increased reliance on natural gas and coal as the leading fossil fuel options for power generation in large centralised plants.

In the statistics compiled by the IEA WEO 2004, the current global power generation capacity of 3719 billion watts electrical (GWe) is composed of 1135 GWe of coal, 893 GWe of gas, 454 GWe of oil, 801 GWe of hydro, 359 GWe of nuclear and 77 GWe of biomass and other renewable energy based power plants. Coal and gas are the two largest sources of power generation today, and this situation is forecasted to continue with the doubling of total power generation capacity expected to be serviced by 2030 in the IEA WEO.

Oil has continued to be the main feedstock used for the production of liquid transportation fuels, hydrogen and chemical production for the manufacture of industrial, agricultural and consumer products. However, with continuing concerns over rising oil prices and security of supply, a greater emphasis is being placed on the use of natural gas and coal as alternative energy sources for the production of liquid fuels, hydrogen and chemicals. Large plants are in service today, e.g. in Qatar and Sasol in South Africa, for the synthesis of liquid transportation fuels from natural gas and coal via Fischer-Tropsch gas to liquids technology. Natural gas and coal have also emerged as the largest sources of fuel in the commercial production of hydrogen, and increasingly significant amounts of these fuels are also being used today in chemical synthesis.

The IEA WEO 2004 and its revision in 2005 is based on the premise of a current oil price of US $60 per barrel that is predicted to ease to a price of US $40 per barrel in 2010, and to increase once again to US $65 per barrel in 2030. Current levels of the global oil price have already exceeded the forecast price for oil in 2030.

From the above, it is likely that amongst fossil fuels, the shift towards an increasing use of gas and coal for power generation, hydrogen, liquid fuel and chemical production in the global market place will continue. It should be noted that recent events coupled with the rising oil prices have also driven up the price of natural gas and liquefied natural gas (LNG) to record levels in Europe and North America - it can therefore be expected that the future increase in gas prices will also closely track rising oil prices. This situation will be further exacerbated by the fast growing inter-regional/continental trade from the shipping of LNG and the movement of natural gas through trunk pipelines.

The upward price trend for LNG and natural gas, if realised, will additionally shift the balance towards the increasing use of coal in a future energy market. Coal is currently the largest global fossil energy resource that exceeds the identified combined reserves of oil and gas. Its distribution practically in every region of the world is unlikely to encounter dramatic price rises from supply and demand issues (in quite the same manner as for oil), nor raise concerns centered on the security of energy supply for many nations. The fastest growing developing countries in the world, particularly China and India also have large indigenous coal reserves that they are able to exploit. Australia is in a very similar situation, albeit it is currently also the world’s largest coal exporter.

Figure 8 shows the pathway for the deployment of CCS technologies. As noted in the brief overview of the current status of CCS technologies in Section 3, CO_2 is captured in large centralised industrial or power plants with the use of energy to produce value added industrial products, electricity and/or hydrogen.

CO_2 would be transported directly for its permanent storage in spent oil and gas fields or saline reservoirs, or further utilised either in enhanced oil (EOR) or enhanced coal bed methane (ECBM) recovery with storage. In the process of co-utilisation with storage, the additional oil or gas recovered will also offset future emissions from the burning of the recovered fossil fuel - by the amount of CO_2 stored per unit of energy produced using the enhanced recovery techniques. Additionally, the combined global CO_2 storage capacities in these reservoirs and underground saline formations as noted in Figure 7 are on a scale large enough to achieve deep reductions in greenhouse gas emissions to mitigate climate change.

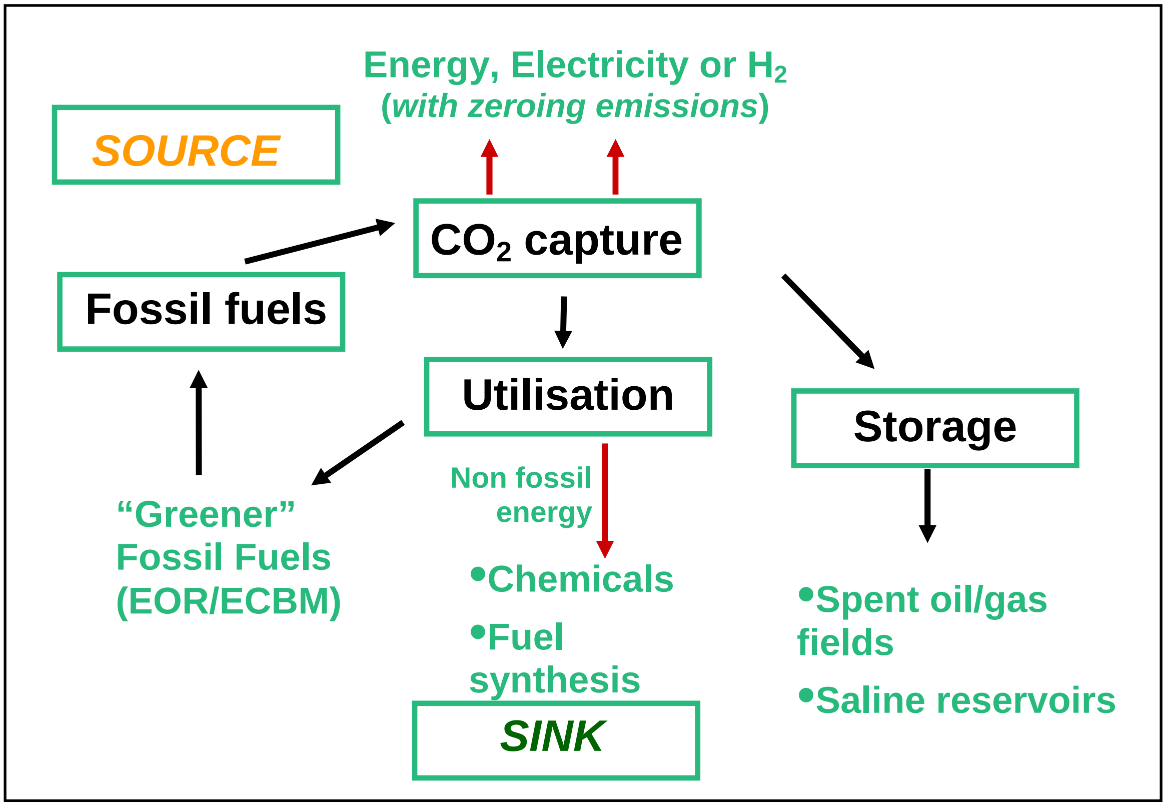


Figure 8. A vision map for CO_2 Capture and Storage (Thambimuthu, 2006).

An alternate utilisation option for the captured CO_2 is its potential use in the synthesis of fuels or chemicals. However, the direct conversion of CO_2 into fuels and chemicals is very energy intensive (often requiring the same amount of energy as that produced from burning the fossil fuel that generated the CO_2). In order not to generate more CO_2 emissions from the chemical conversion of CO_2 into fuels or chemicals, non fossil fuel energy resources, such as renewable or nuclear energy would be required. In a situation where fuels are synthesised from captured CO_2 for use in the transportation and distributed energy use sectors, the approach provides a means to roughly double the amount of energy used (in these sectors) per unit of carbon emission into the atmosphere. The approach, whilst having the potential to halve the net carbon emissions into the atmosphere from energy use, will also require the supply of renewable or nuclear energy resources at a cost considerably cheaper than that for fossil fuels – to economically compete with similar fuels currently produced directly from lower cost fossil fuels (see below). A very significant change in the cost of renewable or nuclear energy would be needed to implement this approach as a viable mitigation strategy for climate change.

Figure 9 shows the role of the CO_2 capture plant in a future transformed energy infrastructure. The example shown is for a centralised process plant based on the conversion of coal or natural gas by gasification or steam reforming/partial oxidation to convert these fuels into a carbon monoxide (CO) and hydrogen, synthesis (or syn) gas mixture. In this application, the syngas is further converted by reaction with steam to produce either a H_2 and CO_2 stream, or a H_2, CO_2 and CO stream. Existing and emerging technologies that operate or can be adapted to operate in this configuration include natural gas reforming, partial oxidation and auto thermal reforming plants and coal gasification and coal and oil residue based integrated gasification combined cycle (IGCC) power plants.

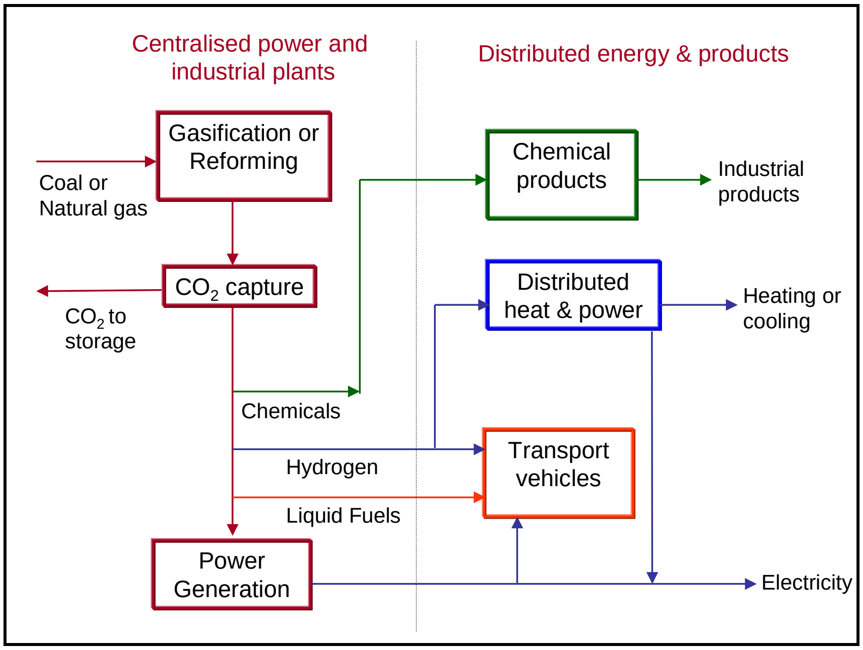


Figure 9. The role of a centralised CO_2 capture plant in a future transformed energy infrastructure (Thambimuthu, 2006).

In an application for the production or co-production of decarbonised electricity and/or hydrogen energy vectors (and also in the synthesis of industrial chemical products without carbon), a H_2 and CO_2 gas mixture is produced and CO_2 is captured for storage or utilisation.

In an application for the direct production of liquid transportation fuels and chemicals with carbon, a H_2, CO_2 and CO stream is produced with the capture and storage of some of the original carbon contained in the fossil fuel as CO_2. This mode of operation can also be implemented to co-produce an entire suite of products from a single, centralised CO_2 capture plant, i.e., decarbonised electricity, hydrogen, liquid fuels and chemicals.

In the examples described above, the production of decarbonised electricity, hydrogen or chemicals products without carbon, would result in the removal of between 85-95% (based on the cost optimisation of the capture process) of the original carbon contained in the fuel as CO_2 for storage.

In the case involving the production of carbon containing liquid transportation fuels and chemicals, the capture and storage of CO_2 will partially offset CO_2 emission into the atmosphere at the point of use of the liquid fuel or from degradation of the carbon containing chemical product. The extent of carbon leakage into the atmosphere that will occur from use of these products, is determined primarily by the carbon content of the synthesised products. As a rule of thumb, the net burden of CO_2 emissions into the atmosphere would be less for liquid fuels produced from natural gas (with or without CO_2 capture) compared to similar fuels produced from oil. For liquid transport fuels produced from coal with CO_2 capture, the net burden of CO_2 emissions will be no worse than that resulting from the production of the same fuel from oil.

In addition to the example given above, the centralised capture plant could also be operated in a mode where decarbonised electricity and/or heat are the only outputs from the plant. In this mode of operation the process would rely upon the direct combustion of coal and gas to produce power and heat with CO_2 capture. With the bulk of the global power generation capacity in the world today based on the direct combustion of pulverised coal and natural gas to produce the cheapest sources of electricity, it would be the initial approach adopted by electricity producers to transform the global power generation stock to reduce carbon emissions into the atmosphere.

In the longer term, transformation of the energy system to the comprehensive use of decarbonised electricity and hydrogen energy vectors produced with CCS across all sectors of the global economy (covering industrial, residential, transport and resource sectors; Figure 5), would be necessary in order to significantly reduce the greenhouse gas emission burden into the atmosphere. Ability to meet this need for the production of these energy vectors from large centralised plants with CCS for use across all sectors of the global economy is also shown in Figure 9.

In pursuing this strategy with CCS there must be a realisation that the total global fossil fuel resource base is finite. It could take several decades if not centuries to reach this limit. *Low emission fossil fuel technologies with CCS are therefore bridging technologies in the transformation to a future climate sustainable, energy infrastructure.*

Ultimately (see also Section 3), the journey towards the above goal would have to incorporate renewable energy resources as the end source of supply of decarbonised electricity and hydrogen energy vectors in a transformed global energy infrastructure. Whilst saving the planet in the interim with the near to mid term application of CCS technologies to achieve deep reductions in greenhouse emissions, work must also proceed in developing improved renewable energy technologies that could ultimately supply, at competitive cost, the large fluxes of energy required in the form of electricity and hydrogen to meet global energy demand.

Thus, a balanced portfolio approach involving the development and deployment of all forms of energy technologies with low or no carbon emissions is required to avoid global climate change. Early action to achieve deep reductions in greenhouse gas emissions can be met with the deployment of low emission fossil fuel technologies with CCS.

5: Technology maturity and the global economic potential of CCS

As noted in Section 3, several near term commercial opportunities have emerged for the application of CCS in natural gas processing and EOR operations. In virtually all of these, low cost CO_2 capture or supply and/or the incremental oil recovery that occurs, is able to partially offset the cost of CCS. In a recent scan of other potential early applications of CCS (IPCC, 2005), it was found that several opportunities exist globally for capturing CO_2 from relatively high purity and low cost CO_2 sources (primarily associated with hydrogen production from fossil fuels in industrial applications), its transport over distances of less than 50 kilometres coupled with storage with or without co-utilisation benefits. The potential for such niche opportunities today would be able to capture and store about 360 Mt/y of global CO_2 emissions (IPCC, 2005).

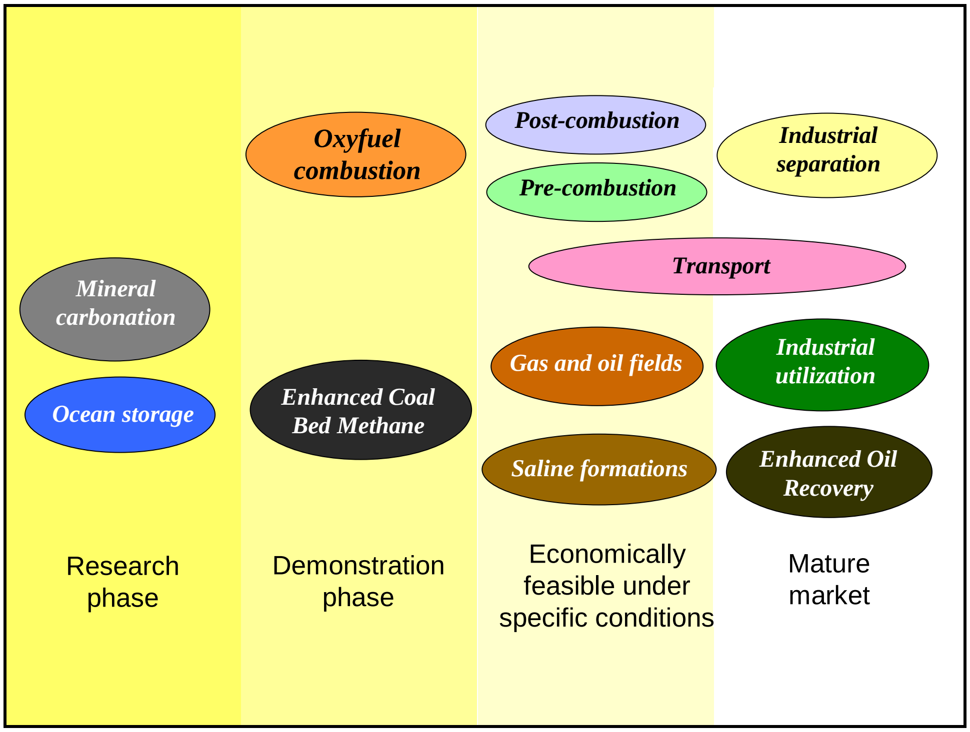


Figure 10. The technology maturity of CCS components (IPCC, 2005).

The technology maturity of CCS is shown in Figure 10. The technology components for the removal of CO_2 using oxyfuel combustion, post and pre-combustion separation techniques from less dilute streams found in power generation and other sectors such as cement manufacture, minerals and metals processing, are less mature or are in the early phases of demonstration activity. This is primarily due to the lack of operating experience on a large scale and relatively high energy penalties and costs incurred for the separation of CO_2 from dilute streams that has prevented more widespread implementation of CCS in these energy use sectors. Likewise, storage options involving ECBM, mineral carbonation or sequestration of CO_2 in the ocean are either in the demonstration or early research phases of activity.

As was noted sections 3 and 4, the largest sources of CO_2 emissions and the opportunities to produce decarbonised electricity and hydrogen with CCS, will require their use in the power generation and transport sectors. As shown in Figure 10, virtually all of the capture technologies for implementation in large centralised power plants require further development to reduce energy use and capture costs, coupled with storage in saline formations – with storage in saline reservoirs being necessary due to the large volume of both current and anticipated future emissions from power generation and transport.

Based on the current understanding of the state of maturity of these low emission fossil fueled technologies, Table 1 shows estimated costs for the implementation of CCS (including the capture, transport and storage) in large centralised plants for the production of decarbonised electricity or hydrogen energy vectors (IPCC, 2005).

For electricity production without CCS, cost data show that natural gas combined cycle (NGCC) and pulverised coal-fired power plants are the most cost competitive options for power generation in the world today. The relative use of gas or coal as the preferred choice for power generation is dependent on the prevailing costs for natural gas and coal in different regions of the world. The analysis in section 4 suggests that in a future world without carbon constraints, coal will likely be the fuel of choice due to the anticipated price rises for gas that would be coupled to the rising world price of oil. Amongst the options for power generation from coal without CO_2 capture, IGCC power plants are also shown to be marginally more costly – a feature demonstrated also by the fact that coal-fired IGCC capacity in operation in the world today is 1 GWe, or less than 0.1% of the current total global coal-fired power generation capacity.

For low emission power plants with CCS and the geological storage of CO_2 without incentives, Table 1 shows that NGCCs, given the current fuel price (and lower amounts of CO_2 capture that occurs because of the lower fuel carbon content relative to coal), is the cheapest option for the production of decarbonised electricity. Amongst the coal-fired options, IGCC with CCS due to the lower incremental energy use penalty for pre-combustion CO_2 capture, is marginally more cost competitive for decarbonised electricity production compared to pulverised coal with post combustion capture. However, unlike the combustion based NGCC and pulverised coal-fired plants with CCS, the IGCC plant with CCS can be readily adapted with little or no additional cost to produce a combined output of both decarbonised electricity and hydrogen. As noted in Section 4 and Figure 9, with natural gas, the combined cycle plant would need to be initially modified to use an upstream reactor to produce a syngas using a partial oxidation, steam or an auto-thermal reforming process with increased cost. No equivalent possibilities exist to convert a combustion based pulverised coal-fired CCS plant to economically co-produce hydrogen. Additionally, with both IGCC and natural gas, a centralised CCS plant could also be adapted (see Figure 8) to produce multi-product streams of decarbonised electricity, hydrogen, transport fuels and chemicals - albeit with a higher investment cost to build such a plant.

Table 1 – Range of cost for electricity and hydrogen production with CO_2 capture, transport and storage with and without the benefits of EOR (IPCC, 2005).

	Natural gas CC	Pulverised coal	IGCC	Hydrogen Plant
Cost of electricity or H_2 without capture, US$/MWh or US$/GJ	31-50	43-52	41-61	6.5-10
Cost of electricity or H_2 with capture and geosequestration, US$/MWh or US$/GJ	43-77	63-99	55-91	7.6-14.4
Incremental cost of electricity or hydrogen with capture and geosequestration, US$/MWh or US$/GJ	12-27	20-47	14-30	1.1-14.4
Cost of CO_2 avoided with geosequestration, US$/t	38-91	30-71	14-53	3-75
Cost of electricity or H_2 with capture and EOR, US$/MWh or US$/GJ	37-70	49-81	40-75	5.2-12.9
Incremental cost of electricity or hydrogen with capture and EOR, US$/MWh or US$/GJ	6-20	6-29	(-1)-14	(-1.3)-2.9
Cost of CO_2 avoided with EOR US$/t	19-68	9-44	(-7)-31	(-14)-49

Table 1 additionally shows the cost of decarbonised electricity expected for CCS plants coupled with EOR. Across all types of power plant options, the total and incremental cost of decarbonised electricity becomes less for the plants with revenue benefits derived from EOR. The lowest incremental cost of decarbonised electricity is also found to occur for the coal-fired IGCC option. As a general observation, any increase in the future level of the world price of natural gas relative to coal will make both the pulverised coal-fired and IGCC options with CCS and EOR less costly for carbon emissions abatement.

Table 1 also shows cost data for producing hydrogen with and without CCS using a range of fuels that include natural gas, coal and other oil derived residues such as petroleum coke. The cost of hydrogen production from these fuels increases with CCS and lowest costs are again seen for hydrogen production and CCS combined with EOR.

For both the decarbonised electricity and hydrogen production options, costs are also presented in Table 1 in terms of the $ per tonne of CO_2 avoided. This metric is a measure that is often used to examine the impact of fuels, technologies, products and services on carbon abatement costs and emission reductions achieved in energy technology and future scenario models. The table shows that the avoided cost of CO_2 for decarbonised electricity production, is lower for the IGCC and PC plants with CCS compared to NGCCs and lowest again for IGCC amongst all of these 3 options.

The lower range limit for hydrogen production with CCS also shows that this option for energy production is likely to have the lowest carbon emission abatement costs, and which become significantly more negative when hydrogen production is coupled with CCS and EOR. A negative carbon abatement cost denotes a situation where there is a profit derived in pursuing carbon emissions abatement. As noted earlier in the introduction to this section, many of the early opportunities with low CO_2 supply costs are also identified to occur in existing industrial plants that produce hydrogen. However, despite these cost benefits, these early opportunities are currently limited to a cumulative abatement potential of 360 Mt/y worldwide. Although representing a relatively large amount of CO_2 that can be sequestered, this opportunity is insignificant in comparison to the scale of the cumulative emissions reduction needed to mitigate global climate change.

A potentially lower carbon abatement cost for hydrogen with CCS might also indicate that it is a preferred energy vector to decarbonised electricity for use in a future carbon constrained world. However, it should be noted that with today's technology, hydrogen will not provide the same end use service as decarbonised electricity would. For example, the use of electricity to drive a motor will incur losses of the order of 1-5%, whereas the use of hydrogen will require its conversion to produce the electricity to drive the same motor. Allowing for the additional compression, transport and storage losses for hydrogen would mean that the overall efficiency loss in using hydrogen to drive the motor would be of the order 30% or less. This efficiency loss will effectively more than triple today's CO_2 abatement cost of using hydrogen to power the motor compared to its CO_2 abatement cost at its point of production.

To extend this argument to the use of decarbonised electricity or hydrogen to propel a vehicle for transportation, the net carbon abatement cost of using an electric vehicle using today's technology would be less than that relying on the combustion of a hydrogen gas to propel a vehicle. This situation may change in a future world with the establishment of an efficient hydrogen distribution and storage infrastructure (that currently does not exist) and the advent of fuel cell vehicles that would more efficiently convert hydrogen into motive power. However, in other situations such as the synthesis of a chemical product, the direct use of hydrogen would be more efficient and will have lower carbon abatement cost than the use of electricity – since electricity will have to be first inefficiently converted to hydrogen (i.e., by the electrolysis of water) before chemical synthesis. *Hence, as technologies evolve for the more efficient distribution, storage and use of hydrogen, it would emerge as the preferred energy vector in a future carbon constrained world.*

Using specific carbon abatement cost data of the type evaluated above for energy generation from low emission technologies, several scenario models have assessed the system wide macro-economic impact of the carbon abatement potential of CCS.

A review of the results of these models (IPCC, 2005) show that *in most scenarios for the stabilisation of global greenhouse gas (CO_2) concentrations between 450 – 750 ppmv using a least cost portfolio of options, the economic mitigation potential of CCS would amount to 220 - 2,200 Gt of CO_2 cumulatively. This would mean that CCS contributes* *between 15-55% to the cumulative mitigation effort worldwide until 2100 averaged over a range of baseline scenarios. In most scenario studies, the role of CCS in mitigation portfolios increases over the course of the century, and inclusion of CCS in the mitigation portfolio is found to reduce the costs of stabilising CO_2 concentrations in the atmosphere by 30% or more.*

The IPCC also noted that the cost competitiveness of CCS systems occurs because these technologies are compatible with the current energy infrastructure and permit a smooth transition to a less carbon intensive system. In general, most energy and economic models reviewed indicate that a major contribution of CCS to climate change would occur from its deployment in the electricity sector and *most models assessed in the study also showed that CCS will begin to deploy at a significant level when CO_2 prices begin to reach approximately US $25-30 per tonne.*

6: The cLET R&D program on low emission clean coal technologies

A *'first generation'* IGCC scheme for the production of electricity and hydrogen from coal with CCS using the current best available technology (as noted previously in Section 5) is shown in Figure 11. The process can be divided into five steps as follows:

1. Gasification & Air Separation;
2. Gas Cleaning;
3. Gas Conditioning;
4. Gas Separation;
5. Power Generation with or without flue gas clean-up.

In the first step the coal is gasified in an oxygen-blown, entrained flow gasifier to produce the syngas, which is then cooled and scrubbed in the second step to remove particulates. In the third step the syngas is then shifted in sour water gas shift reactors to convert CO to CO_2 by reaction with steam, at the same time increasing the hydrogen content. The water gas shift reaction is exothermic and the conversion is limited by thermodynamic equilibrium; the conversion to H_2 & CO_2 decreasing with increasing temperature. The reaction is therefore carried out in two stages, in high and low temperature shift reactors with inter-stage cooling, and further cooling to reduce the temperature to that acceptable in the next step. In the fourth step gas separation using a physical solvent (e.g. Selexol or chilled methanol, as in the Rectisol process) is carried out. A two stage unit is needed, the first to remove hydrogen sulfide (H_2S) for recovery from a concentrated stream (>50% H_2S) as sulphur (S) in a Claus plant, and the second to remove CO_2 for compression and storage.

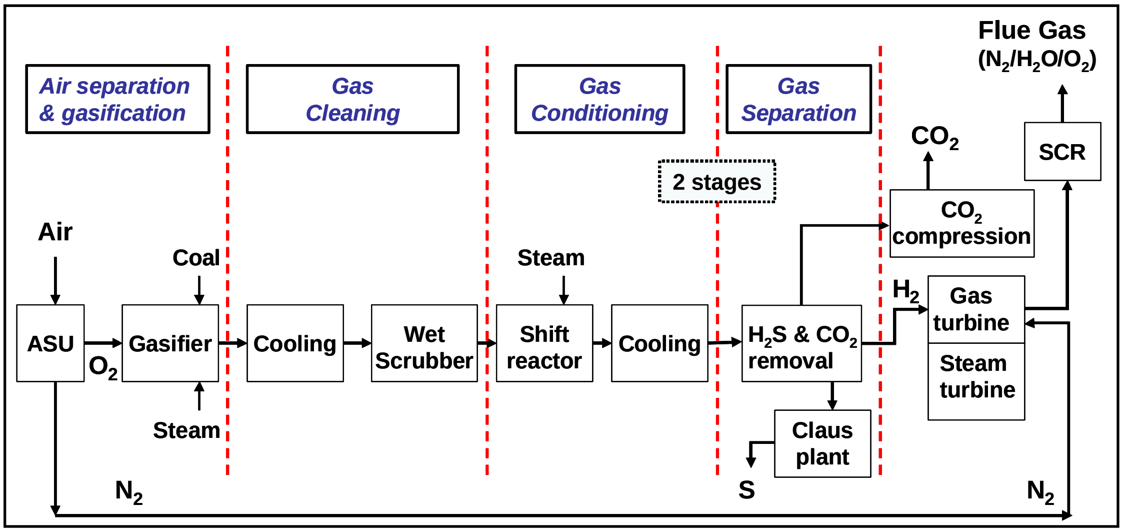


Figure 11. A conventional or *'first generation'* scheme for IGCC with CCS.

In the fifth and final step, H_2 can be directly exported (but with further purification) for use as an energy carrier and/or combusted and the heat recovered in a conventional combined cycle to generate electrical power. In the latter application, the nitrogen from the air separation unit (ASU) re-injected to the gas turbine to abate temperature and a selective catalytic reduction (SCR) unit is used to remove NO_x from the flue gases, which will be mainly nitrogen (N_2), water (H_2O) and oxygen (O_2).

The scheme described above is clearly complex and capital intensive, with thermodynamic limitations to the overall efficiency with several staged operations that also require cooling and reheating of the process gas. There is potential for improvement by combining the gas conditioning and separation steps, the next development in this direction being shown in Figure 12.

In the configuration shown in Figure 12, the cooling before H_2S and CO_2 removal has been reduced by substituting a warm dry gas cleaning system, comprising a particulate filter and solid sorbent desulphuriser operating at 300 to 500°C. The reduced water consumption of the process given by dry gas cleaning is a very tangible advance for application in the dry, hot Australian landscape as well as with partial syngas cooling in improving the thermal and cycle efficiency of the overall process. The need for cooling downstream is again removed by using a membrane separator to separate the H_2 from the CO_2. The membrane may be integrated with the shift reactor in such a way that the removal of the hydrogen reduces the concentration within the catalyst bed, thereby driving the achievable conversion higher at a specific temperature and enabling the potential for a reduction in cost.

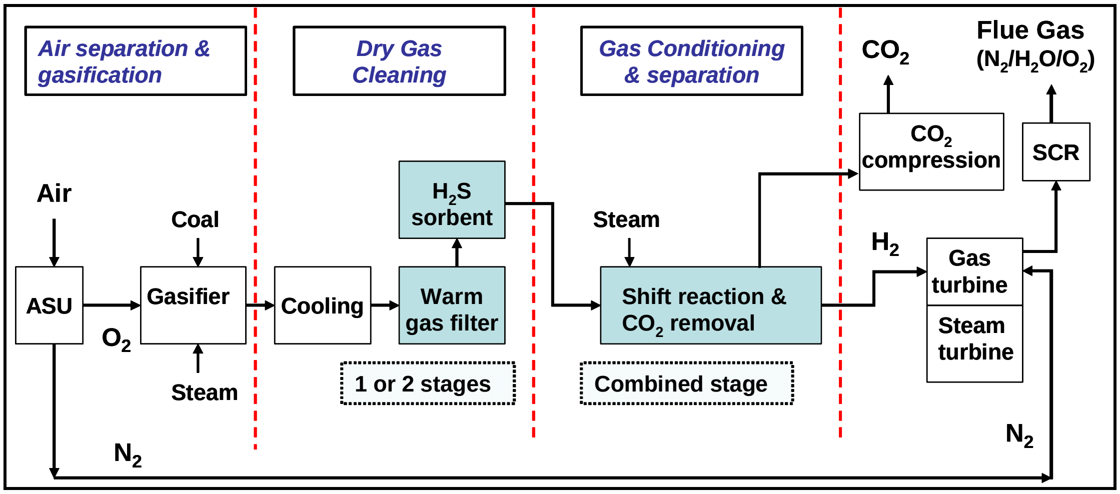


Figure 12. An improved '*second generation*' scheme for IGCC with CCS.

A further advance is depicted in Figure 13 below; here a higher temperature membrane allows further simplification of the gas conditioning and separation step and some further improvement in the thermal and overall cycle efficiency by either further reducing or even completely removing inter-stage cooling.

This scheme requires both a low cost high temperature membrane tolerant to the syngas and a hot gas cleanup system capable of particulate and sulphur removal at hot conditions between 600 and 800°C.

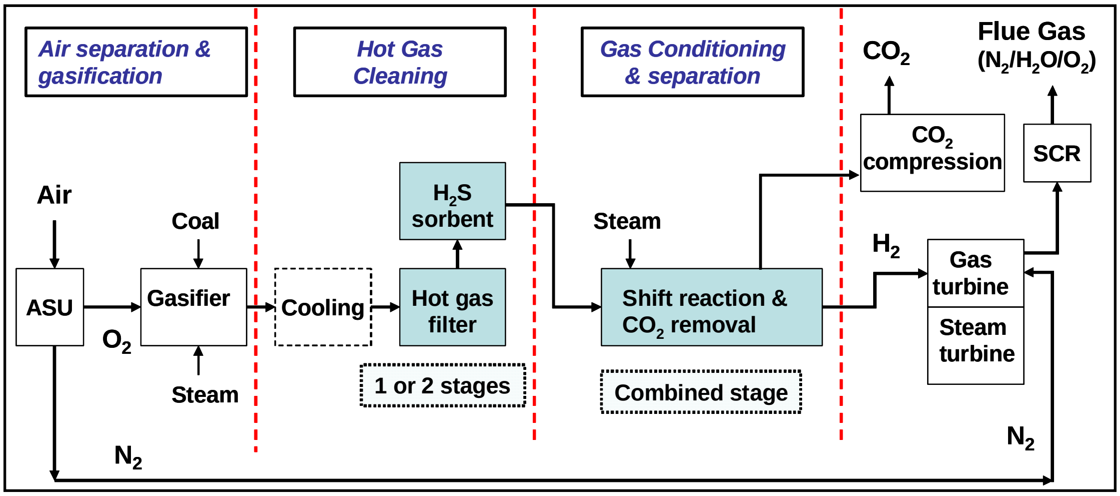


Figure 13. An advanced '*second generation*' scheme for IGCC with CCS.

The primary focus of cLET's current initiatives is on the research and development of next generation low emission technologies such as those shown in Figures 12 and 13. The R&D program is presently focused on improvements to the gasification, gas cleaning, gas processing and gas separation technologies that are needed to realise the development potential of IGCC with CCS, for advanced power, hydrogen and/or synfuels production. The program of work was initiated in April 2005, within four areas of process development as follows:

1. Gasification and Core Facility Development;
2. Gas Cleaning;
3. Gas Processing;
4. Gas Separation.

An outline of the research projects within each of these program areas is given below.

Gasification and core facility development

GCF001: Gasification Performance of Australian Coals - Pilot Gasifier Trials
This project aims to conduct a series of gasification trials using an existing pilot scale gasification facility. It is proposed that the project be conducted as a partnership between the CRC for Coal in Sustainable Development (CCSD) and cLET. The proposed project will provide the first coherent set of gasification performance data for a well understood suite of Australian coals in a globally recognised pilot scale entrained flow gasification facility.

GCF002: National Low Emissions Gasification Test Facility
In order to reduce the technical and commercial risks of implementing the low emissions technologies being developed generally, a gasification pilot plant of around $5MW_{th}$ is needed in Australia. This plant referred to as the *'National Low Emission Gasification Test Facility'* (NLEGTF) will provide a "backbone" facility for testing Australian coals at a realistic scale, in order to assess their suitability as feedstock or for use as a blended fuel with foreign coals and other fuels (servicing the export market) and their impact on gasifier performance. Optimisation of the gasifier technology for CCS (which is a development yet to occur in the commercial arena), and the development and integration of advances in dry gas cleaning will also be enabled. Such a facility will additionally enable the scale-up and testing of advances in syngas processing and separation that have been conceived in Australia and elsewhere, to the position of readiness for commercial demonstration. It will also be capable of extension to investigate concepts for co-gasification of biomass with coal (a benefit which additionally reduces carbon leakage when producing transport fuels from coal; see Section 5), hydrogen storage and power technologies such as fuel cells, and synthesis of liquid transport fuels. The scope of the "backbone" facility and its relationship to these optional concepts is shown schematically in Figure 14.

The funding of such a strategic facility will require the resources of government and industry. An initial submission was therefore made to the NCRIS to register the requirement with Federal Government and the coal industry's Coal 21 Fund. Work towards obtaining a reliable cost estimate for the facility and development of a business plan has commenced.

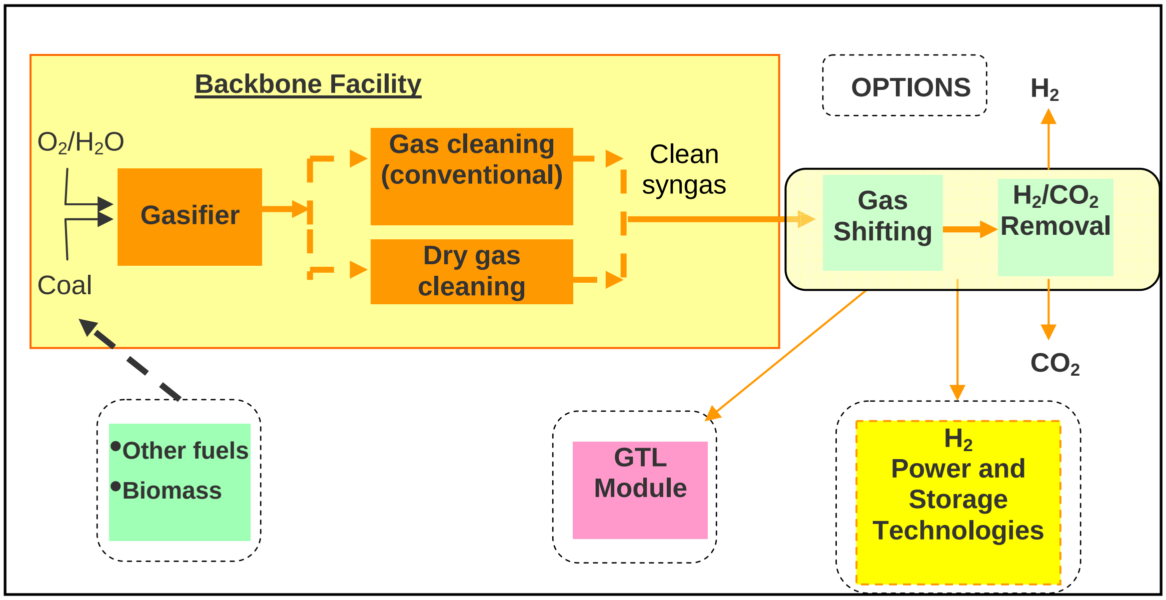


Figure 14. The proposed National Low Emissions Gasification Test Facility (NLEGTF) and optional components.

GCF003: Syngas Generator
This project aims to establish a relatively simple syngas generator which will be capable of gasifying approximately 20-40 kilograms per hour (kg/h) of coal to provide a stream of high pressure, 'real' coal-derived syngas**.** The stream will enable research scale test units to be provided with real syngas in quantities sufficient to support the experimental proof of concept program being conducted in the gas cleaning, processing and separation areas**.**

A supplier for the syngas generator has been identified, and a contract for a detailed design and costing has been placed with that supplier. The second phase involves the fabrication, installation and commissioning of the facility at CSIRO-QCAT in Brisbane where cLET is located.

Gas cleaning

GC001: Dry Gas Cleaning
The aim of the project is to develop cost effective filter protectors, sorbents and polisher bed materials to produce ultra clean syngas from coal for clean power generation and hydrogen production. Current objectives are identification of the best candle filters for performance and durability, protectors for candle filters to ensure reliable ash removal and protection from corrosion, and cheap, once through or recyclable sorbents and guard bed materials for contaminant removal to protect downstream components and the environment. The achievement of these objectives involves rigorous thermodynamic modelling, important experimental tests and development of the required laboratory test facilities.

Gas processing

GP001: Catalysts for Water Gas Shift Reaction with Coal-Derived Syngases in Fixed-Bed and Catalytic Membrane Reactors

While catalysts for the water gas shift reaction are commercially available and could well be ranked as mature for application to natural gas-derived syngases, where the CO concentrations are in the range 5-10%, this is not necessarily the case for coal-derived syngases. CO concentrations in these systems are in the range 40-60%, so a considerably higher degree of shifting is required. Coal-derived syngases are also likely to have much higher H_2S concentrations and other impurities that can severely degrade catalyst activity. This project therefore seeks in the first instance to measure the performance of commercially available catalysts in the environment that they might encounter when applied to coal-derived syngases. This includes high partial pressures of CO in the feed gas, and atmospheres that have high concentrations of H_2 or CO_2 as might be encountered in a packed–bed membrane reactor application. This phase of the work will identify whether there is a need for further catalyst development to meet the particular challenges of this application.

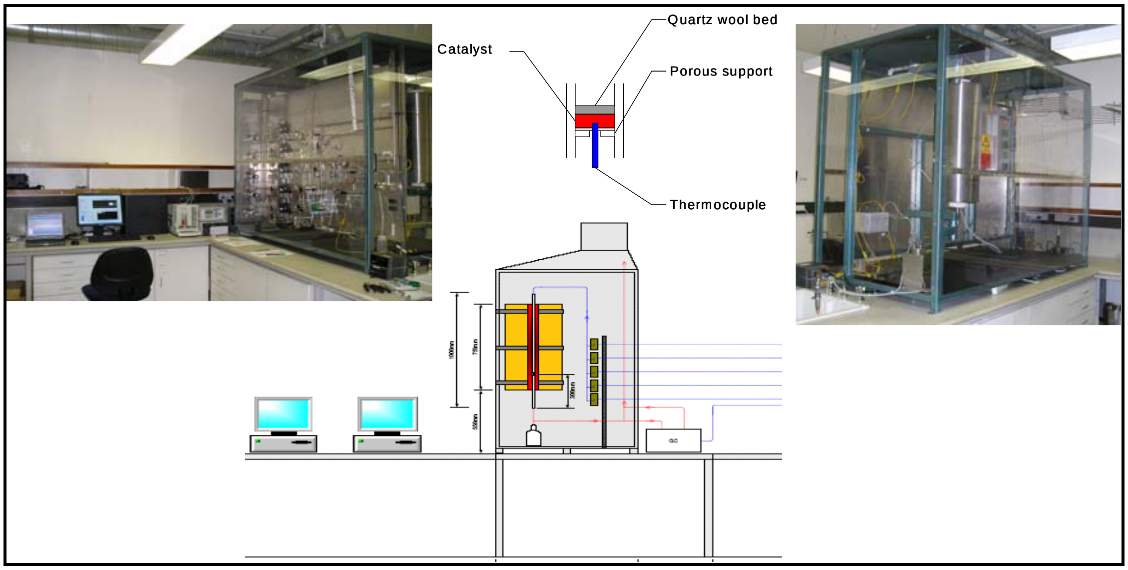


Figure 15. View and internal details of the cLET syngas processing rig.

A bench scale experimental rig shown in Figure 15 has been established for this purpose at CSIRO-QCAT, and test work on catalysts from commercial suppliers is underway.

GP002: Water Gas Shift Reactions in High Temperature Membrane Reactors

Metal membranes are being considered as potential means of separating H_2 from other process gases because of their very high selectivity to H_2 (approaching 100%). Recent work suggests that at elevated temperatures metals used in the fabrication of the membrane support (such as Nickel [Ni]) could become active for the water gas shift reaction. The project is therefore investigating the catalytic activity for the water gas shift reaction of metal alloys that might be used to fabricate the porous metal supports.

The aim is to make a high temperature metal membrane separator that can also function as a water gas shift reactor without the need for added catalyst.

A range of metal alloys with the potential to meet this purpose have been obtained in powder form, and are being evaluated for their water gas shift activity in the rig shown in Figure 15.

Gas Separation

GS001: Proof of Concept Engineering Membranes and Catalytic Membrane Reactors
Membrane separators have considerable development potential for reducing the cost of separating H_2 from processed syngas, relative to the commercial physical solvent processes that would be used in a current state-of-the art design for an IGCC plant with CCS (Figure 11). There is further potential for cost saving if the membrane is integrated with the shift reactor, a concept known as a Catalytic Membrane Reactor. The advantage of this arrangement is that the removal of the hydrogen reduces the concentration within the catalyst bed, removing the thermodynamic limitation to the achievable conversion at a specific temperature.

This project aims at developing proof-of-concept membrane separator and catalytic membrane reactor systems for application to syngas. In Catalytic Membrane Reactors, the arrangement of the catalyst bed with respect to the location of the membrane is an issue with respect to both the performance and membrane/catalyst material compatability.

Porous silica membranes have potential advantages over metals in terms of resistance to embrittlement and corrosion in a syngas atmosphere. Background IP held by the University of Queensland has reduced the susceptibility of silica membranes to hydrolysis by steam in the syngas, but further refinement is required to improve their permeance and selectivity to H_2 rather than CO_2.The micro-structure of the substrate used to support the membrane is critical in these respects, with a pore structure having progressively finer surface layers known to show superior performance. A ceramic substrate is a better match to the thermal expansion characteristics of a silica membrane, but subsequent mounting and sealing this substrate within a pressure vessel in a scaleable manner then become key issues. The form of the membrane array (tubular or planar) may also influence the optimum gas distribution arrangement; this is being studied using computational fluid dynamics (CFD) software.

GS002: Thin Film Metal Membrane for Hydrogen Separation
The aim of this project is to develop metal membranes for separating hydrogen from syngas. Metal membranes may be classified as either crystalline or amorphous in nature; both are being investigated within this project. Crystalline palladium (Pd) membranes may achieve high performance, but are very expensive and rely upon a scarce metal of strategic importance. There is considerable incentive to reduce or eliminate the Pd component to develop a lower cost crystalline metal membrane. Current amorphous alloy membranes have the necessary thermal stability for operation at the temperature of conventional water gas shift catalysts (450^oC), but lower permeance for H_2 than current

crystalline Pd membranes. Refinement of the membrane alloy composition and structure to overcome the problems of failure due to phase transitions during thermal cycling, hydrogen embrittlement and poisoning by syngas impurities such as H_2S and CO is required.

The aim of this project is to develop a high temperature metal membrane compatible with the process requirements of hydrogen separation from the syngas of IGCC with CCS, and the potential for use in a Catalytic Membrane Reactor.

A high temperature and pressure membrane test rig to evaluate membrane performance in a syngas system has been established at CSIRO-QCAT, as shown in Figure 16. This rig is being used to test membranes developed by CSIRO and their collaborators to increase thermal stability.

Figure 16. Metal membrane test rig.

The roadmap for the development of IGCC with CCS

Figure 17 shows the pathway for the development of coal-fired IGCC technologies with CCS for power generation.

The current state of development of coal-fired IGCC plants without CCS may be classed as being near commercial, with 4 plants in operation globally in the USA, Spain and the Netherlands with a total power generation capacity of around 1 GWe. The cycle efficiency of these early power plants is in the range 38-44% lower heat value (LHV) depending on the fuel feed, gasifier type and operating conditions.

The highest efficiency plant located in the Netherlands operates in a dry feeding mode using low sulphur coals and uses a water cooled membrane wall gasifier operating at relatively high gasification temperatures. The plants operating in the USA in Florida and Indiana employ wet slurry feed systems and refractory lined gasifiers that operate at slightly lower gasification temperatures and hence lower cycle efficiencies. Both of these plants have also been recently converted to operate on high sulphur petroleum coke residues due to the cheaper fuel costs. The fourth plant located in Spain, although based on dry feeding with higher temperature gasification, operates at an intermediate efficiency due to the use of lower quality fuel that is a mixture of high sulphur petroleum coke and a high ash coal.

The first applications of IGCC plants with CCS as noted in Section 5 (and Figure 11) will likely involve the use of solvent based precombustion capture technologies that currently do not operate in a mature market. This being due to the fact that there has been no experience in operating CO_2 capture technologies on a large scale in fully integrated power plant systems. Thus as shown in Figure 11, the '*first generation*' or conventional IGCC plants with CO_2 capture will require a relatively high degree of learning for the implementation of fully integrated commercial scale power systems with CCS.

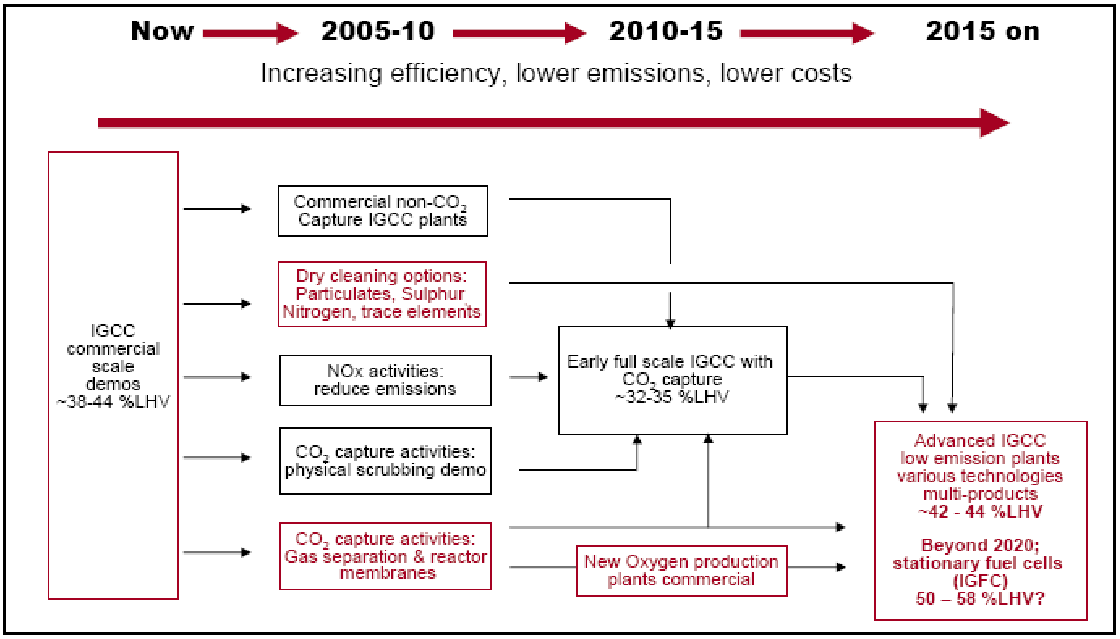


Figure 17. Technology pathway for the development of IGCC plants with CCS.

As shown in Figure 17, the cycle efficiency of these early '*first generation*' IGCC plants with CCS is also expected to be much lower at 32-35% LHV compared to the standard achieved currently for the base IGCC plant without CO_2 capture. Further improvement in the power generation efficiency in future plants would require improvements to the base cycle efficiencies of the power generation block and a range of enabling technologies as discussed earlier in this section to achieve improvements to the gasification, gas cleaning, processing and separation processes in '*second generation*' IGCC plants (Figures 12 and 13). Additionally improved membrane based technologies for oxygen production will also improve the net cycle efficiency. These developments shown in Figure 17 are expected to increase the cycle efficiency of future IGCC plants with CCS to the 42-44% LHV range when operating in a combined cycle mode. Even higher cycle efficiencies in the 50-58% range could be achieved with the use of hydrogen in fuel cells developed for stationary power generation.

As noted in Section 5 and Table 1, the cost of electricity production in the early *'first generation'* applications of IGCC plants with CCS (due to the current state of technology maturity), is expected to increase by between 34-50% relative to the base technology without CCS. Moreover, from our current understanding of historical trends in cost reductions achieved as a result of technology learning and implementation, it is expected that these costs will reduce by at least 20-30% over the next decade with more widespread deployment (IPCC, 2005).

Even higher cost reductions may be anticipated with the development of advanced technologies in *'second generation'* IGCC plants that increase the efficiency of the power cycle, reduce the energy penalty for CO_2 capture and which reduce the complexity and capital costs of a number of process units deployed in the power plant. *The current cLET R&D program, in pursuing both efficiency and technology improvements, clearly seeks to achieve a substantial cost reduction goal for electricity and/or hydrogen production in emerging IGCC CCS plants.*

It is not clear at the present time which projects for early, large scale demonstration of IGCC with CCS are likely to be implemented in Australia under the Commonwealth Government's Low Emission Technology Demonstration, the Queensland Clean Coal Project and the Coal 21 funds. Once determined, cLET will link its program initiatives to support these technology platforms and to achieve commercial outcomes from its current program of work. Additional funding of the cLET program would be required to address these latter outcomes.

7: Public awareness and social acceptance of CCS technologies

The main thrust of research into low-emissions electricity has been focused on technology solutions which work towards meeting the imperatives of sustainability without impacting on society. Technology alone however, cannot change energy behaviour if it is not taken up by society. For example, one only has to look to earlier technology examples including biotechnology such as genetically modified foods and the introduction of nuclear power in Europe to recognise the potential for things to go wrong. Given that CCS is a perceived high risk technology, it requires carefully considered communication activities to ensure stakeholders understand the benefits it offers as part of the solution to climate change.

There are only a small number of studies to date that measure public perceptions of CCS with the majority using large scale surveys for their methodology. The resounding finding, of all of these studies, is the limited knowledge the lay public holds about the technology. As such, there is an identified need for increased education and dialogues around CCS to ensure the range of public stakeholders are well informed about its pros and cons.

This need has been recognised at the international level by Article 14(a) of the Gleneagles G8 forum communiqué (July, 2005) which encouraged the IEA and the Carbon Sequestration Leadership Forum (CSLF) to “work with broader civil society to address the barriers to public acceptability of CCS technology”.

Recognising this need, and the need to establish a better understanding of where the Australian public sits in relation to CCS, cLET has engaged in a program of social research around low emission technologies. The main aims of the research are to:

- Establish a baseline of attitudes to low emission technologies;
- Understand the issues and concerns associated with clean coal in more depth;
- Inform the decision making processes of cLET partners;
- Provide an opportunity for the social shaping of low emission technologies;
- Engage with environmental organisations and influential stakeholders.

The cLET research program has utilised a mixed methodology including both quantitative and qualitative approaches which included two large scale CATI surveys conducted 12 months apart combined with smaller facilitated workshops in various regional locations. The research has focused on Queensland but is currently being extended into New South Wales.

Like other international studies, the state-wide survey confirmed the limited knowledge the general public hold about CCS. As shown in Figure 18, when asked the question “what do you understand by the term carbon capture and storage?”, 70% (637) of the 900 participants did not know the answer and another 15% (120) gave no meaningful response in their answers. Further analysis showed the two demographic indicators that differentiated between those who had some understanding of CCS from those who had not was education and location. The more educated participants were the more likely they were to know about CCS and if they were situated in a region where CCS was being investigated they knew more about this technology.

This was also confirmed in the qualitative study which showed that across the range of low emission technologies, on average, participants rated their knowledge about CCS lowest. On a scale of 1 (low) to 7 (high) the mean rating across the first workshop was 3.4. Interestingly, it was also the topic most participants (74%) requested to be included in the follow up workshop. By the end of the second workshop, on average, participants rated their knowledge at 5.7.

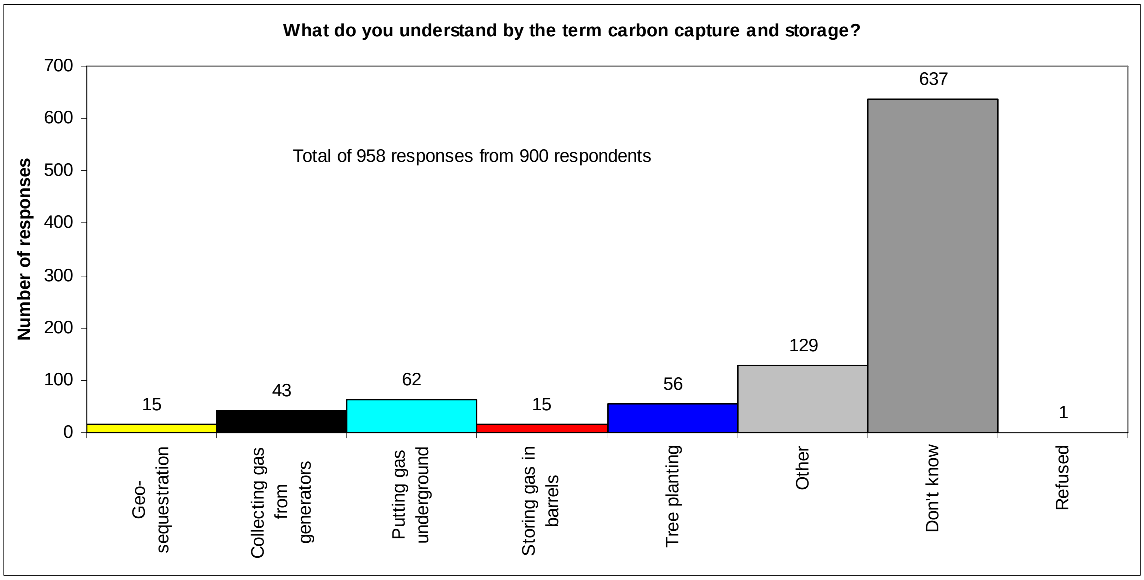


Figure 18. Understanding of the term carbon capture and storage.

Questions and Concerns about CCS

The major concerns arising from the international studies about CCS tend to focus on:

- The technology being still relatively unproven;
- The possibility of leakage from either transportation site or from the sequestration site;
- Overall effectiveness of CCS as a mitigation strategy;
- The development of CCS should not be at the expense of renewables - both need continued funding for research and development;
- Storage in oceans and waterways is generally unacceptable; and
- Energy security.

Similar concerns were replicated in the qualitative results of the cLET research and are best highlighted in the questions raised about CCS throughout the workshops. These included:

- How is CO_2 transported? Is it in a fluid form?
- What is the process for capturing?
- What sort of leakage do you get from pipelines?
- How far are we talking about transporting CO_2?
- Is anyone worried about terrorists?
- Is anybody doing this?
- What’s the worst case scenario putting carbon back?
- Is it odourless?
- So would we have to be careful in putting anything back down into the ground that it would not wipe out a whole town? So it can’t blow up?

- Is there a difference between ocean and land storage?
- We know that the ocean takes up CO_2 and would do the same if it escaped? What effect would this have?
- If we are putting it underground and storing it near water streams for 50 – 100 years what if it leaks and goes into the water system?
- Something worries me about the geo-sequestration. How long has it been going on and how can we actually guarantee that we aren't going to be suddenly consumed by a huge bubble of carbon dioxide after an earth tremor or something?

During the workshop information to demonstrate there is already a pipeline carrying CO_2 which has experienced no significant negative effects and the oil industry has been using CO_2 in EOR helped to overcome many of the concerns that individuals raised in relation to CCS.

In all countries the general public demonstrated a preference for renewables in some form however, when presented with cost and reliability issues individuals were happy to consider CCS as part of the portfolio of options and were more positive about CCS being part of the solution which is best demonstrated in the quote from one of the workshops shown below.

> *I have been doing more research in the area and I guess I know a little bit more about carbon sequestration, which I am still a little bit distrustful of, but I'm more open minded about it now. I think it's being more open minded to the options and not seeing things in black and white. The whole idea of a mix of energy is what we need to do not just wishing it was all renewable.*

Recommendations for CCS acceptability

To enhance the acceptability of CCS a number of recommendations can be made by drawing from the results of the work that has been done to date on public perceptions to CCS. One important message is that education is crucial to developing an understanding of the technology. However, any information that is presented on the topic must be seen as balanced and independent and be delivered from a trusted source. Setting discussions around CCS in the broader context of climate change is also important as it allows people to understand the seriousness of the problem and the need for effective mitigation strategies.

The idea of an independent regulator to manage and monitor any CCS projects was also raised in most studies. It was suggested this if such a regulator was comprised of government, industry and environmental NGO's it would seriously enhance the acceptability of the technology to be part of the portfolio of solutions. Most of the studies also recognised the importance of the media's portrayal of CCS in shifting attitudes about the technology.

There is no doubt that a major education initiative on climate change and the range of options to mitigate greenhouse gas emissions is required in the near future to bring about the required changes to achieve a 550ppmv target. Such an initiative must focus on the range of stakeholders including media, government departments at all levels, industry, schools and the wider public. Using an approach similar to cLET's which incorporated a steering committee of NGO's, industry and independent research organisations is also essential as it ensures credibility and independence in the information presented.

8: Conclusion

The global demand for energy is expected to grow substantially during the 21st century, with the affordability and availability of the resources and exploitation technology determining that fossil energy will be used to meet most of this demand.

In the near term, energy efficiency measures and renewable technologies will be an inadequate response to reducing the carbon emission consequences of meeting the growth in energy demand to 2030, and can make only a minor contribution towards stabilising atmospheric carbon dioxide levels in the atmosphere.

The distribution, amount and cost of coal resources relative to oil and gas with a lower carbon content implies that substitution by these fuels will have little impact on the energy demand or in reducing carbon emissions.

Fossil fuel technologies with carbon dioxide capture and storage (CCS) present a viable low-cost option for carbon emissions reduction to mitigate climate change, with the potential to achieve a very deep reduction in these emissions without disruption of either the existing global energy infrastructure or the economic drivers needed to make a transition to a sustainable energy system possible.

The goal of a climate sustainable energy supply and distribution system may be realised through decarbonised electricity and hydrogen production in stationary units; low emission fossil fuel technologies with CCS therefore provide a means of bridging the supply of these commodities during transformation of the energy infrastructure.

The inevitable depletion of global fossil energy resources would dictate that the ultimate goal of achieving a climate sustainable energy supply and distribution system requires the parallel development of renewable energy resources in a mixed portfolio approach together with energy efficiency and conservation measures to reduce global energy demand.

An Integrated Gasification Combined Cycle (IGCC) unit with CCS is comparable in the cost of electricity production from coal to other coal-fired CCS technologies, and is unique amongst them in having the potential to become the lowest cost technology for hydrogen production when the demand for natural gas forces a future upward adjustment in price.

There is substantial development potential in optimising IGCC for CCS, and in reducing the cost of electricity and hydrogen production through improvements in the gasification, gas cleaning and gas processing systems; these issues are the focus of the concepts being developed in the Centre for Low Emission Technology’s current R&D program and its forward plans.

It is in the Australian interest that IGCC with CCS should be demonstrated, and that improvements to the technology may continue in order to achieve an environmentally sustainable outcome for the economic exploitation of our coal reserves.

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Executive Summary
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1: Introduction
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2: The nexus between climate change and energy
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3: Technology options for a carbon constrained energy infrastructure
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Centre for Low Emission Technology, Brisbane

4: Vision for low emission technologies in a transformed global energy infrastructure
Kelly Thambimuthu
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5: Technology maturity and the global economic potential of CCS
Kelly Thambimuthu
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6: The cLET R&D program on low emission clean coal technologies
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7: Public awareness and social acceptance of CCS technologies
Peta Ashworth
CSIRO Exploration and Mining, Brisbane.

8: Conclusion

Graham Reed and Kelly Thambimuthu
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Layout

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