Research Opportunities in Post Combustion CO_2 Capture

Lead Authors
Paul Feron[1]
Barry Hooper[2]

Contributing Authors:
Moetaz Attalla[1]
Narendra Dave[1]
Sandra Kentish[2,3]
Geoff Stevens[2,3]
Leigh Wardhaugh[1]
Paul Webley[2,4]

[1]CSIRO Energy Technology
[2]CO2CRC
[3]University of Melbourne
[4]Monash University

October 2009

A report commissioned by Australian National Low Emission Coal R&D Program

ACKNOWLEDGMENT

The authors wish to acknowledge the financial support provided by the Australian National Low Emissions Coal R&D (ANLEC R&D) Program, which is funded in part by the Commonwealth Government of Australia and the Australian Coal Association Low Emissions Technology Pty Ltd.

Disclaimer

Use of the information contained in this report is at the user's risk. While every effort has been made to ensure the accuracy of that information, neither the Australian National Low Emissions Coal R&D (ANLEC R&D) nor the authors make any warranty, express or implied, regarding it. Neither ANLEC R&D nor the authors are liable for any direct or indirect damages, losses, costs or expenses resulting from any use or misuse of that information.

The views offered in this report may not be considered as necessarily representative of organisations commissioning or undertaking this work.

Copyright

LIST OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Executive Summary

ANLEC R&D has commissioned CSIRO and CO2CRC to execute a PCC scoping study with a particular aim to investigate how the existing knowledge basis for PCC in Australia can be best utilised in the upcoming PCC demonstration plants, thus providing a clear line of sight between the research and the ultimate commercial application. The study recognises and builds upon the recommendations from the PCC state-of-the-art review completed in 2006 by Wibberley et.al, recognising that the global PCC activities have increased considerably, both in terms of research and development and in terms of technology demonstration.

An updated overview of PCC technologies is presented, clearly confirming that reactive gas-liquid absorption technologies are the leading technologies. Globally there are now significant publicly and industry funded research, development and deployment programmes in place which solely focus on PCC. In future power companies are expected to be able to choose from a range of technology suppliers, as many traditional power plant component vendors have set up PCC R&D programmes. Twelve such technology suppliers have been identified in this study. At least 25 PCC pilot and demonstration projects have been announced or realised over the last two years, firmly establishing reactive gas-liquid absorption technology as the leading capture technology. Australia has two significant R&D programmes in place. CSIRO is focusing on the reactive gas-liquid absorption with a pilot plant programme utilising real flue gas and a supporting research programme. CO2CRC has a broader research programme also with test facilities operating with realistic flue gases. These programmes are significantly different but to a large extent complementary.

The deployment issues with PCC processes are well-documented. They have also been confirmed through discussions with stakeholders like the generators and technology suppliers. In summary the main issues are:

- The high costs of PCC deployed in Australian power plants, predominantly as a result of the increased capital costs
- The presently limited emission controls in Australian power plants
- The increased cooling water demand due to PCC
- The high energy penalty of PCC, in fact any capture process
- The limited knowledge around the environmental impacts of PCC process and in particular its emissions
- The large impact of integration of PCC into power plants both on the steam cycle as well as the flue gas path
- The lack of experience of scale-up of PCC technology
- The stability of reactive liquid absorbents and fabrication materials
- The dynamics in operation as a result of the variability in the Australian electricity market.

While several of these issues are addressed in the current offerings from vendors, it must be recognised that none of these technologies have been operated at commercial-scale on coal-fired power station flue gases. Moreover it is recommended that some of these issues require different approaches in the Australian environment and as minimum the vendors' offerings need to be evaluated under the Australian conditions.

Recommendations

The following **recommendations** for PCC-research were arrived at as a result of the assessment of current research activities, both nationally and internationally, and the desired research outcomes by ANLEC R&D as presented in this study:

Develop PCC solutions dedicated to Australian flue gas quality issues
The flue gas impurity issues for PCC with Australian flue gases are well-known but potential solutions would come at a high cost. Also these solutions need to be developed differently for Australian conditions than might be considered by vendors for overseas settings. A research focus on the investigation of interactions between SO_x, NO_x and other trace components and the liquid absorbents is likely to provide an insight into lower cost solutions for handling of the flue gas impurities.

Continue PCC Pilot Plant Programs
Since PCC solvents are sensitive to flue gas impurities, all flue gases are to a greater or lesser extent different, and the cost of large solvent degradation rates are high, it is necessary to trial existing and new solvents in pilot plants on a range of power plant technologies and coal types. In order to reduce the risk and cost for demonstration and commercial operation of PCC, it is therefore necessary to develop and compile a comprehensive data base of solvent performance against flue gas properties for existing solvents that are currently proposed and new solvents that will be developed in the future.

Address PCC environmental impacts in their totality
Environmental issues, such as water usage, the dispersion of NO and in certain cases solvent and solvent breakdown product emissions need to be addressed from a rigorous scientific perspective. In addition to existing environmental research, activities need to be targeted at understanding the fate of PCC process emissions to the atmosphere, in addition to developing prevention, handling and remediation methodologies for waste products and waste streams.

Support PCC implementation in Australian power plants
The implementation of PCC in Australian power plants requires a thorough understanding of retrofit applications, including controllability, flexibility and power plant gas path and heat integration issues.

Reduce parasitic PCC process energy requirements
Research into options which limit the parasitic energy requirements of PCC continues to be at the forefront in many R&D programme, world-wide, as it leads to increased specific resource use and leads to an undesired step-change downwards in generation efficiency.

Integrate the use of renewables into PCC
In order to reduce the parasitic energy load of PCC on the power plant, there is an opportunity in Australia to utilise renewables, particularly concentrated solar thermal, to provide heat for CO_2 stripping from the solvent. Research is required to develop and demonstrate the integration of renewables into the PCC technology.

Reduce equipment size and costs
Capital costs are dominated by the equipment size, in particular those in the gas path. Important cost benefits in the Australian situation can be achieved through an R&D focus on reducing these costs in particular.

Reduce PCC process cooling requirements
Cooling requirements are closely linked to the energy penalty of a PCC process, but the resulting additional cooling water requirements can be reduced by other approaches as well.

Continue liquid absorbent process development and process validation
Underpinning research in reactive liquid absorbent technology is necessary as it is the technology of choice in the upcoming PCC demonstrations. The potential for improvement is large, but as yet untapped. Realisation of the full potential of reactive liquid absorption processes is best done by an integrated programme of demonstration plants, pilot plants and laboratory research, using the analytical facilities and pilot plants already available within the research organisations.

In addition to the identification of the scientific and technological areas of prime interest it is equally important for the researcher community to be able to engage with, and review, existing pilot and demonstration PCC projects. This will enable the provision of sound advice to key stakeholders and project proponents and will be a key part in the dissemination of these results and findings to a larger audience (research community, government and general public). The research results will also provide valuable feed-back to the research community, allowing the validation of research tools and capabilities and underpinning technology improvements and anticipated break-throughs.

Finally, the research facilities available in Australia (pilot plants, process and plant models, lab-based material and process evaluation tools) provide an excellent platform for the targeted development of PCC in Australia and it is recommended that this platform is used in support of the smaller and larger PCC demonstrations. International collaboration, e.g. with overseas technology providers, is an essential part of the technology development paths.

1. Introduction

1.1 Study background and rationale

ANLECR&D is developing an Australian national program for collaborative low emission coal research and development, and will oversee its implementation and operation. This R&D will be undertaken in ANLECR&D research nodes, which will be based on existing research centres. Post-combustion CO_2 capture is one of the seven research nodes. Post Combustion Capture R&D in Australia has two natural foci – CSIRO and CO2CRC, both with established programs and associated projects. The 2008 Lowe and Simento update to the IEA Study of Australian CCS R&D capability noted that the programs are complementary, high quality and address different issues [1]. CSIRO and CO2CRC were therefore invited to collaborate on the PCC scoping study.

The focus of ANLECR&D will be on facilitating early demonstration projects in the 2015 to 2020 timeframe. The PCC R&D program will necessarily focus on facilitating commercial deployment and optimising and adapting commercial technologies to local conditions and circumstances. While ANLECR&D will be focused on near term commercial scale deployment, identifying productive areas for near term research focus and constructive linkages to fundamental R&D would be very useful.

Consistent with the focus of ANLECR&D to facilitate early PCC demonstration projects in the 2015 to 2020 timeframe, it is recognised that the delivery of such research product and services will be one or a combination of the following purposes:

- Research that targets identifiable performance breakthroughs for equipment and processes envisaged by technology vendors/operators for significant cost reductions in next generation deployment of low emissions coal technologies
- Research that ensures robust validation and reporting of demonstration low emissions coal technologies performance in the public interest
- Research that identifies the unique features (benefits and impacts) that will inform technology specific measures of Australian coal quality used in low emissions coal technologies.

The main methodology followed in this report has been drawing on the existing experience and national and international contacts in the PCC field. In addition to this the publicly known proponents of PCC demonstration projects (power companies) have been approached using a short standard questionnaire which you can find in Appendix 1.

1.2 Previous work and its relevance to present study

In 2006 CSIRO and CO2CRC completed an extensive state-of-the-art review of PCC [2] consisting of:

1. International and domestic RD&D activities relating to post combustion capture (PCC) that were underway or planned at the time.
2. The development priorities that were being progressed for PCC.
3. The issues requiring resolution when applying PCC to the Australian context.

4. The prospectivity of PCC as compared to other coal based low emission technology options.
5. The development needs for PCC in the Australian context, by carrying out a gap analysis. This analysis is to provide the technical basis for developing the strategy for an Australian based integrated R&D, pilot and demonstration program.

The study recognised that reactive liquid absorbent technology was the most suitable near term technology for PCC applications because of the following advantageous attributes:

- Developments in PCC will enable it to be integrated into existing and new supercritical pf plants, to achieve a range of GHG intensity reductions down to low emissions (*i.e.* less than 75 kg CO_2/MWh).

- The overall cost of generation with capture by retro-fitting PCC to existing (older) plants, is likely to be comparable to that for new build, due to a lower capital charge which offsets the higher energy/CO_2 penalty for the older plants.

- Part of the cost effectiveness of solvent-based PCC is that most of the energy for the process is provided by low temperature heat (around 120°C) rather than by electricity. The smaller parasitic electrical demand for PCC reduces the capital cost multiplier, especially compared to oxy-pf combustion.

- PCC has higher operational flexibility (partial retrofit, variable zero to full capture operation) and can match market conditions for both existing and new pf plant. For instance, at a time of high power prices, PCC can be turned off and maximum power delivered to the market. There are a number of ways of achieving this flexibility without compromising the efficiency of the low pressure steam turbine due to the steam demand for stripping – partial, work-based or autonomous capture.

- Developments in PCC will lead to a lower technology risk compared to competing CO_2 capture technologies. This is further enhanced by the ability for staged implementation, which is not possible with competing all-or-nothing technologies (IGCC or oxy-pf).

- PCC has significant synergies with renewables. It will enhance the uptake of renewables via 1) direct integration, with solar thermal providing heat for the capture process, and 2) grid connection, with PCC providing a discretionary load to cover intermittency of renewables. PCC therefore provides a means for meeting peak demand.

- Overall, solvent-based PCC still has significant development potential, through process improvements and new sorbents, and the rate of these developments will be enhanced by the high flexibility and adaptability of the process. The alternative processes, especially the more novel Generation IV adsorption and membrane separation technologies, are not expected to be commercially viable for full scale pf applications until post-2020.

The review presented a PCC development and deployment vision based different technology generations as illustrated in figure 1.

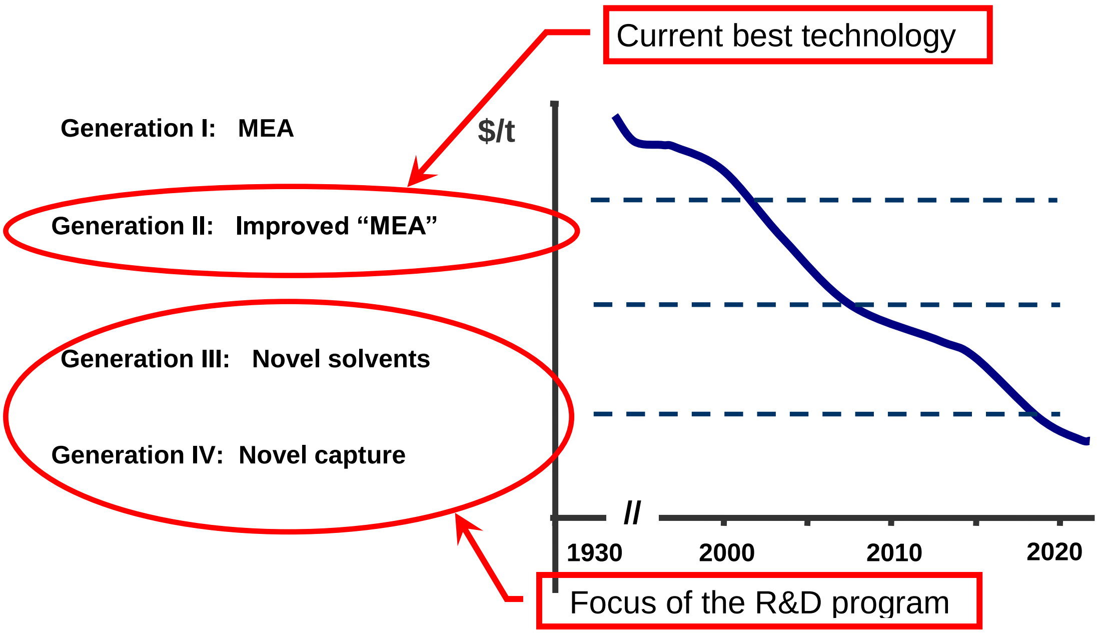

Figure 1: Generation based vision for PCC technology development [2]

The review resulted in the formulation of seven RD&D gaps:

Gap 1: Requirements (equipment, maximum readily achievable capture rate and emissions regulations) associated with the retro-fit of an existing pf plant using Generation II and III technologies.

Gap 2: The implementation of PCC in Australia offers the opportunity for integrated emissions control – removal of SOx, NOx, mercury, fine particulates, and CO2 in an integrated process.

Gap 3: PCC with fresh water cooling limitations due to 20% additional cooling/MWh, and a strong need to provide some cooling water below 30-35°C to minimise solvent slip and to provide sufficient cooling for liquefaction of CO2.

Gap 4: For Australia, the co-location of coal and power stations provides an opportunity for integrated PCC with ECBM, with an autonomous PCC based on hybrid repowering with an ECBM fuelled gas turbine providing the heat for both capture and an uprated base pf plant.

Gap 5: The opportunity to use solar thermal to provide stripping heat, which would be assisted by solvents that are stripped at lower temperatures.

Gap 6: Internationally there is no commercial scale demonstration of PCC on pf power station flue gases (i.e. there is no FutureGen equivalent for PCC). For the purposes of demonstration, 50-200 ktpa would be sufficiently large to demonstrate all of the features and performance of the larger scale.

Gap 7: The provision of facilities and resources to trial and develop Generation IV technologies.

Since 2006 considerable PCC developments have occurred both in Australia and abroad, such as:

- The successful establishment of CSIRO's PCC research and pilot plant programme as described in section 3.4
- The successful establishment of CO2CRC's research programme including on site test facilities as described in section 3.4
- The adoption of all major power plant technology suppliers of PCC as a core technology for CO_2 emissions reductions from power plants
- The announcement of financial support from Commonwealth and State Governments to two PCC demonstrations (New South Wales and Victoria).

In addition to this the now widely accepted urgency for Low Emission Coal Technologies to start making an impact on CO_2-emission reductions from coal fired power stations, as evidenced by the recently announced Clean Energy Initiative and the launch of the Global CCS Institute by the Australian government, require a recalibration of current research and development needs. The resulting recommendations for future research and development activities in Australia therefore need to ensure a clear focus on results and outcomes which can accelerate deployment of PCC as part of a CCS-chain. The present PCC scoping study will necessarily build on the previous state-of-the-art review [2]. It aims to extend and focus the ongoing research activities and (inter-)national collaborations with the aim of supporting the realisation and successful operation of a pre-commercial first-of-a-kind PCC plant. It is also intended that the continued low emission coal research will prove technology options for second generation plants, through an optimum combination of research engagement before and during the first-of-a-kind plant phase. Further information was obtained from a questionnaire which was sent to a number of leading power companies in Australia as well as international technology suppliers. The views presented by these stakeholders provided input into the research requirement for successful PCC deployment.

2. PCC Technologies

There is a wide range of separation processes being researched for carbon dioxide removal from flue gases. The State of the Art Review 2006 [2] went into some depth in the alternatives available and this report builds on that but focuses on reactive gas-liquid absorption, adsorbents, membranes and low temperature processes. Brief references are made to a range of dry reactive systems still under research.

2.1 Reactive gas-liquid absorption

Although several different processes are currently under development for the separation of CO_2 from flue gases, absorption processes using aqueous solutions of reactive gas-liquid absorption is the leading technology. The typical flow sheet of CO_2 recovery using chemical absorbents is shown in figure 2.

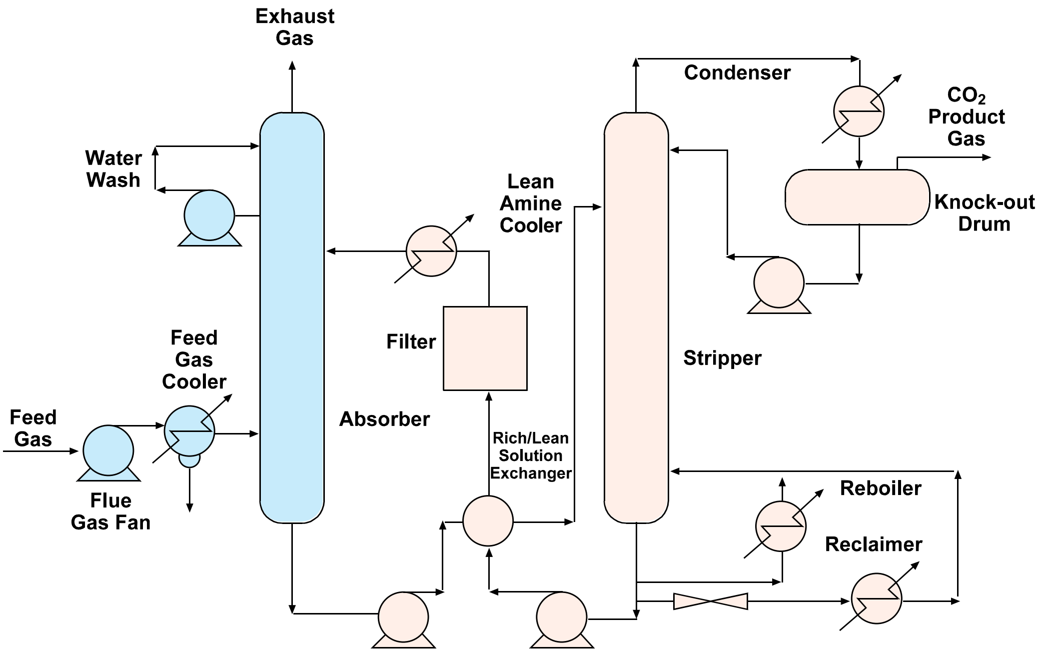

Figure 2 : Process flow diagram for CO_2 recovery from flue gas using reactive gas-liquid absorption

After cooling the flue gas, it is brought into contact with the chemical absorbent in the absorber. A blower is required to pump the gas through the absorber. At temperatures typically between 40 and 60 ^{o}C CO_2 is then bound by the chemical absorbent in the absorber. After passing through the absorber the flue gas undergoes a water wash section to balance water in the system and to remove any droplets or vapour carried over and then leaves the absorber. The “rich” absorbent solution, which contains the chemically bound CO_2 is then pumped to the top of a stripper, via the lean-rich heat exchanger. The regeneration of the chemical absorbent is carried out in the stripper at elevated temperatures (100 – 140 ^{o}C) and pressures between 1 and 2 bar(a). Heat is supplied to the reboiler to maintain the regeneration conditions. This leads to a thermal energy penalty as a result of heating up the solution, providing the required desorption heat for removing the chemically bound CO_2 and for steam production which acts as a stripping gas. Steam is recovered in the condenser and fed back to the stripper, whereas the CO_2 product gas leaves the condenser. The CO_2-product is a relatively pure (> 99%) product, with water vapour being the main other component. Due to the selective nature of the chemical absorption process, the concentration of inert gases is low and the CO_2 is compressed to pressures between 100 and 200 bars, ready for transport and storage. The "lean" absorbent solution, containing far less CO_2 is then pumped back to the absorber via the lean-rich heat exchanger and a cooler to bring it down to the absorber temperature level. CO_2 removal from the recycled solvent is typically around 90%.

One of the reasons for selecting liquid absorption processes for post-combustion capture processes is their state of development. This is demonstrated in figure 3 [3] which shows the application range of different technologies for CO_2 separation from atmospheric pressure gas streams in a graph of CO_2-production versus feed gas stream. A distinction is made between absorption processes only (light blue areas) and technologies based on adsorption, membranes or absorption (dark blue areas). Absorption processes are clearly the leading technology because they have been commercially deployed at the largest scale, but not yet in the scale of power plant flue gases.

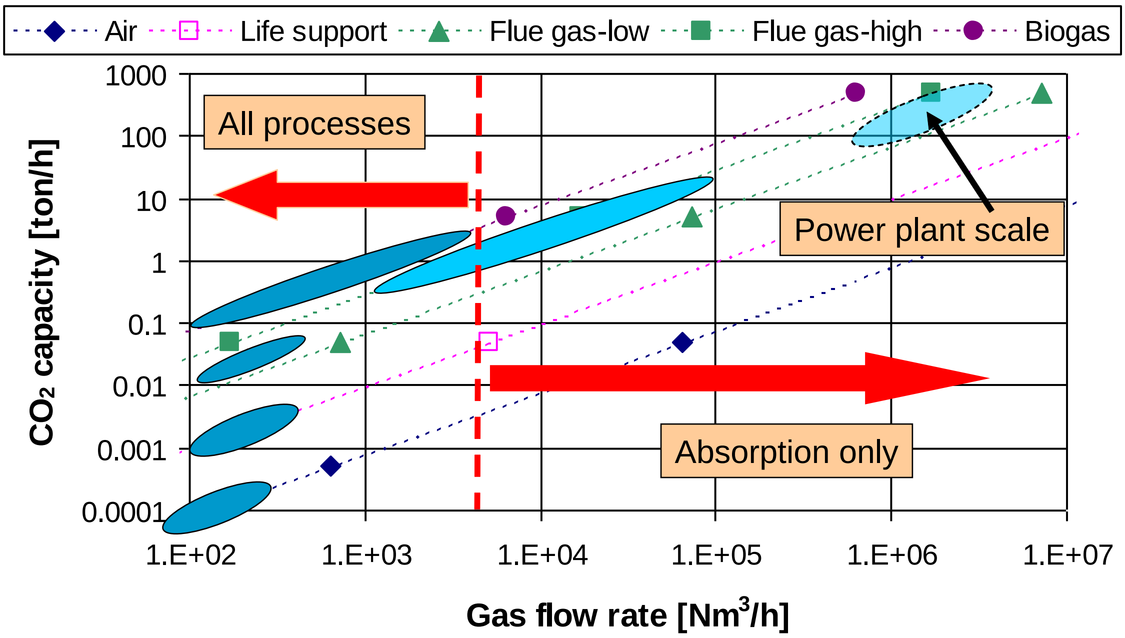

Figure 3 : Application range for different technologies for CO_2-separation from atmospheric gas streams

The impact of post-combustion CO_2 capture using a chemical absorption process on the power generation efficiency has been well documented [4]. The efficiency decrease is estimated to be 22.5% for 90% capture from a coal fired power station. Such decreases in efficiency result in commensurate increases in the resource consumption per unit of electricity output and even higher increases in the cooling water consumption per unit of electricity output. The latter is caused by the fact that any heat not converted into electricity will be discarded to the environment. The question arises whether these negative impacts of a post-combustion CO_2 capture process can be reduced to such an extent that they are acceptable both in economical terms and in terms of environmental impact.

Examples of solvents being investigated are (which are elaborated under Section 3.3):

- MEA (monoethanolamine) – the most commonly studied capture sorbent
- KS-1 – Mitsubishi Heavy Industries' sterically hindered amine
- Potassium Carbonate – commercially available solvent most often used at high pressures
- Aqueous Ammonia (various forms) – newer solvent process requiring low temperatures
- Amino Acids – nitrogenous solvents
- Ionic Liquids – novel solvents displaying extremely low vapour pressures
- Physical solvents such as Rectisol – requires high pressure or low temperatures to function

2.2 Adsorption

These processes use solid adsorbents such as alumina, zeolites and activated carbons. Gas adsorption is a cyclical continuous operation involving multiple beds in which at least one bed remains on line whilst the others are being regenerated by either the pressure swing (PSA), the temperature swing (TSA) or electrical swing (ESA) methods (figure 4). In a post combustion application, the flue gas would pass through a bed of solids and the CO_2 would be preferentially adsorbed. The flue gas, with most of the CO_2 removed, would then be emitted to atmosphere. The CO_2 laden solid in the fixed bed would then be subjected to a number of processing steps, using differences in either pressure or temperature, to remove and concentrate the CO_2 for storage.

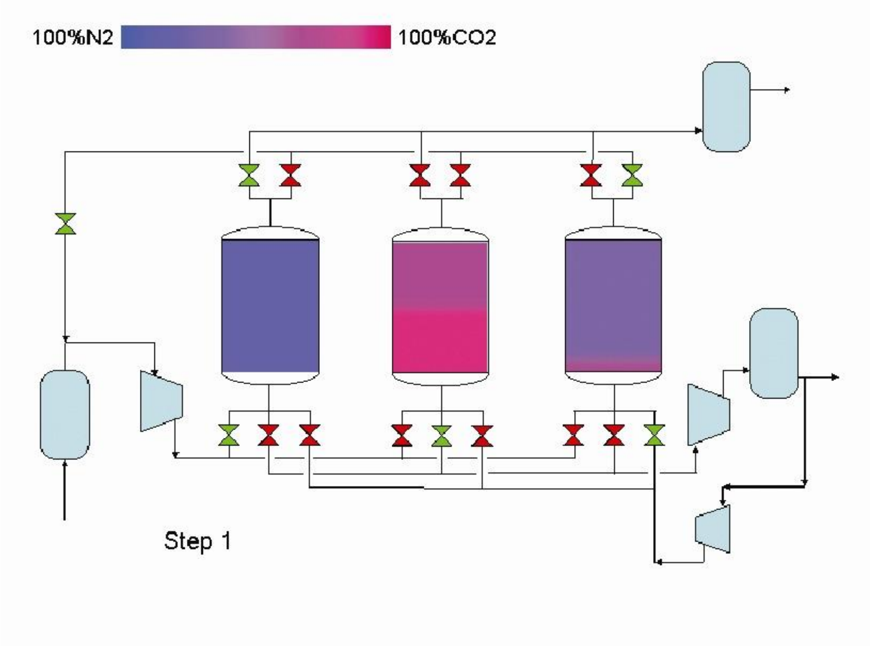

Figure 4 : Vacuum Swing Adsorption process configuration.

The key to developing any adsorption process is to select or develop an adsorbent material demonstrating the preferred relative adsorption characteristics for the gases involved and to then design the most advantageous form of cycle and/or process steps to achieve cost effective separation.

Adsorption is a well developed process in the field of bulk oxygen removal from air (in the form of vacuum swing adsorption or VSA) and is the process of choice for the removal of hydrogen for synthesis gas streams. Air Products Inc (USA) has commercialized Gemini®-5 pressure swing adsorption (PSA) processes to remove CO_2 from landfill gas.

In the last 3 years there has been increased activity in the adsorbents area not least in that of the CO2CRC. The relationships of process cost and process parameters are being examined through detailed simulation of VSA cycles and experimental validation.

As with all separation techniques for large scale CO_2 removal from power plant there are issues about impurity removal and the equipment is large. There are also issues of water removal should conventional zeolites be used. Many of these issues have been tackled in other adsorption applications and there is confidence that, with research, the challenges can be met. Larger scale plants based trials are underway as part of the CO2CRC H3 project in Victoria.

Economic evaluations by the CO2CRC still indicate a potential for adsorption as a prospective and emerging technology for the large scale CO_2 capture from flue gas.
As mentioned earlier, the other critical parameter in any adsorption process is the adsorbent material development and considerable advances are expected in this area. The materials are used either in pellets or in monolithic forms depending on the process requirements, particularly pressure drop.

Apart from the traditional zeolites, which still appear highly prospective work continues on mesoporous silicates, with various hybridised sorbents, carbon and the more recently developed metal organic frameworks (MOF's) and related high surface area materials.

2.3 Membrane separation

There are two broad areas of membrane separation being investigated for CO_2 capture, namely gas separation membranes and gas absorption membranes. The term facilitated membranes is also used to describe membranes that have enhanced selectivity through the inclusion of complexes that react with target molecules (these will not be covered here but are covered in the previous report [2].

Larger scale plants based trials are underway for these technologies as part of the CO2CRC H3 project in Victoria.

Gas Separation Membranes

This technology relies on the different permeabilities of gas molecules through a dense polymeric membrane. By knowing the permeabilities of different gas pairs, a process can be designed. This process relies on a pressure gradient to push the molecules through the membrane, thereby increasing the concentration on one side of the membrane (figure 5)

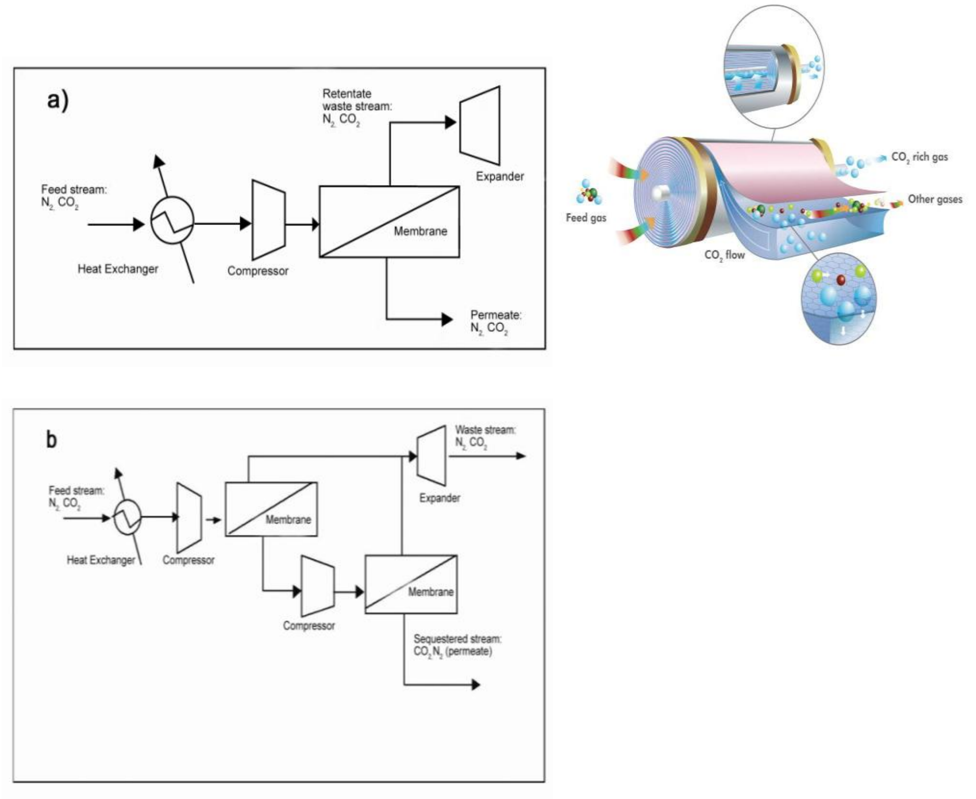

Figure 5 : Process Configurations for Gas Separation Membranes (Ho et al., 2005)

This technology is applied in commercial operation for CO_2 removal from natural gas, but it is only at an early stage of development for post combustion. A number of organic membranes have been used for separation of gases involving (H_2, CO_2, N_2, O_2, CH_4) using cellulose acetate, polyimides, polyamides, polysulfones, and polyphenylene oxide.

Inorganic membranes can be either ceramic or metallic. For the separation of CO_2 from flue gas, only the ceramic type is relevant. The ceramic membranes may be made of alumina, zeolites, carbon, silica or hydrotalcite type clay materials. Depending upon the pore size, they could be macro-porous (pore diameter >500 Å), meso-porous (pore diameter ~ 20 to 500 Å) or micro-porous (pore diameter <20 Å). Unless the membrane is functionalised only nanoporous membranes (3-8 Å) will work for CO_2 separation.

Early work in the area suggested that gas separation membranes were not economic for post combustion capture however this was based on high pressure configurations. Provided membranes of the appropriate permeability and selectivity can be produced, studies, by the CO2CRC and others, have shown that vacuum configurations of gas separation membranes can achieve competitive capture cost processes. Facilitated membranes appear to offer the ability to tailor the required permeability and selectivity parameters. Work is proceeding in a numbers of centres around the world in these areas, including CO2CRC, Meiji University, RITE, University of Texas at Austin, Lawrence Livermore National Laboratory, in collaboration with Enerfex Corporation, Membrane Technology Research Inc, and at NETL.

Recent new membranes developments by the CO2CRC and CSIRO have independently identified pathways to higher permeability materials that may lead to the breakthrough required for this to be a competitive process.

Key work on impurities impacts with various polymers structures have been published recently [5,6].

Membrane Gas Absorption

This is largely a gas-liquid contacting device that potentially lowers the cost of the absorption step for solvent processes. It has a robust membrane separating gas and liquid. Gas fills the pores and contacts the liquid to achieve the absorption step. It is possible to envisage a regenerator vessel using this technology (figure 6) and research is underway looking at this option b y the CO2CRC.

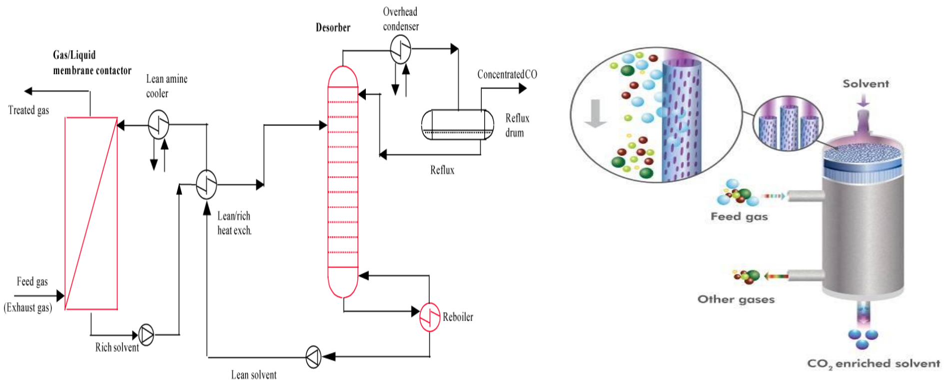

Figure 6 : Membrane Gas Absorption layout (after Aker Kvaerner).

The technology has been trialled in several settings but no commercial installation is yet built. While the trials have included power stations, the first commercial installation is likely to be on natural gas treatment.

The main requirement for the device is that the membrane used must not be wetted by the solvent, as this can result in the liquid blocking the pores, destroying the performance. Aker Kvaerner, the major supplier of these units, uses a robust Teflon membrane which is flexible, but also quite costly. Attempts to use cheaper membranes have, as yet required modifying the traditional amine solvents due to the wettability issue. The CO2CRC has patented cheaper membranes with superior surface characteristics to reduce costs.

Over the next 10-15 years, this could reduce the cost of the absorbers substantially. The cost of the membranes could potentially offset some of these costs; however the overall potential cost reductions tend to be embedded in projected solvent technology reduction figures.

One particularly novel system by Carbozyme involves the use of a solution of a carbonic anhydrase derivative (carbonic anhydrase is an enzyme involved in removal of CO_2 from the blood). This is included in the US DOE CCS Roadmap and warrants regular review.

The determining feature of the economics of post combustion capture with these materials, as gas separation membranes, will be their resultant permeability and selectivity parameters. Irrespective of the material any competitive such process is likely to be in a vacuum configuration (figure 7).

This data is from 2006 and is purely indicative of the relative merits of certain alternatives technologies. This supports the continued efforts in this area and will be need to be further validated as current demonstration programs proceed.

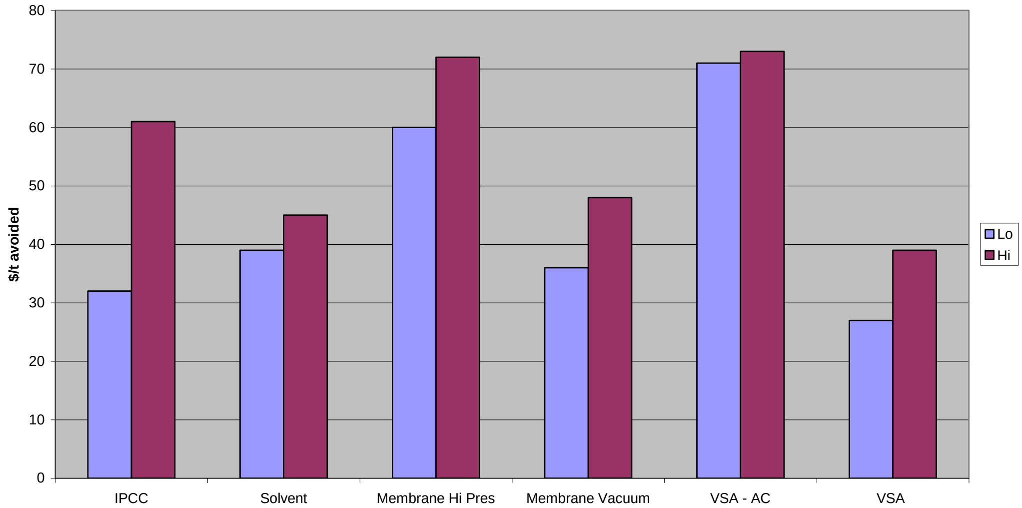

Figure 7 : Screening cost estimates for different technologies for PCC (CO2CRC)

As membranes are a relatively new technology, there are no large scale results from this process as yet. Integrating gas separation membranes into power plants is somewhat different to integrating solvent absorption, as they only require power rather than heat. Treatment of the gas will be required but the membrane system simply requires power for compressors and vacuum pumps.

Temperature and particulates will be issues and care must be taken with clearances and passage widths. Temperatures of 120°C have been cited as limitations but this tends to be for current formulations of glues rather than the membrane itself – the newer polyimide membranes are more resistant. Plasticisation of the membrane material (reaction with the CO_2) is an issue for the gas separation membranes.
One final point to note is that membranes are modular and hence scalability should be easily manageable.

2.4 Cryogenics

Cryogenic technologies are high pressure/low temperature systems in which CO_2 is separated either by liquefaction or by using a solvent or hydrates. This technology has potential for PCC but needs significant development.

The Ecole des Mines in association with Alstom, have been developed an anti-sublimation process as has Brigham Young University.

2.5 Dry Reactive Systems

For some years work has been progressing on processes involving the reaction of CaO with CO_2 in flue gas streams to produce $CaCO_3$ and then the reversal of that process at higher temperatures to release pure CO_2. The processes utilise solids being conveyed between an adsorber vessel and a regenerator.

This principle is also being investigated with MgO and dry processes involving carbonate/bicarbonate cycling. These latter systems, utilising Na and K carbonates operate at considerably lower temperatures of around 150 deg. C in the regenerator.

Considerable effort is underway in this area by a number of groups in the US, supported by the US DoE, and in Korea by KEPRI. Much of the research is on the performance of the particulates in the process and issues of solids handling. The inventors claim significant benefits in the costs of these systems and plans are in place for further scaling up of these processes in the next three to five years.

3. PCC State of the art

3.1 Significance of CCS

CCS is clearly recognised by the International Energy Agency, and other similar energy modelling groups around the world as a critical component of future low emissions energy mix (figure 8). The graph below from the IEA's Technology Perspectives (2008) shows one scenario projection and the importance of CCS in that mix.

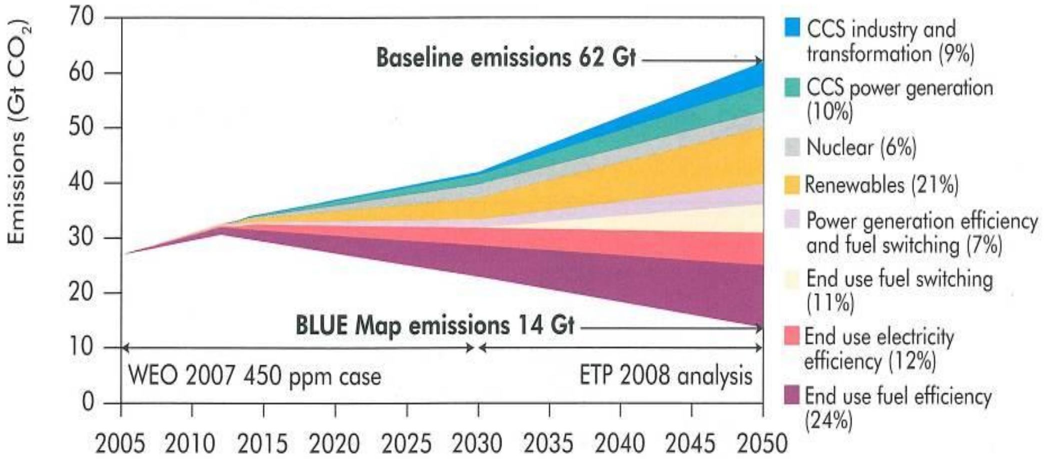

Figure 8 : IEA Technology Perspectives (2008) Emission reduction options, 2005-2050

Recognising the significance of CCS the Australian Government has announced the Global Carbon Capture and Storage Institute (GCCSI) to help facilitate the G8's plan for 20 large scale demonstrations by 2020. The institute has initiated a number of international reports on the state of the art however they are yet to become available.

The authors have provided an overview based on our international connections and this provides a strong basis of the global status in PCC. Nevertheless once GCCSI provides the results of its findings and database it would be appropriate to check for omissions from either report to identify any significant differences that may create. The information presented in section 3.2 and 3.3 had been to a large extent derived from [7].

3.2 Global PCC developments

European Union

PCC research started gaining momentum in the European Union in 2004 with the start-up of the CASTOR project (www.co2castor.com). This 10 MEuro project partly funded by the EU 6^{th} Framework Programme and supported by leading companies like Statoil, Vattenfall, RWE and EON resulted in the establishment of the first PCC pilot plant at a coal fired power plant in Esbjerg, now operated by Dong Energy. The pilot plant is based on reactive liquid absorption for the capture process. Although the CASTOR project finished in 2008, work is continuing in EC funded follow-up projects like CESAR (www.co2cesar.eu), partly funded through the 7th Framework programme. International cooperation was established with Canada, China and Russia through the CAPRICE project (www.caprice-project.eu). The research thrust in these projects is provided by a strong partnership of research organisations in the Netherlands (TNO), France (IFP) and Norway (SINTEF/NTNU).

Netherlands

CCS research in the Netherlands was started up in the late 1980's, already. PCC research activities in the Netherlands received a significant boost in 2004 through the establishment of the CATO programme (www.co2-cato.nl), which was completed at the end of 2008 and moved into a second phase in 2009. During the first phase a PCC pilot plant was established by TNO at the Maasvlakte on a coal fired power plant operated by EON. The pilot plant utilises reactive liquid absorption as the capture process. Other capture work, including PCC, was initiated through the CAPTECH project (www.co2-captech.nl), a smaller consortium of companies, research organisations and universities. The PCC activities are focused on reactive liquid absorption, but also some membrane research is part of the programme.

Norway

The CLIMIT Programme is the Norwegian national programme for research, development or demonstration of technology for the capture, transport and storage of CO_2 in connection with gas-based energy production. The Programme is managed by Gassnova in cooperation with the Research Council of Norway.

Responsibilities have been divided: whereas the Research Council of Norway is in charge of the research projects, Gassnova is responsible for the prototype and demonstration projects. Through the CLIMIT Programme, Gassnova allocates grants to projects that aim to develop know-how and solutions for:

- Processes for natural gas-based power generation with CO_2 management
- Technology for CO_2 capture in connection with power generation
- Compression and transport of CO_2
- Long-term removal of CO_2 from the atmosphere, either by injection in geological formations or developing other areas of application
- Linkage of technologies in a value chain to ensure the realisation of gas-fired power plants in Norway with CO_2 management

Under the CLIMIT programme, Gassnova SF and the Research Council have an annual budget of NOK 80 million and NOK 50 million, respectively, and both organisations are responsible for final approval of grant awards and following up projects receiving funding. The intention of the CLIMIT programme is to promote technology development through close cooperation between industry and the authorities. Project support is expected to maintain a ratio of 2:1 industry funding to public sector funding, which implies overall research activity totalling more than NOK 400 million per year in Norway.

United Kingdom

The UK CCS Demonstration Competition was launched in November 2007 to build the world's first full scale CCS power plant in the UK. The criteria against which proposals will be assessed are likely to include the need for any project proposal to:

- be located in the UK;
- cover the full chain of CCS technology on a commercial scale power station (capture, transport and storage);
- be based on sound engineering design (reliable and safe) underpinned by a full front-end engineering and design study;
- set out the quantum of financial support requested;
- be at least 300 MW, and capture and store around 90% of the CO2 and thereby contribute at least an additional 0.25 Mt/yr of CO_2 savings to the UK's domestic abatement targets (relative to gas-fired power station of equivalent size without CCS);
- start demonstrating the full chain of CCS at some point between 2011 and 2014;
- address its contribution to the longer term potential of CCS in the UK, (for example, through the potential of shared infrastructure) and to the international development of CCS; and be supported by a creditworthy developer entity.

In the 2007 White Paper, the UK Government signalled support for up to three different demonstration projects. It was since decided that the competition will be restricted to a single post-combustion coal-fired project. In May 2009, however, the Government again signalled a greater appetite for projects and the funding of up to four demonstration projects. It is our understanding that the competition for the single post-combustion project will go ahead as planned and that the three other projects will be announced separately. The 2007 decision to limit the competition to post-combustion was founded on the argument that post-combustion capture is the most relevant technology to the vast proportion of coal-fired generation capacity globally. The rationale is that a commercial-scale demonstration of this technology, as part of a full CCS chain, opens up huge possibilities, not just for UK but also for the world.

To incorporate an international dimension, project developers will be expected to include proposals for knowledge and know-how transfer to third parties. These will need to be sufficient to meet the Government's aims to encourage the wider deployment of CCS in the UK, Europe and internationally, particularly in countries with significant future energy needs such as China and India. The UK is working with the EU Commission to ensure that the development of CCS in the UK fits with the objective agreed at the European Council in March 2007 to have in place up to 12 CCS demonstration projects in Europe by 2015.

Scottish Power is planning to convert the Longannet and Cockenzie power plants to clean coal technology by fitting supercritical turbines and boilers. The plants would incorporate post-combustion carbon capture technology on the combined generation capacity of 3390MW, and the new plants could reduce carbon emissions by 20%. The Longannet plant is in the run-up for the Government funding competition. Partners are Aker Clean Carbon for the capture technology, Marathon Oil for the transportation via existing North Sea pipes, and Edinburgh University for the identification of long-term storage in sub-sea rocks. Alstom Power and Doosan Babcock will provide the design input for the 'supercritical' turbines and boilers. Aker

Clean Carbon opened its 1 MW sized mobile test unit at Longannet in May this year. It is the first time that CCS technology is in use on an operational coal-fired power station in the UK. The new 'supercritical' turbines and boilers, which will burn coal at ultra-high temperatures and pressure, may be built within the existing power station buildings.

Plans to build two new supercritical units of 800 MW at the Kingsnorth coal-fired power station in Kent have been announced by E.ON UK. The units would be built next to the existing power station, reducing carbon emissions by 2 million tonnes per year. The units would be designed as capture ready, to be fitted with post-combustion carbon capture and storage at a later stage. The Kingsnorth plant is one of three finalists in the Government funding competition. The partners supporting E.On on Kingsnorth are:

- Arup for project management,
- EPRI for international technology dissemination,
- MHI (Mitsubishi Heavy Industries) as carbon capture technology supplier
- Penspen for pipeline transportation, and
- Tullow Oil for CO_2 storage

MHI and Foster Wheeler Energy Ltd. have been chosen to carry out the FEED study
E.ON UK is planning to replace the four existing coal-fired 485 MW units at Kingsnorth Power Station with two new cleaner coal units rated at 800 MWe each. The 1 billion GBP investment is planning to use state-of-the-art technology to produce power from coal far more efficiently and far more cleanly than ever before in the UK. The carbon emissions are expected to drop with 20% or two million ton a year from 2012. The new units, which would operate at an efficiency of 45% and above compared to existing units' 36%, would be built next to the existing four 485 MWe coal-fired units, which will cease operation and be demolished once the new units are fully operational and proven. The current plan is to phase out the old units by end of 2015 under the strictures of the EU's Large Combustion Plant Directive. If approved, these would be the UK's first supercritical coal-fired units, and they would produce enough electricity to supply around 1.5m homes. If built these units would be the first new coal build in the UK for over 20 years and could set a new benchmark for cleaner coal-fired generation in the UK. E.ON has announced that it will not build Kingsnorth if it does not win the competition, given the new requirement of CCS on all coal new-builds. Instead, E.ON would consider building a gas-fired power plant.

RWE npower has announced plans to design and build a carbon capture pilot plant at a UK coal power station. The first phase is to be located at Aberthaw Power Station in South Wales. An initial £8.4 million investment will focus on a 3 MW capture plant, with further investment planned to support a capture and storage demonstrator plant of at least 25 MW. The larger capture and storage demonstrator plant would form part of one of the new supercritical power stations which are currently under feasibility and planning at npower's existing sites in Tilbury, Essex and at Blyth, Northumberland. The pilot plant is expected to be operational in 2010 and the costs are expected to be about £8.4 million. RWE npower's team includes BOC (a Linde Group company), Cansolv Technologies Inc., I.M Skaugen SE, The Shaw Group Inc., and Tullow Oil. I.M.

RWE npower has taken a 75% stake in Peel Energy CCS Ltd, which was formerly jointly owned by Peel Energy and Danish company DONG Energy. The restructured joint venture, with RWE npower's involvement, has pre-qualified for the Government's CCS Demonstration competition. Peel Power is a subsidiary of the property and transport company Peel Holdings. Other partners include Senergy and Mott McDonald. The plant is a new coal (and biomass) - fired 1.6 GW plant in Hunterston, Scotland. The project will, should it be qualified, comprise a capture facility of up to 400 MW which would form part of a new cleaner supercritical coal fired power station. It is proposed that the CO_2 would then be transported to disused gas fields in the North Sea where it would be permanently stored. The project could be up and running by 2014.

Germany

In Germany COORETEC (www.cooretec.de) is an initiative by the Federal Ministry of Economics and Technology (BMWi) for the development of a power plant fired by fossil fuels with prospects for the future. COORETEC stands for CO_2 reduction technologies for fossil-fired power plants. Under this heading, two strategic approaches are taken in joint projects involving industry and research:

- Technologies for improving power plant efficiency
- Technologies for the separation and transport of CO_2 with the aim of safe long-term storage in geological formations.

With this focus, COORETEC is integrated into the German Federal Government's 5th Energy Research Programme on "Innovation and New Energy Technologies". The aim is to promote the transition to a reliable, economic and environmentally safe energy supply. COORETEC thus makes a significant contribution towards implementing the Federal Government's energy and climate policies.

The first PCC pilot plant in Germany, launched in August 2009 at the RWE Coal Innovation Centre in Niederaussem, is a joint project between the power company RWE and technology suppliers BASF (reactive liquid absorption) and Linde (engineering). The project is supported by the COORETEC programme. At the pilot plant all aspects of CO_2-scrubbing are to be trialed for 18 months under real power plant conditions to examine their functioning state and gain experience for later commercial scale systems. The aim of the project is to reduce efficiency losses and costs associated with post combustion technologies to €30/t of CO_2 through energy optimised amine scrubbing solvents supplied by BASF, and improvements in the process and plant technology. The overall project aim is to have the technology commercially available by 2015 with a parasitic power loss of less than 10 percentage points.

In addition to this COORETEC is funding a large study (Poseidon) on evaluation, dynamic operation and optimisation of absorption process based PCC at the technical university in Hamburg/Harburg, supported by E.ON, RWE, Vattenfall, EnBW. Another project, coordinated by the Universities of Stuttgart and Duisburg-Essen is aimed at the development and optimisation of scrubbing columns, the analysis of earth alkali solvents and adaptation of corresponding processes. The project is supported by power companies RWE, E.ON, Vattenfall, EnBW and technology suppliers Evonik and Hitachi.

Although E.ON has been approaching CCS technologies carefully, E.ON is now planning seven smaller pilot plants, all of which are aiming to optimize post combustion methods for capturing CO_2. E.ON plans to pursue the development of post combustion technologies with a budget of € 100 million until 2014. Four of the projects are planned in Germany in cooperation with Siemens, Fluor, Cansolv and Mitsubishi. One of the projects is located at E.ON's coal fired power plant in Wilhelmshaven and is scheduled to start operation in 2010. Fluor and E.ON Energy have formed a strategic partnership for the development of a retrofitted pilot plant using Fluor's Econamine FG+ technology. The technology uses monoethanolamine as the solvent for efficient capture of CO2. The pilot plant will be small in scale with only 5.5 MW and has a budget of € 10 million. In North Rhine Westphalia E.ON Energy will work together with Canadian Cansolv Technologies at its location in Heyden. The objective of this project is again to improve efficiency of post combustion by testing different solvents. The pilot plant which is expected to commence its operation in 2009 is planed to produce 7 MW. In cooperation with Siemens E.ON is planning a pilot at the Staudinger power station near Hanau east of Frankfurt. The pilot plant will have a capacity of 1 MW and will be run with part of the flue gas from Staudinger's unit block 5 between 2009 and 2010. The project has a budget of € 10 million and is supported through the COORETEC program. Another pilot unit is planned in cooperation with Mitsubishi Heavy Industries. The location of the pilot plant will be at a coal fired power station in Germany and will begin test operations in 2010. It will be the first unit to test, under realistic operating conditions, the latest carbon scrubbing processes and solvent technology developed by Mitsubishi Heavy Industries. The pilot will operate at a flow rate of 20,000 cubic meters of flue gas per hour and will provide important insights into the integration of carbon scrubbing into power plant operations. Figure 9 provides an overview of the pilot plants that E.ON is involved in, in Europe

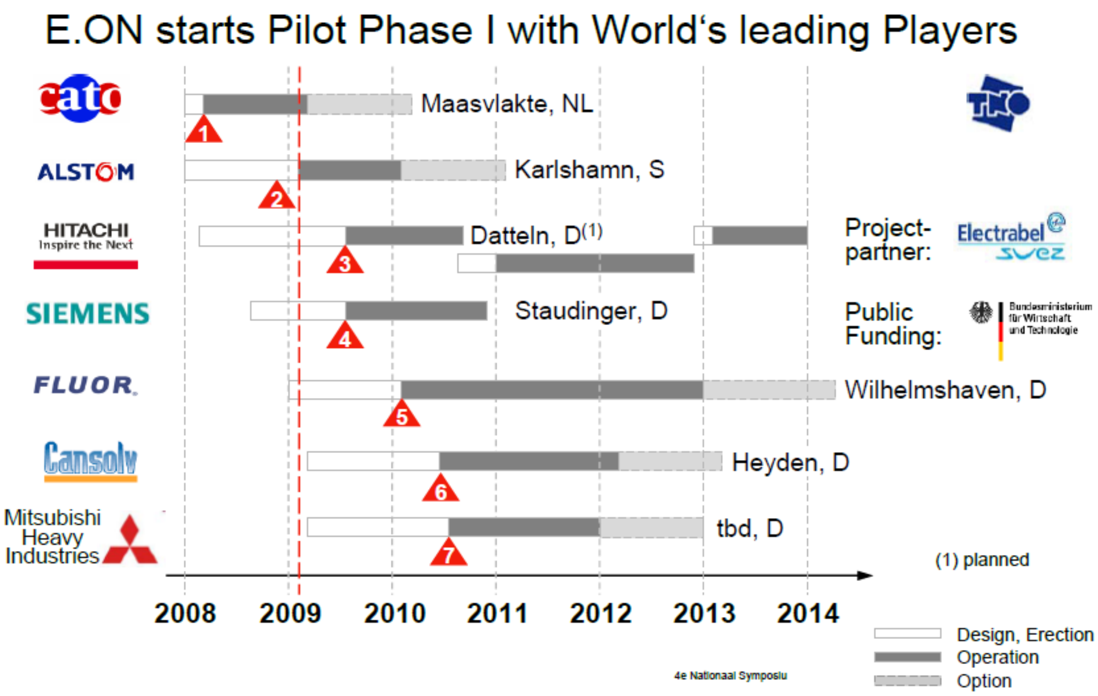

Figure 9 : Snapshot of E.ON pilot plants in Europe [8]

USA

The Luminant Carbon Management Program at the University of Texas includes 17 Ph.D. students, 6 faculty, and 6 professionals working on CO_2 rate and solubility measurements, amine degradation, systems modelling, pilot plant testing, sequestration modelling, and policy/systems analysis. The effort is currently funded by $500,000/yr from Luminant, and by more than $700,000/yr from 28 industrial sponsors in the Luminant Carbon Management Program and other affiliated activities including 9 process suppliers (Alstom Power, Babcock & Wilcox, Fluor, GTC Technology, IFP, Shell Global Solutions/Cansolv, Mitsubishi Heavy Industries, URS, Siemens), 7 power companies (LS Power, Southern Company, SaskPower, RWE npower, E.ON, NRG, EPRI), 5 oil companies (Aramco, Chevron, BP, ConocoPhillips, Exxon), 5 others (AspenTech, Codexis, Huntsman Chemical, CSIRO, Battelle) and 2 equipment donors (Emerson, Alfa-Laval).

The US DoE has developed a Carbon Sequestration Roadmap (www.netl.doe.gov/technologies/carbon_seq/refshelf/project%20portfolio/2007/2007Roadmap.pdf) which covers all areas of CCS including post combustion capture. Considerable effort is going on in the more novel technologies of adsorbents and membranes and funding is being provided across a broad range of technologies.

Canada

The ITC at the University of Regina has two main components: a pre-commercial scale chemical absorption technology demonstration pilot plant at the Boundary Dam power plant near Estevan, and a technology development pilot plant at the Petroleum Technology Research Centre (PTRC), University of Regina. Contributors include Natural Resources Canada, Saskatchewan Energy and Mines, the Government of Alberta, and the Canada/Saskatchewan Western Economic Partnership Agreement. Industry partners include Sask Power, Fluor Daniel, Luscar, BP Amoco, EPCOR, TransAlta Utility Corporation, Canadian Occidental and Encana.
At the pilot plant and demonstration plant scales, ITC have established baseline operating conditions and costs for CO_2 capture from flue gases (produced at either a coal-fired or natural gas-fired power plant) using an MEA solvent. After base operating standards and costs for MEA systems were established, cost and operating improvements were investigated for the base MEA process. Results indicate that the overall parasitic energy penalty to operate a retrofit MEA CO_2 capture facility could be reduced to 50% of the previously reported values. Mixed-amine (MEA-MDEA) has also been examined to investigate cost/energy optimization beyond the base and optimized MEA process. This research indicated that even further reduction in reboiler heat duty is achievable.

Japan

Kansai Electric Power Company (KEPCO) and Mitsubishi Heavy Industries (MHI) have collaborated on small scale CO_2 capture from KEPCO's gas fired Nanko power station near Osaka since 1991. The pilot plant capacity is 2 ton CO_2/day. The project has been invaluable development of new solvents, such as MHI's patented and commercial KS1 solvent. KEPCO and MHI further also collaborate on a chemical plant in Kurosaki with a CO_2 capture capacity of nominal 283 ton/day and maximum

330 ton/day. The feed gas is flue gas from natural gas or heavy oil boilers. The start-up of this project was in October 2005. MHI has also installed a CO_2 capture pilot plant on J-Power's coal-fired Matsushima Power Station in Nagasaki. The capacity is 10 tons/day and the focus has been on understanding the long-term effects of impurities on the amine scrubber process. The project has been operating more than 4000 hours since July 2006.

The Research Institute for Innovative Technology for the Earth (RITE) has been developing reactive liquid absorbents since 2004 in the COCS project (Cost-saving CO_2 Capture System). RITE is the project leader with other team members Kansai Electric Power Company, Mitsubishi Heavy Industries, Nippon Steel Engineering and Nippon Steel. The aim is to half the costs of capture and this is to be achieved by a reduction of the thermal energy requirement for regeneration to 2.5 GJ/ton CO_2 and by the utilisation of waste heat in the steel industry. The project results indicate that the energy targets can be achieved through an optimised blend of amines. The stability and corrosion properties of the new blends are also favourable. The technology development has focused on blast furnace gases in the steel industry with the establishment of a pilot plant at the Kimitsu Works of Nippon Steel. RITE is cooperating with CSIRO to also advance the technology for applications in power plants.

China

In China a PCC pilot plant has been established by the China Huaneng Group at the Huaneng Beijing Cogeneration plant. The plant has been designed by Thermal Power Research Institute (TPRI) and started operation in July 2008. The plant capacity is 0.5 ton/h and the CO_2 produced is purified and sold to the local beverage industry. The project has also been supported through the Asia Pacific Partnership on Clean Development and Climate, which enabled CSIRO to provide technical assistance and training. Based on the successful establishment of the Beijing pilot plant a larger plant (100.000 ton/a) has been designed and is being constructed in Shanghai. Commissioning is due to start in early 2010. The CO_2 thus produced is again sold to meet local demand.

Italy

The Italian power company ENEL is establishing a PCC pilot plant in Brindisi, due to start operation in 2009. The pilot plant will capture 2.25 ton CO_2/hr using a high concentration MEA-based liquid absorbent, developed by IFP and under commercialisation by Prosernat. It is the first stage in a larger development which should ultimately lead to a PCC demonstration plant fitted to an ultra-supercritical power plant which currently constructed. The PCC demo with a capture rate of the order of 1 to 1.5 million ton CO_2/year is to be realised by 2012, including storage of CO_2.

3.3 Technology suppliers

Fluor

FLUOR has acquired PCC technology based on monoethanolamine originally developed by DOW Chemical in 1989 and has marketed this technology as the Econamine process [9]. In later years the technology was updated and its performance improved and is known as the Econamine FG Plus[SM] technology. It is optimised for flue gas applications and corrosion is said to be negligible. The process also incorporates absorber intercooling, lean absorbent vapour recompression and a low temperature reclaiming process for improved process performance. The heat requirement for absorbent regeneration is 2.95 GJ/ton CO_2 [10]. FLUOR advocates the use of non-metallic absorbers which can be manufactured in diameters up to 20 m for a 500 MW_e train, resulting in capital cost reductions of 60%. At present more than 20 technology licenses have been sold world-wide, mainly for CO_2-production for the beverage industry.

Mitsubishi Heavy Industries

Mitsubishi Heavy Industries (MHI) has been developing a PCC process based on a sterically hindered amine since the early 1990's [11]. The technology is now marketed as the KM CDR process. Four commercial plants have been realised over the past decade with sizes between 200 and 450 ton CO_2/day, capturing CO_2 from flue gases from natural reformers, mainly for urea-production. Five more plants are expected to come on line over the next couple of years. Apart from this alternative liquid absorbent the process also include heat recovery methods leading resulting in a heat requirement of 2.77 GJ/ton CO_2 [12].

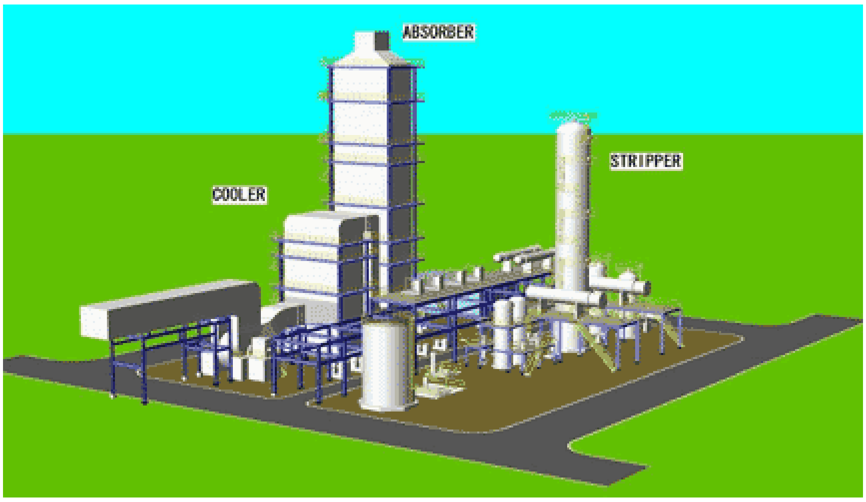

Figure 10 : Lay-out of KM CDR process

Aker Clean Carbon

Aker Clean Carbon (www.akercleancarbon.com), based in Norway, has developed a proprietary absorption technology based on an amine solvent. An 'energy converter' (no technical details) in the lean solvent stream from the stripper is the only component of the system that differs from the conventional amine CO_2 capture process. The Aker Clean Carbon process can be linked to a bio-energy plant which provides steam and energy to the amine plant making the overall facility CO_2 negative and independent of the power station. A mobile test unit has been in operation since late 2008 at Risavika, Norway and is now located at Longannet, Scotland for trials on a coal-fired facility. Aker Clean Carbon technology will be part of the European CO_2 Test Centre Mongstad (TCM) in Norway.

BASF

BASF is a leading global chemical company producing a comprehensive range of chemical products. It is a technology supplier of reactive liquid absorption processes, not just the liquid absorbents. The aMDEA technology from BASF is used in many gas treating plants throughout the world, including the plants separating CO_2 from natural gas at the Sleipner and Snovhit CO_2-storage projects. In the PCC area BASF cooperates with RWE and Linde, have jointly established the first PCC pilot plant in Germany. BASF also provide some alternative solvents and their Puratreat F amino acid solvent is being trialled at the Hazelwood Power Plant in Victoria.

Cansolv

Cansolv was formed in 1997 to commercialise and market the CANSOLV SO_2 Scrubbing System developed at Union Carbide Canada. Since this date, Cansolv Technologies has demonstrated the capabilities of its regenerable SO_2 control technology in a variety of applications with oxygen containing gases. Cansolv has built on its experience with diamines to develop specific absorbents for CO_2 capture. Cansolv offers a unique concept with the integrated SO_2-CO_2 capture technology. This patented technology uses an aqueous amine solution, Cansolv absorbent DS, to achieve bulk removal of both sulphur dioxide and carbon dioxide. The thermal energy requirement in a fully integrated plant can be brought down to 2.2 GJ/ton CO_2 [13]. On 1 December 2008 Shell Global Solutions International B.V. acquired Cansolv.

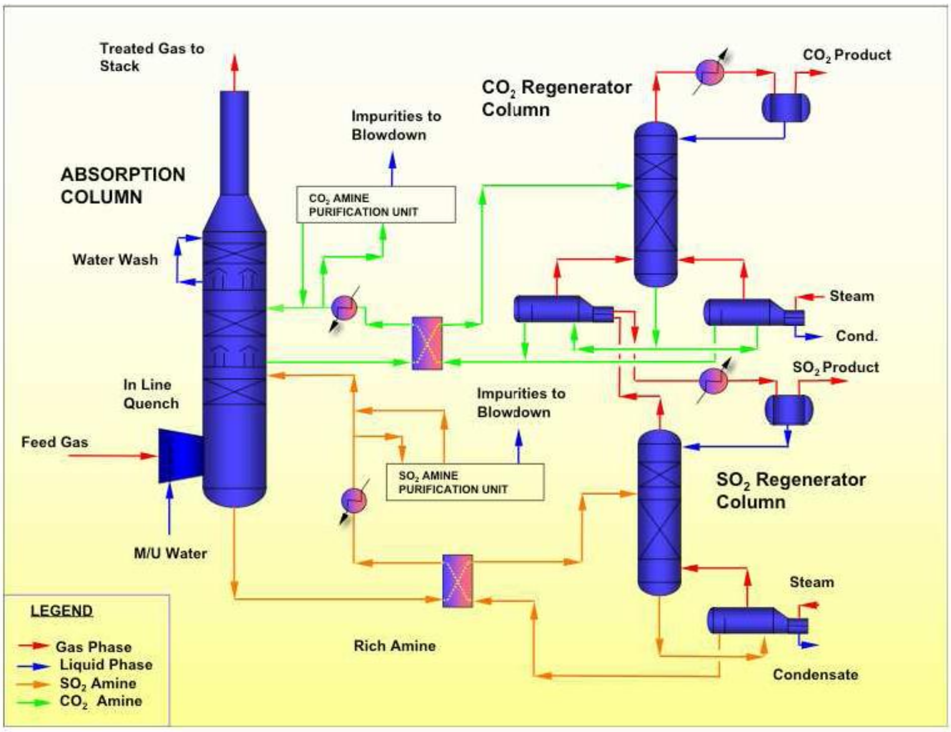

Figure 11 : Cansolv's Integrated SO_2/CO_2 recovery

Alstom

Alstom [14] developed the Chilled Ammonia Process in which the flue gas is cooled, treated with ammonium carbonate to form ammonium bicarbonate which is separated and heated to release pressurized CO_2. The active solvent is low cost, more resistant to impurities and degradation, however the process requires energy to cool the feedstock below ambient. The technology has been piloted at WE Energies Pleasant Prairie Power Station (4500 operational hours) and at E.ON Karlshamm (commissioning) both at the 15000 ton CO_2/a scale, with a demonstration scale plant (100,000 ton CO_2/a) due to start-up at AEP Mountaineer coal-fired Power Station which will include on-site sequestration. A second demonstration (at 80,000 ton CO_2/a) has been approved for the StatoilHydro Mongstad gas facility due to be commissioned by October 2011 in parallel with an advanced amine based PCC process.

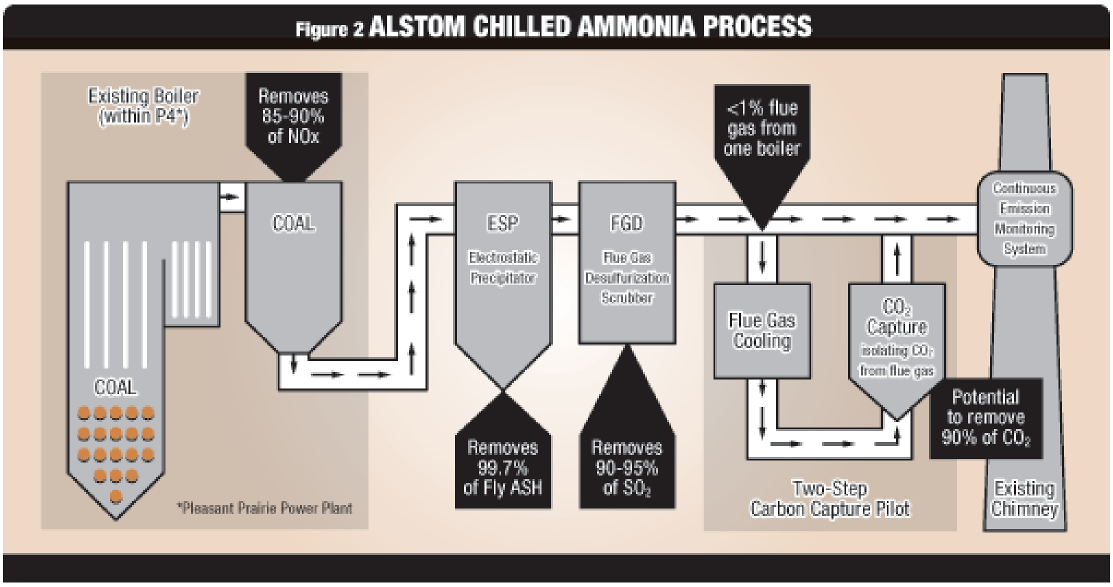

Figure 12 : Alstom Chilled Ammonia Process

Alstom are also in partnership with Dow Chemicals (world's largest supplier of amines) with Alstom providing an improved PCC amine process. A pilot facility is has recently started up at Dow's South Charleston's (WV) facility.

Siemens

Siemens are developing a process based on amino acids rather than amines which boast an improved environmental impact and lower energy costs (2.3 GJ/t CO_2). Laboratory scale continuous trials are underway to prove the concept and investigate under controlled conditions the corrosion and degradation effects. A 150 nm^3/hr flue gas pilot plant at E.ON's Staudinger power plant in Germany was scheduled for start-up in August 2009. The technology is to be adapted to operate under the special conditions of combined-cycle power plants (low CO_2 high O_2 content of flue gas, frequent load cycling) for the Norwegian utility Statkraft. Siemens have signed an agreement with TNO to further develop the amino acid solvent process.

Babcock & Wilcox

Babcock & Wilcox Power Generation Group (PGG) has begun using their pilot-scale facility ($11.8 million) to test what is described as its Regenerable Solvent Absorption Technology (RSAT). Located near the B&W PGG headquarters in Barberton (Ohio), the test facility links into their combustion test facility.

HTC Pure Energy

HTC Purenergy (www.htcenergy.com) has close links with the University of Regina and the International Test Centre for CO2 Capture (ITC) and carries out feasibility and design studies in the CCS and EOR areas. The company has developed a modular transportable CO2 capture system (CCS 1000™). HTC Purenergy recently carried out a site specific feasibility study for Loy Yang Power utilizing the HTC Purenergy technology. EESTech have acquired (Dec 2007) the exclusive rights to commercialise the CCS technology in East Asia, India and Australasia. On September 3 2008, HTC signed a global licensing agreement for carbon capture and storage technology with one of the world's leading power plant equipment supplier and power plant constructors – Doosan Babcock Energy of the UK and with Doosan Heavy Industries of Korea. In support of their newly developed partnership, Doosan has created a business group within their Power and Technology business stream, called Post Combustion Capture and Storage (PCCS).

Figure 13 : HTC Purenergy's modular transportable CO_2 capture system

Toshiba

Toshiba Corporation are installing a 3650 ton CO_2 per year amine-based pilot plant at the coal-fired Mikawa Power Plant in Omuta City, Fukuoka, Japan at an estimated cost 1 billion yen ($US10.7 million) and 1.5 billion yen. The plant was due to be commissioned in August 2009.

Powerspan

Powerspan (www.powerspan.com) has been developing a CO_2 capture process, called $ECO_2^{®}$, since 2004 in conjunction with the U.S. DOE National Energy Technology Laboratory (NETL). The ECO2 process is a post-combustion, regenerative process, which uses an ammonia-based solution to capture CO_2 from the flue gas of a power plant and release it in a form that is ready for further compression, safe transportation, and geological storage. Powerspan has initiated a pilot test program (20 ton CO_2/day) with FirstEnergy at the R.E. Burger Plant, which will run through 2009. The pilot program will also prepare the technology for a commercial scale (120-MW) CCS demonstration projects planned with Basin Electric Power Cooperative for the Antelope Valley Station in Beulah, North Dakota, planned to be operation in 2012.

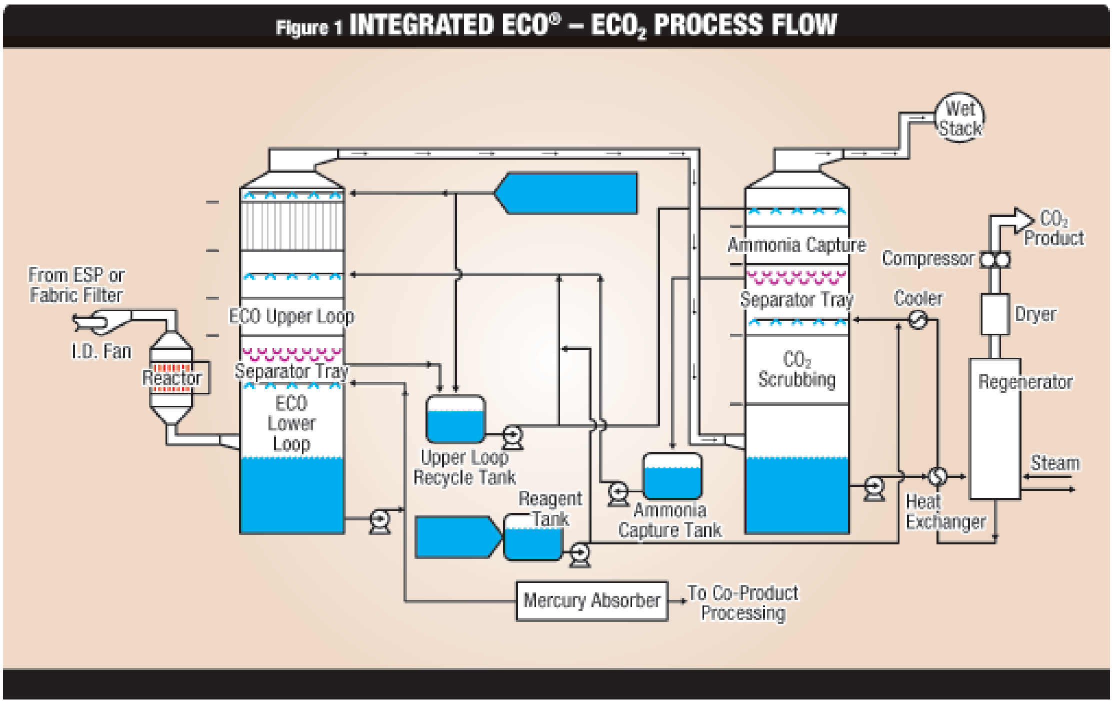

Figure 14 : Powerspan's integrated $ECO_2^{®}$ process

Hitachi

Hitachi Europe is involved with E.ON and Electrabel in the realisation of a mobile PCC pilot plant to be used on sites in Germany, Belgium and the Netherlands using liquid absorbents developed by Hitachi.

A list of all pilot plant initiatives know to the authors is given in Appendix 2.

3.4 PCC R&D in Australia

CSIRO PCC Programme

In 2004 CSIRO commenced a comprehensive assessment of the potential of reactive liquid absorbent based PCC for both retro-fit and new coal fired power stations. This has led to the establishment of the CSIRO PCC programme. The overall objectives of the CSIRO PCC Programme are:

- Halving of the costs of CO_2 capture by 2025
- Realisation and adoption of PCC for reduction of CO_2-emissions from coal fired power stations aiming at an average emission intensity of 0.6 tonne CO_2/MWh by 2025.

The CSIRO PCC R&D research programme has been developed along two lines with in total 12 projects:

1. A programme of pilot plants [15]

The pilot plant program is aimed at providing operational experience in the use of PCC plants. The pilot plants will provide an important opportunity for the industry to gain experience in these types of technologies before going to a large scale. In addition to this the pilot plant program will result in the identification of operational issues and detailed understanding of the technology requirement. These issues can be resolved at an early stage and if not straightforward they will lead to the specification of research tasks. A pilot plant operating on real flue gas will also be a testing ground for novel technologies/solvents brought forward by laboratory based research, as these technologies can be tested under realistic flue gas conditions (temperature and composition). Pilot plants have been realised or are being realised in three locations in Australia:

- Loy Yang Power focusing on application of amines for CO_2 capture in brown coal operations

Within the Latrobe Valley Post-combustion CO_2 Capture Project supported through the ETIS programme from the Victorian Government, the pilot plant technology has been based on amines and is being tested on flue gases from Victorian brown coal at the Loy Yang power plant. Brown coal flue gases are available at high temperature, have high water content and contain alkaline ash. This provides a challenging environment for chemical absorption processes. This plant is the first of its kind in the southern Hemisphere and was started up in March 2008. The pilot plant is shown in figure 15. Currently a series of 7 experimental campaigns is being executed using different chemical absorbents. The first campaigns will be based on a 30% w/w MEA aqueous solution to provide the baseline for the process performance.

Figure 15 : Loy Yang pilot plant (brown coal)

- Delta Electricity Munmorah power station focusing on the application of ammonia for CO_2 capture in black coal operations

This pilot plant has started capturing CO_2 in February 2009 (figure 16) supported through the Asia Pacific Partnership on Clean Development and Climate. This pilot plant is based on the use of aqueous ammonia for CO_2 capture and the power station has no FGD or deNOx. The design is very flexible allowing the absorber and stripper to operate over a range of different pressures and temperatures. This flexibility is needed to fully explore the benefits and pitfalls of an aqueous ammonia process for CO_2 capture.

Figure 16 : Munmorah pilot plant (black coal)

- Tarong power station focusing on application of amines for CO_2 capture in black coal operations (commissioning due to be started in August 2010)

This pilot plant is also supported through the Asia Pacific Partnership on Clean Development and Climate.

These Australian based PCC pilot plants have all been equipped with a sophisticated FT-IR based gas analysis system allowing the identification of contaminants in both the flue gases emitted to the environment, as well as the identification of contaminants in the CO_2-product.

Furthermore the establishment of a fourth pilot plant at the Huaneng Beijing Cogeneration Plant was supported by CSIRO through the provision of design documents, a hands-on training programme for the future Chinese operators and practical assistance during start-up. This pilot plant uses conventional amine technology on a flue gas from a black coal fired power station. It is supported by the Asia Pacific Partnership on Clean Development and Climate and encompasses a partnership between China Huaneng, TPRI and CSIRO.

Figure 17 : Pilot plant Huaneng Beijing Cogeneration Plant (black coal)

The number of pilot plants and the breadth of testing environments for PCC is unique and unprecedented in a world-wide context. The capture plant capacities range from 100 kg/h CO_2 to 500 kg/h CO_2, using flue gases from brown and black coal firing. The wide operational scope of the pilot plants is needed to properly prepare the next steps for the development of carbon capture and storage (CCS) in Australia, which will be a much larger scale demonstration plant incorporating the full chain of capture and storage of CO_2.

2. Laboratory research programme [16]

The laboratory research programme provides support to pilot plant operation and interpretation of results, enabling the development of novel sorbents and sorbent systems, but also addressing Australian specifics (flue gas quality, water availability) Five projects are focused on development of the materials science aiming at the development of new or improved liquid and solid CO_2 capture agents:

- Development and optimisation of solvents for CO_2 capture using advanced screening methods and methods for determination of relevant physio-chemical properties and their effect on process performance
- Development of novel solvents for CO_2 capture using the understanding of interaction between CO_2 and the molecular structure of the reacting agents in the liquid solution
- Development of novel capture techniques based on solid sorbents, exploring the potential for improved process performance over liquid sorbents
- Enzyme methods for promotion of CO_2 absorption and desorption in liquid absorbents, mimicking natural processes for efficient transfer of CO_2 in biological materials.
- Ionic liquids for CO_2 capture, which have the potential to lower losses of liquid absorbents and provide a breakthrough in energy requirement due to their non-volatile nature

Beside the development of novel capture agents, it is equally important to investigate their use in the overall capture process and its integration in the power plant. Three projects are underway in this area, which is anticipated to grow in the coming years:

- Novel process development focusing on the use of different process flow sheet configurations, use of membranes and innovative equipment in PCC. This project is expected to initiate a number of additional research activities which will be validated with the existing pilot plants on location.
- Economics & Integration which will provide policy relevant cost information for PCC, investigate ways for integration of PCC into power plants to aid speeding up implementation of CO_2 capture in the power generation sector. It also provides the basis for assessment of novel and an improved PCC process developed in the research programme and thus provides best directions for further research and development.
- Determining the environmental impacts of PCC-processes based on reactive liquid absorbents. As demonstration projects for PCC are being proposed, concerns are raised regarding additional emissions from the liquid absorbents used to capture CO_2. This project investigates the fate of contaminants emitted using e.g. data from smog chamber experiments and mathematical/chemical models to describe atmospheric pollutant formation in the atmosphere, including integration into air quality models.

The research thus far has led to 7 patent applications in various areas. The PCC patent portfolio is expected to grow over the next couple of years. Internationally, CSIRO is supporting the PCC research programme at Texas University in Austin, USA, led by Prof. Gary Rochelle. Furthermore collaboration is set up with ETH in Zurich, Switzerland in the area of process modelling. Finally, a two-way technical exchange programme with RITE in Kyoto, Japan, has been executed, which will be deepened through the executions of tests on developmental solvents in one of CSIRO's pilot plants. Nationally the collaboration with the University of Newcastle (A/Prof. Meader – Chemistry Department) has received support from the CSIRO Flagship Collaboration Fund and is providing useful scientific support to the PCC-programme. The group of Dr. Meader is fully focused on providing the chemistry underpinnings for chemical absorption processes.

A pictorial view of the current overall research programme is given in figure 18.

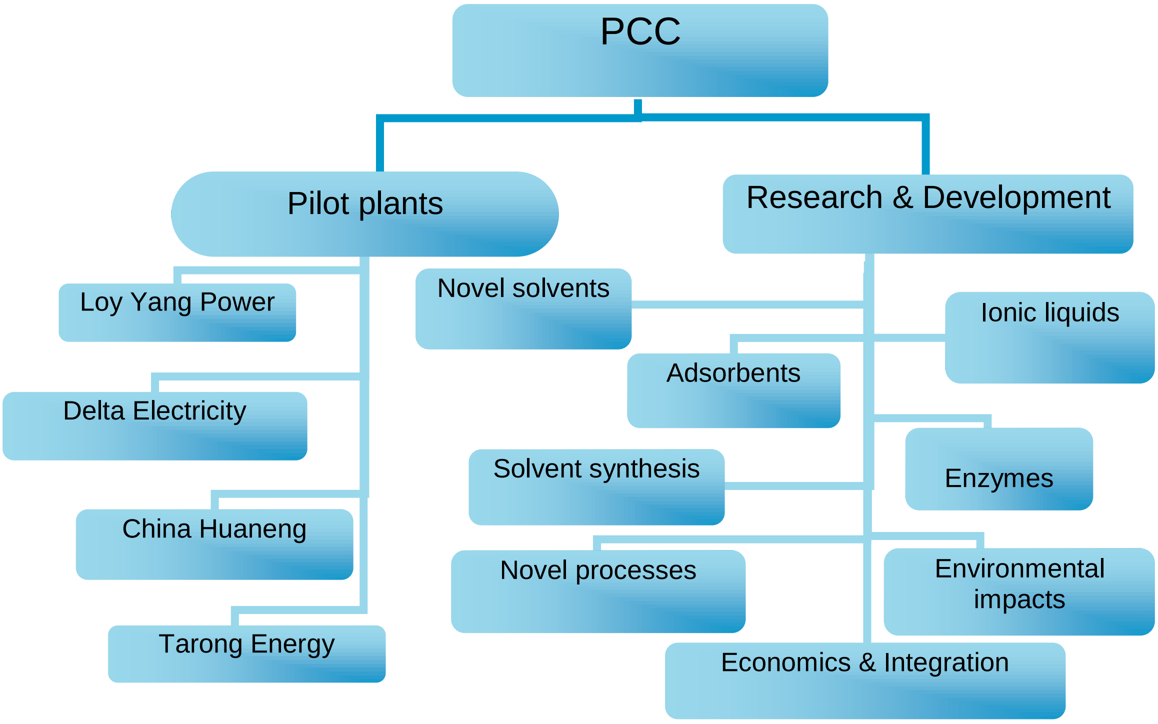

Figure 18 : Overview of current PCC programme with CSIRO

The laboratory research programme will be supported by an absorption/desorption test facility (10 kg CO_2/h) at the Newcastle Energy centre, allowing testing of novel capture agents and solvent technologies prior to testing in pilot plants with real flue gases.

CO2CRC PCC Programme

The CO2CRC Capture Program has been active in the area of post combustion since its inception in 2003. It currently has research activities in Sydney, Melbourne, and Perth. It has 12 world-class academics and research leaders directing the work of about a 19 post-doctoral researchers and a further 13 post-graduate students.
It has strong international links; including agreements with universities and research organisation in the United States, Canada, Norway, Japan and China. The Capture Program has signed several MOU's, and in particular with leading international research organisations in the area of post combustion and membranes, namely,

- ITC
- University of Regina
- University of Texas at Austin
- NTNU in Trondheim
- University of Melbourne

Through these international links, the CO2CRC has remained informed on the current and emerging trends in all aspects of capture including post combustion. The program is focused on the separation processes considered relevant to all applications of CCS and is actively working to define cost effective separation processes for all sectors of a multi-dimensional grid of processes, applications and fuel types (figure 19Figure 19)

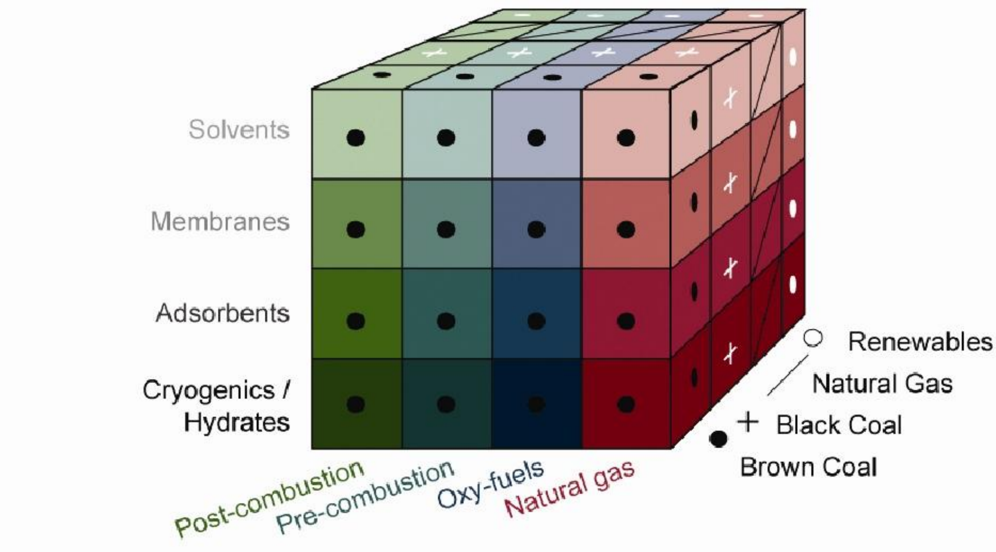

Figure 19 : CO_2 capture matrix (CO_2CRC).

The approach has been to maintain a broad overview of the separation technologies and to that end the CRC has programs in,

- Solvents
- Membranes
- Adsorbents
- Cryogenics/Hydrates.

Capture cost reduction of 50-75% is the goal of the centre activities and the research program maintains its relevance through regular reviews with the CO2CRC Research Advisory Committee. Projects have been both introduced and curtailed based on their ability to meet technical performance parameters and ongoing techno-economic potential.

The core research program covers projects in the following areas:

Solvents: Investigating environmentally-friendly and cost effective solvents

- Potassium carbonate solvents with enhanced CO_2 absorption
- Potassium carbonate as a high temperature solvent
- Investigating the effect of impurities on absorption
- Column packing to improve absorption
- Adaption of membrane/solvent systems to absorption and desorption processes

Adsorbents: Development of new materials and testing of new processes for CO2 adsorption

- Water-tolerant commercially available adsorbents (zeolites)
- Metal-organic frameworks with increased CO2 adsorbent capacity
- Adding chemical structures to the pores of sorbent materials to increase adsorption
- Pilot adsorption system to release CO2 from adsorbents by creating a near-vacuum
- High temperature adsorbents
- Testing CO2 release from adsorbents by low electrical voltage

Membranes: Testing commercially viable membranes and developing new membranes

- New polymer membranes with increased gas separation capacity and selectivity
- Carbon nanoporous membranes
- Double layer hydroxide membranes
- Superhydrophic membranes for gas absorption membrane operation
- Optimisation of membrane module design

Cryogenics/Hydrates: Testing cryogenic processes and developing hydrate processes

- New hydrate processes for integrated gasification combined cycle

The core program has been supplemented since 2007 with two major research demonstration facilities, one in post combustion (CO2CRC H3 Capture project) and one in pre-combustion (HRL/CO2CRC Mulgrave Capture Project).

In the first half of 2009 International Power and the CO2CRC commissioned two interlinked post combustion capture projects at the Hazelwood Power plant in the Latrobe Valley. This has created a significant, and indeed unique, capture demonstration and research hub and represents a critical milestone on the pathway to large scale abatement of greenhouse gases by carbon dioxide capture and storage from fossils fuels and particularly Victorian brown coal.

The first component of the hub is the International Power Carbon Capture Project which captures up to 15,000 tonnes per annum of CO2 from flue gas using an amino acid based solvent process. The CO_2 is being used on site for neutralization of ash water which replaces the current use of sulphuric acid and results in the formation of calcium carbonate in a form of mineral sequestration. The plant has a footprint of 20 m x 10 m and a height of over 28 m and provides an imposing introduction of CCS to the site.

The second project is the CO2CRC H3 project which is being used to research novel and conventional CO_2 capture techniques at a range of sizes. The H3 project is testing solvent systems, the membranes processes of gas separation and gas absorption membranes and adsorbents processes using vacuum swing adsorption. The absorption/stripping processes are being tested in the large scale solvent plant initially with the amino acid solvents and then using potassium carbonate utilizing patented technologies developed by the CO2CRC. The novel processes are being trialled in purpose built rigs designed specifically for the task. Particular emphasis is being given to the impact of real impurities on each of the processes. The H3 project is part of the Latrobe Valley PCC project funded in part by the Victorian ETIS Brown Coal R&D fund.

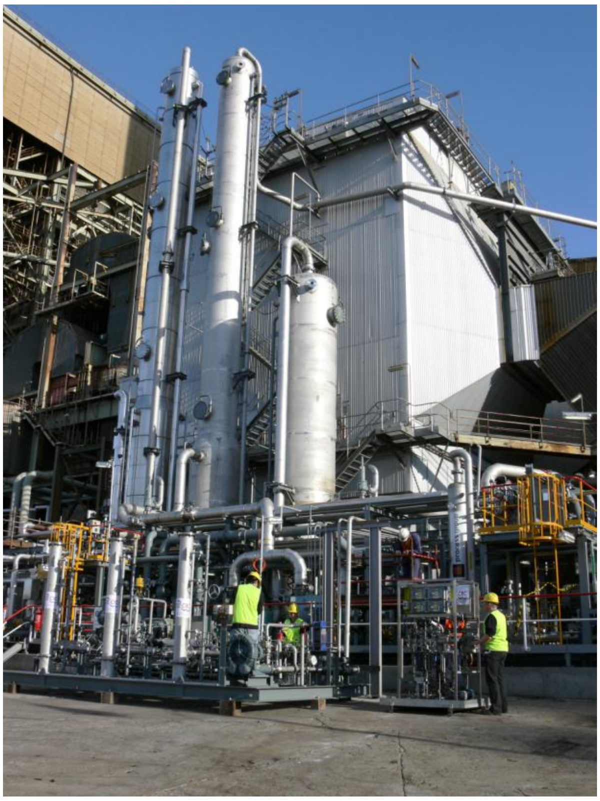

Figure 20 : CO2CRC H3 Capture Project - Hazelwood – three technologies

The project has a three year duration and is designed to identify significant advances in PCC for brown coal applications.

The CO2CRC capture program has developed some valuable intellectual property including;

- Carbonate solvent process and know-how
- Designs concepts for alternative absorption equipment construction materials
- Novel membranes for both gas separation and gas absorption separations
- Adsorbent processes

Furthermore the work on heat integration is identifying significant reductions (30-65%) to previously documented energy penalties by careful use of heat for the entire power plant and capture processes [17].

The Capture Program incorporates research on the techno-economic modelling of CCS from the team at the School of Petroleum Engineering at the University of New South Wales. The techno-economic work has been established for many years and the methodology for calculating and reporting the capital, operating and specific cost of geological storage of CO_2 has been widely reported and has been documented [18].

Techno-economic modeling is used to define the costs of providing compression, transport, and injection for many different scenarios and uses an integrated capture and storage model. The model uses a cash flow modeling approach to design capture, compression, transportation and injection components of any source-sink combination. Capture costs are dependent on a number of variables including the type of fuel, type of application and type of capture technology.

Using this methodology the CO2CRC has worked with power generators to perform a range of sensitivity studies on a range of applications applicable to the program goals. Furthermore the methodologies are being widely used in screening studies for consulting assignments internationally and particularly in the transportation area to define likely national CCS pipeline networks. Sensitivities for both greenfield and retrofit configurations were provided in the 2006 review.

3.5 PCC demonstration plant initiatives

Victoria

On the back of successful ETIS research funding rounds the Victorian government has launched ETIS 2 to demonstrate large scale integrated CCS. The grant provides for $110 million of state money to be supplemented by industry and Federal government funds. The original plan was for a 600,000 to 1 million ton CO_2/a project however the indications from industry are, that this will be a rather ambitious for the funds available. Bids are now closed and it will be likely that a large scale demonstration project will be commenced in 2010.

New South Wales

On behalf of the NSW generators Delta Electricity has been actively developing a PCC demonstration, of the order of 100,000 ton CO_2 /a. This is expected to cost in the $200 million mark and will be funded through a mix of company, state and federal funding.

4. Deployment issues for PCC in Australia

4.1 Overview of barriers to deployment

General CCS deployment issues

World-wide 8 Gton CO_2 is being emitted from approx. 2000 coal based power plants. This is equal to 60% of the global CO_2-emissions from stationary sources [19]. Post-combustion capture of CO_2 (PCC) as a technology has the ability to reduce these emissions significantly, when linked to an appropriate CO_2-storage facility. The most-advanced PCC technology, based on reactive absorption with a liquid, is however expensive and leads to a large efficiency drop in the power generation. The resulting increase in resource consumption and the resulting environmental impacts are important obstacles for the implementation of PCC.

Currently there are no commercial drivers which would support implementation of CCS-technology. An essential pre-condition for CCS-deployment is that there must be a market which can absorb the technology. Although unrelated to the research development, it is clear that policies must be in place, which allow commercial benefits to be achieved with the reduction of CO_2-emissions in a sustained manner, i.e. over the lifetime of power plants as a minimum. Only then will technology suppliers and power generators take the actions and decisions needed for commercial application.

A PCC process capturing CO_2 from power plants is only of value if it is combined with a CO_2-storage facility able to take in the large amounts of CO_2 produced. The development and deployment of PCC therefore needs to run concurrently with the development and qualification of CO_2-storage and the transportation options. A mismatch would reduce the value of a capture demonstration project as the benefit of emission reductions would not be achieved.

Another general prerequisite is also availability of suitably qualified personnel at all levels required to operate the PCC plant. A PCC plant is essentially a chemical engineering activity, to which Australian power generators are not accustomed to. The application of emission controls (DeNOx and FGD) in the EU, USA and Japan has given those power station operators a familiarity with chemical process technology. There have been no large scale chemical processes applied in the Australian power industry for chemical process experience to be developed. This issue requires the early development of training programmes, including operator training facilities.

Power generation in Australia

Power generation in Australia is 80% coal based (brown and black). Current CO_2 emissions from Australian coal fired station amount to 170 Mtonne per year coming from approximately 60 sources. The presence of easy to mine coal reserves and the close proximity of power plants to both coal mines and end users make electricity generation costs in Australia amongst the lowest in the world. However, this low cost is only possible at the expense of sizeable CO_2-emissions. Table 1 shows key data for Australia's coal fired power generation fleet [20].

Table 1 : Key data for Australian coal fired power stations

Parameter	Data
Generation capacity	28 GW
Electricity production	170 TWh/a
Average generation efficiency and	
CO_2 emission	35.6 % - 0.9 tonne CO_2/MWh
- Black coal	25.7 % - 1.3 tonne CO_2/MWh
- Brown coal	
Overall CO_2-emissions and no of sources	170 Mton CO_2/annum from ~ 60 flue gas streams
Typical SO2 level range in flue gas	
- Black coal	200 - 600 ppm
- Brown coal	100 - 300 ppm
Typical NOx level range in flue gas	
- Black coal	300 - 700 ppm
- Brown coal	100 - 200 ppm
Typical flue gas temperatures	
- Black coal	120 ^oC
- Brown coal	180 ^oC
Cooling water requirement	1.5 - 3.0 m^3/MWh

Estimated costs for PCC in coal fired power plants in Australia

Figure 21 shows a typical flow sheet for a power plant fitted with PCC.

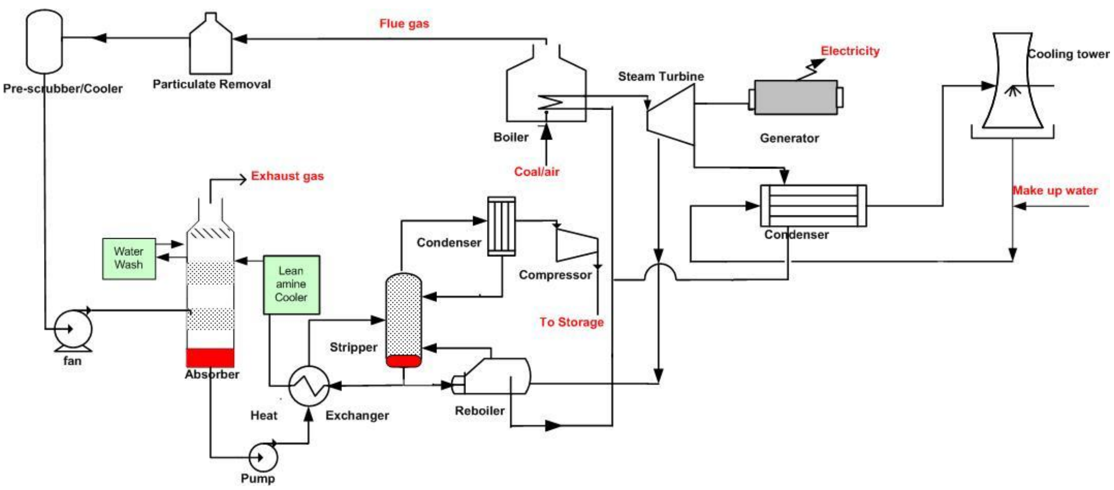

Figure 21 : Power plant with PCC under Australian conditions

The cost for PCC in power plants are usually evaluated for a fixed capture rate (typically 90%) by comparing the costs of power generation before PCC and after PCC is implemented. The difference between cost of generation and CO_2-emissions in both cases then allows the costs of CO_2-avoidance to be determined. Capture and compression costs generally make up 2/3 of the overall costs for the avoidance of CO_2-emissions and therefore dominate the overall economics of a CCS-chain [20]. In recent years costs of engineering equipment and design services have escalated. A study for a full-scale PCC-application on a coal fired power station in Australia has not been carried out, hence detailed information on costs for Australian conditions is lacking. CSIRO and CO2CRC have developed separately their own procedures for techno-economic evaluations. These costs produced by these evaluations provide bench-mark costs for PCC. Table 2 gives an overview of the assumptions used in the techno-economic analysis.

Table 2 : Assumptions for techno-economic analysis of PCC

Design CO_2 capture rate	90%
Thermal energy for capture process	4 GJ/ton CO_2
Delivery temperature pressure CO_2 product	40 ^oC / 10 MPa
SO_2 / particulate matter in flue gas before CO_2-capture	3 ppm / 10 mg/m^3
Fuel costs	Black coal: 1.0 $/GJ Brown coal: 0.5 $/GJ
Interest rate	10%
Amortisation period	30 years
Plant capacity factor	85 %

The techno-economic analysis has concentrated on the whole range of power plants from subcritical steam conditions to ultra-supercritical steam conditions, with 500 to 600 MW installed capacity. Whilst the existing black coal-fired power plants in Australia are almost entirely of the subcritical type, supercritical conditions have been applied recently at the CS Energy's Kogan Creek (750 MW) and Callide-C (2 x 457 MW) power plants. Similarly, Intergen's Millmerran (2 x 430 MW) and Tarong Energy's Tarong North (443 MW) power plants use supercritical steam conditions. Supercritical and ultra-supercritical conditions are expected to be applied in the future to all plants larger than about 350 MW in capacity. Also the type of cooling will influence the costs of power generation and both cooling water and air cooling options have been analysed. The PCC process was based on a generic 30% MEA used in a standard absorber/desorber operation. Typical values for the generation efficiency, specific capital costs and costs of power generation with and without capture are given in table 3.

Table 3 : Typical efficiencies, costs of generation and avoided CO_2-emission costs (March 2008) under Australian conditions [21, 22]

Generation efficiency without PCC	35 – 41 %	Efficiency range determined by type of steam cycle and type of cooling
Generation efficiency with PCC	25 – 29 %	
Capital costs without PCC	1800 – 2000 AUD/kW_e	Cost range determined by type of steam cycle and type of cooling
Capital costs with PCC	4000 – 4600 AUD/kW_e	
Cost of generation without PCC	15-45 AuD/MWh	Lower costs refer to fully amortised power plant; higher costs to new-built power plant
Cost of generation with PCC	55-105 AuD/MWh	
Avoided CO_2 emissions cost	60 – 90 AuD/ton	

The implementation of PCC with 90% capture of the CO_2-emissions from a coal fired power plant resulted in an increase of the cost of generation of 40 – 60 AuD/MWh and avoided emissions costs of 60 – 90 AuD/ton CO_2. The higher costs of generation are only to a small extent due the decreased power generation efficiency (typically 30 % equivalent to 10-12 %-points decrease). Table 3 clearly shows that the capital costs will double with the implementation of PCC and this constitutes the main component in the increased costs of generation.

Emission controls in Australian power plants

Australian coals are generally low in sulphur (<1 wt %) and high in ash (as much as 25 wt %) compared to the coals from other regions of the world. The Australian power generators have currently no statutory requirements for FGD and DeNOX as observed in USA or Europe primarily due to the power plants being located away from the major population centres. As a result, except for the particulate emission controls such as the fabric filters and electrostatic precipitators, the Australian power stations have no dry or wet FGD systems and manage to limit their NOX emissions through the use of primary means such as the tangential burners in the furnace. As a result, the black coal fired power stations emit around 200 to 600 ppmv SO_X and roughly 300 to 700 ppmv NO_X in the flue gas (table 1). For the brown coal fired power stations, the corresponding figures are somewhat less but in the range 100 to 300 ppmv. The reactive liquid absorbent based post combustion CO_2 capture processes have very low tolerance for SO_X, NO_X and particulate matter in the flue gas. This now poses a problem for implementation of CO_2 capture as all commercial processes have limited tolerance to SO_2, ranging from max. 100 ppm for a low concentration MEA-based process down to less than 10 ppm for processes based on new amines or formulated absorbents [23]. It is well known that the presence of SO_X and NO_X (particularly NO_2) not only causes degradation of the CO_2 solvent but its degradation products contribute to the equipment corrosion as well. As a result in estimating the costs for PCC in Australia, one has to make an allowance for incorporating improved and additional emission control systems. This means that in addition to flue gas cooling a separate scrubber will be necessary for deep removal of SO_2, increasing the capital costs of the overall capture system. The costs for FGD equipment added on to a 600 MW_e is estimated to be 60 MAuD, which makes it the third most expensive part of the power plant. This additional cost has already been absorbed in markets with more stringent emission controls, but is sizeable additional cost increase to enable PCC in Australia. The use of an aqueous ammonia based process or a carbonate based process might provide an alternative to the use of amine based process, as the liquid absorbents are likely to be less affected by flue gas impurities.

Cooling water demand

A wet cooled black coal fired subcritical power plant (600 MWe installed) loses around 1180 tons/hr of cooling water through the wet cooling towers when no CO_2 capture is involved. However, the water loss rises sharply to 1425 tons/hr, if the 90% capture plant is also water cooled. As less electricity is produced when CO_2 is captured more heat will be discarded to the environment, in particular to the cooling water. The cooling water need in a PCC process is coming from flue gas cooling, the lean absorbent cooling, the stripper condenser and the compressor intercooling. Since

Australia is generally regarded as a dry continent such large scale water losses, particularly for the in-land power stations, would be prohibitive as more coal-fired power plants with CO_2 capture are built in future to meet the rising domestic demand for electricity. Whilst the forced draft air cooling mitigates cooling water requirements for a power/capture plant in an arid area, the electrical fans circulating large quantities of air to provide for the necessary cooling consume considerable electrical power and add to the efficiency penalties underlying the capture process. In addition, due to poor heat capacity the air cooled systems require larger heat transfer surfaces compared to the water cooled systems and thereby add to the capital cost of the plant equipment. The cooling requirements of a power plant fitted with PCC require careful analysis given the cooling water constraints. The general topic of water requirement for power plants is currently receiving considerable attention [24]. Apart from water conservation one should also look upon the power plant as a water producer, particularly for high moisture content fossil fuels such as lignite in Victoria. For all power plant alternatives, flue gas temperatures are mostly too high, so that the flue gas must be cooled to enable any removal process. In any case, flue gas desulphurization is mandatory for coal.

Energy penalty

The impact of post-combustion CO_2 capture using a chemical absorption process on the power generation efficiency has been well documented [4]. The efficiency decrease is estimated to be 30% for 90% capture from an Australian coal fired power station, using a generic MEA process. Such decreases in efficiency result in commensurate increases in the resource consumption per unit of electricity output and even higher increases in the cooling water consumption per unit of electricity output. The latter is caused by the fact that any heat not converted into electricity will be discarded to the environment. The question arises whether these negative impacts of a post-combustion CO_2 capture process can be reduced to such an extent that they are acceptable both in economical terms and in terms of environmental impact. A thermodynamic analysis of the energy consumption for CO_2 capture has provided insight into the potential for improvement [25]. The analysis was based on CSIRO's vision of a generational technology deployment, with improvements made from one generation to the other. Using this concept, the expected improvements in the power plant technology and PCC technology can be mapped out. The parasitic energy requirements of the capture process are determined by the thermal energy requirement for the liquid absorbent regeneration, which will be extracted from the steam cycle and the power requirements, in particular compression of CO_2. For the generic PCC process based on MEA, the thermal energy requirement results in about half of the steam going through the LP steam turbine being redirected to the reboiler. This obviously is an enormous impact on the steam cycle. The efficiency of the power plant is also to rise slowly as higher steam temperatures and pressure can be realised as a result of materials development of steam turbine and boiler materials. The results presented in table 4 show that by progressing from G1 power plant technology to G4 power plant technology CO_2-emissions are reduced by 30%. Although this is sizeable emission reduction on its own, the reduction by CO_2 capture and storage would be much higher. Adoption of advanced power plant technology would also lead to a smaller PCC plant as less flue gas would have to be treated per amount of CO_2 captured and the higher efficiency results in less CO_2 needing to be captured per unit of electricity produced.

Table 4 : Synthesis results from overall thermodynamic analysis of energy performance (all based on HHV)

Status PCC technology		G 1	G 2	G 3	G 4
Efficiency (no capture)	[-]	0.350	0.410	0.460	0.500
CO_2-emission (no capture)	ton CO_2/MWh	0.928	0.792	0.706	0.650
Thermal energy absorption process	GJ/ton CO_2	4.56	3.31	2.29	0.95
Equivalent power requirement of solvent regeneration process	MWh/ton CO_2	0.317	0.184	0.095	0.040
Power requirement of capture process and compression	MWh/ton CO_2	0.154	0.138	0.122	0.105
Overall power loss due to capture	MWh/ton CO_2	0.471	0.322	0.217	0.145
Efficiency (with 90% CO_2 capture)	[-]	0.212	0.316	0.397	0.458
CO_2-emission (with 90% CO_2 capture)	ton CO_2/MWh	0.153	0.103	0.082	0.071
Increase in coal use due to capture	[%]	65	30	16	9

The results presented in table 4 give an indication of the large potential for improvement of the post-combustion CO_2 capture process. Going from a G1 to a G4 technology leads to a 70% reduction in the overall power loss due to the CO_2 capture process. Further development of both the absorption process technology and the conventional power plant technology towards G3 technology has the potential to achieve generation efficiencies for coal fired power plants with post-combustion capture similar to current state-of-the-art technologies (G2) without CO_2 capture. The performance is typically equivalent to an overall generation efficiency of ~0.40 with 90% CO_2-capture. For G3 technologies the overall energy requirement for capture and compression is still 90% higher than the theoretical minimum estimated in section 3 (0.114 MWh/ton CO_2), leaving room for further improvements towards G4 technologies. The additional resource consumption for G3-technologies would be 16% compared to the situation without capture.

Integration of PCC into power plants

Australia’s power plants are low efficiency due to the low fuel cost and the resulting capital and operating costs trade-offs at the design stage. In a carbon constrained world the design parameters change and it potentially becomes more effective to utilise available heat for capture processes rather than lose additional power parasitically.

Work by the CO2CRC is systematically identifying target reductions for such plants and the initial studies shows reduction of 30-65% in the energy penalties for a range of power plants under different scenarios or cases as shown in figure 22.

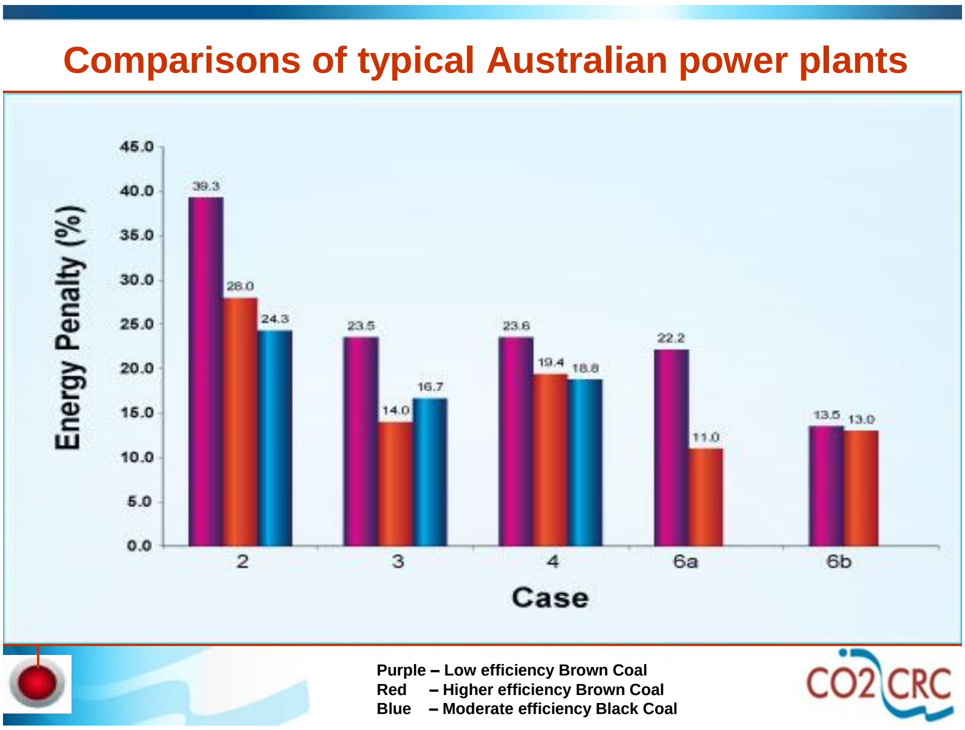

Figure 22 : Comparison of energy penalty of typical Australian power plants.

The bar chart shows the energy penalty from a range of brown and black coal fired power plants as noted in the legend. Each of these plants was evaluated for optimal heat integration using a standard solvent plant requiring 3 GJ/tonne CO_2 regeneration energy and compression to 100 bar dried ready for transportation. Case 2 is a conventional integration approach typical of that described in the capture literature over the last five years or so. Cases 3 to 6 are various heat integration strategies that are developed by using second law pinch technology techniques. Case 6 are only relevant to brown coal as they incorporate coal drying to various extents. Further detail on the studies can be found in the literature [17]. These findings are different from those discussed internationally over recent years and lead one to investigate the potential further, particularly in developing the equipment configurations and plant controllability to achieve these outcomes.

Given the large impact that a PCC process will have on the steam flows in the low pressure steam turbines and the resulting requirements for retrofits, alternative methods to cover the steam demand from other sources (solar thermal, geothermal, additional boiler, etc.) need to be considered.

Environmental impacts

Reactive gas-liquid absorption of CO_2 is likely to be the first technology to be commercialised for PCC. This will require the utilisation of large amounts of liquid absorbents, which different from the usual gas treating applications, are in direct contact with the atmosphere via the exhaust. Hence, the atmospheric emissions of solvents and solvent degradation products (through oxidative and thermal processes) are a potential source of environmental concern. For a subcritical black coal-fired 600 MW_e installed power plant, the daily usage of MEA in a generic PCC-process, capturing 90% of CO_2 from the flue gas, will be roughly 19 tons per day. The generic PCC process has clearly a large chemicals usage with possible adverse impacts on the environment, should the wastes and emissions not be properly handled. Most of the chemicals and degradation products will be contained in a solid waste stream containing the original MEA and degradation products, mixed with components picked-up from the flue gas (other acid gases, fly-ash). In the open literature there is little information on the mass balance of for instance MEA in a PCC-process operation. Also there is currently no detailed study conducted in Australia on the environmental impact of atmospheric emissions of such large quantities of amino compounds and its degradation products. The expected emissions to the air include:

- Entrainment of the amine/ammonia with the treated flue gas and their associated atmospheric chemical reaction pathways such as reactions with hydroxyl radical (OH), ozone (O_3) and nitrate (NO_3).
- Formation of ammonia and other amine degradation products such as formic acid, ethylamine, acetone etc., which can be entrained with the flue gas and released to the atmosphere.
- Potential formation of secondary pollutants that may affect the human health and the environment such as nitrosamines, nitramines, amides and aldehydes.

These issues could be limited by alternative solvents but nevertheless need addressing for amine systems, to provide preventive solution. The challenges associated with slippage events or atmospheric emissions need to be addressed from a rigorous scientific perspective. Expertise in organic amine and atmospheric chemistry/physics is critical for understanding the environmental impact and making informed decisions on reducing environmental impacts. CSIRO has a research activity in this area, which has attracted interest from demonstration project proponents in Europe, because of the availability of unique facilities to perform relevant tests, e.g. smog chamber and the available well-instrumented pilot plants.

The proponents of demonstration projects in Europe have flagged the environmental impacts of PCC processes as a major gap in our current knowledge and hence it figures as the outstanding issue in the risk assessment of these demonstrations projects. Clearly, this is an issue which should be addressed with some urgency in the context of the Australian PCC demonstration projects. It is crucial that this is done in a pro-active manner, which will result in clear emission guidelines or protocols for vendors looking to provide PCC-solutions.

Scale-up of PCC technology

The large volumes of flue gas to be treated by a PCC process require the use of large equipment. This presents considerable scale-up challenges in comparison to technologies used for high pressure gas streams. For instance, in the recent past column diameters were generally limited to around 12 meters [26] using generally accepted chemical industry design procedures. However, more recently it has been proposed that column diameters could be enlarged to 18 m diameter, allowing for the treatment of a single flue gas stream from a 550 MW_e power station [27, 28]. Also different column materials are proposed such as concrete and fibres reinforced plastic with the aim of reducing costs and allowing lower manufacturing costs on site. Operational expertise with such large columns is still lacking, although it is obvious that the learning from scaling up flue gas desulphurisation technologies will be equally applicable to scaling PCC-technologies. Nevertheless, it must be expected that scale-up of PCC technology will result in the identification of new issues which will have been unnoticed or not relevant in small scale pilot plants. The size of Australian power companies is relatively small in a global context, with the generation capacity typically averaging less than 2.5 GW. The deployment of PCC in Australia might therefore be more appropriately carried out using capture modules of say 300 MW_e-equivalent or less rather than retrofitting a full-scale power plant. Such a modular deployment of capture is more in line with the future emission reduction requirements, which aim to achieve an 80% reduction over the next 4-5 decades.

Stability of reactive liquid absorbents and fabrication materials

Reactive liquid absorbents are widely used for acid gas removal at high pressure from e.g. natural gas. One of the challenges in applying reactive liquid absorption to power plants is the decreased stability of the liquid absorbents because of the presence of O_2 which can oxidise solvents. Moreover flue gas impurities like SO_x and NO_x can react with solvents to form heat stable salts which render them inactive over time. The continuous thermal cycling of the liquid absorbent will result in temperature induced degradation over time. Also the liquid absorbent itself and its degradation products might induce corrosion, which leads to higher operational costs and unplanned replacement of plant components. A wide range of degradation products might be formed during the prolonged operation of the capture process.

Australian electricity market

The Australian Energy Market Operator (AEMO) operates the National Electricity Market (NEM). Under the National Electricity Rules AEMO has a dual role as market operation and system operator for the National Electricity Market. AEMO's highest priority as power system operator is the management of power system security and reliability. Security of supply is a measure of the power system's capacity to continue operating within defined technical limits even in the event of the disconnection of a major power system element such as an interconnector or large generator. Reliability is a measure of the power system's capacity to continue to supply sufficient power to satisfy customer demand, allowing for the loss of generation capacity. AEMO conducts the market through a centrally-coordinated dispatch process that pools generation from producers and delivers required quantities of electricity from the pool to wholesale consumers. Specific activities in achieving this include managing the bidding, scheduling and dispatch of generators, determining the spot price, measuring electricity use and financially settling the market. Electricity is a low margin, high volume commodity where competitiveness and viability is based in the unit cost of production. A typical aspect of the Australian electricity market is price volatility at periods of e.g. sharp increases in demand as shown in figure. These prices increase occur over a relatively short amount of time.

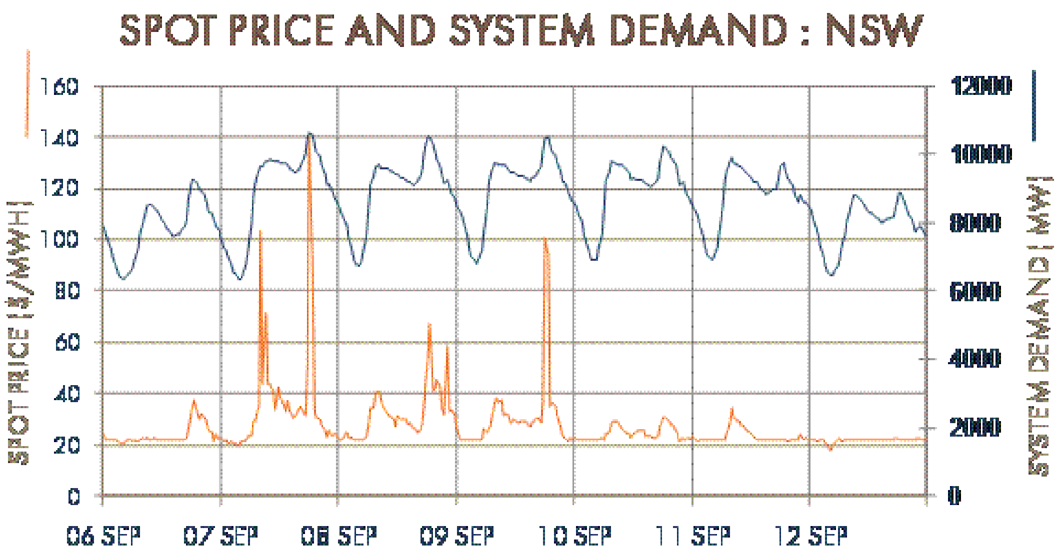

Figure 23 : Example of Electricity spot price and system demand (www.aemo.com.au)

PCC is perceived as a flexible process, i.e. it can be switched on or off over short times or reduced in capacity, allowing the power plant to produced more electricity over the brief periods of high demand and high costs. This requires more information on the dynamic operation of an absorption liquid based PCC process. Also the dynamic operation of the power plants with large variations in the steam flow through the LP turbines needs consideration. This area of research is currently not investigated at great length but seems crucial for the implementation of PCC in the Australian Electricity market. Furthermore the increased electricity generation from renewable sources (solar, wind) is also aided by the availability of flexible generation capacity. A flexible PCC plant could help in implementing large amounts of renewable sources into the electricity grid.

4.2 Stakeholder views

As a part of this review the authors conducted several interviews with key stakeholders in the PCC arena in Australia and with some overseas licensors using a questionnaire developed for the purpose (see appendix 1) The questionnaire sought to elicit key issues that might help to direct further local RD&D effort including industry opinions and commitment to CCS and indeed PCC.
Additional suggestions were drawn from an EPRI facilitated meeting in Brisbane on August 12, 2009 with potential stakeholders.

Responses to questionnaire

The responses indicated recognition amongst the end users of the eventual need for action and commitment to low emissions energy including CCS but there is a fair degree of caution while the future emission regimes, such as CPRS are resolved. The licensors and research community are clearly deeply committed to the issues and are actively engaged in developing technical solutions.

The respondents all see a clear position for PCC in a balanced portfolio of CCS alternatives however none have clear committed plans in place for large scale use of PCC.

The major issues identified for PCC, led by cost, are consistent with global directions, described in the previous section and include;

- Flue gas impurities
- Environmental issues, particularly water usage
- Understanding retrofit opportunities
- Confirming flexibility and control for those situations where PCC may be used in an ON/OFF scenario

The access to storage space and the resolution of CPRS were continually reinforced.

All parties indicated the importance of R&D to support the implementation of PCC and indeed all CCS activities. It was noted, as per the ANLEC guidance, that such input may be less pure science than is usually considered for next demonstration phase.

Training for certain new skill sets within the power companies was mentioned as an important issue going forward but it was noted that PCC was more closely aligned to the current situation than say for IGCC etc. The internal training requirements within the vendors were considered to be well covered, not requiring any additional attention.

All respondents expressed a desire for novel breakthroughs to be sought and provided to help drive the next range of PCC plant.

EPRI Workshop (Brisbane, 12 August 2009)

The notes collected at this workshop included similar areas that were gathered from the formal questionnaire and those for coverage under the ANLEC PCC review guidelines. The issues emanating from the discussions were:

- Getting regeneration steam for the PCC process from alternative sources - synergy with renewables.
- The need for independent performance verification in comparison with e.g. a base line and/or the pre-specification.
- The emissions from a PCC process, i.e. their characterisation, safe handling, requirement for regulations. This is closely linked to the formation of heat stable salts in the liquid absorbent based PCC process. By-products might be formed and separation techniques needed to reduce the amounts and re-use methods need to be identified.
- Matching process dynamics to electricity market dynamics
- The impact of the Australian fuel specifics, i.e. quality and costs on the PCC process are crucial, as well as the resulting Australian flue gas specifics (temperature, SOx and NOx). It is important to identify the most adequate level of flue gas pre-treatment.
- The constraints in availability of process water to power plants, leading to the use of air cooling in power plants. The trade-off between water cooling and air cooling needs to be made explicit. As the combustion process generates water there might be opportunities for collection and use of this.
- The inclusion of the existing pilot plants into the R&D programmes of vendors could lead to solutions optimised for the Australian situation
- The importance of an adequate communication package on the demo-plant results in an impartial manner.
- The scope of PCC retrofits to the Australian power plant fleet. What are the opportunities and limitations to this?
- Links with other PCC developments are required to avoid unnecessary duplication of research and the need for adequate adoption and adaptation of research and development carried out outside Australia requires continued collaboration with international partners.

5. Recommendations for PCC research in Australia

5.1 CCS General

The study identified the appreciation by end users of the need for action in all areas of low emissions technology. Equally however there was a reticence to commit to concrete plans for CCS, let alone PCC, due to commercial pressures and uncertainty of the future carbon management frameworks, such as CPRS.

The status of capture R&D in Australia has many positive features that can support the local industry with relevant and capable technical contributions as the areas of CCS, and indeed PCC progress towards a first-of-a-kind demonstration prior to commercial deployment. The programs of both CSIRO and CO2CRC reflect R&D projects covering all generations of the capture spectrum using appropriate skill sets and credible personnel across multiple institutions. Local researchers are well connected and well regarded internationally both through formal networks and international involvements such as conferences, technical publications and as advisors/reviewers to international CCS R&D programmes. As such the existing network of PCC-researchers in Australia is an extremely valuable and available resource for industrial, governmental and non-governmental stakeholders.

All currently commercially available capture technologies will result in a reduction of the power plant efficiencies. The increased resource use and increased cooling demand per unit of electricity are large and constitute an enormous step backwards compared to the gradual advances achieved over the last decades. This also directly translates into increased environmental impacts, except of course those related to global warming.

Capture technologies will need to be employed into the power sector, which feeds into the highly dynamic Australian electricity market. Capture technologies exhibiting a large degree of flexibility would have an advantage in terms of rapid deployment.

These issues, together with the regular mention about access to storage sites, are general to the CCS areas rather than the PCC area specifically and subsequent comments focus on the key PCC issues.

5.2 PCC General

Cost is the pervading issue for capture and the provision of reliable tools for evaluation of various configurations is fundamental to the direction of CCS research. While technical issues will feature highly in any R&D program the eventual uptake of CCS and PCC will be determined by commercial decisions.

It is recommended the ANLEC PCC R&D program should be driven by a focus on cost reduction which, at high level, will be achieved through:

- Improvements and break-throughs in separation processes, including the necessary development of separation agents and materials
- Enhanced heat integration internal and external to the PCC process and,
- Cost effective fit for purpose equipment

Over time a systematic development of a range of improvements to existing and novel technology, referred to as Generation I-IV, is needed to for cost-effective PCC-solutions.

The immediate focus of the program would have to be on reactive liquid absorption processes for post-combustion CO_2 capture, as they are the most advanced in terms of technical development and readiness for deployment. They are therefore likely to be the first to bring reductions in CO_2-emissions from power plants, provided the CO_2-storage is suitably developed on a similar time scale.

5.3 PCC research - short term

The intent of the proposed program is to focus on the immediate large scale demonstrations however in the short term it is recommended that the program support and nurture the existing programs in a targeted way such that resources and capabilities will be available as required for the large scale projects as they develop in the next 3-5 years.

The short term plan would recognise the significant capability in place across CSIRO and CO2CRC in a range of scale from laboratory to large scale pilot facilities and that key finding are already expected to be delivered under pre-existing programs.

Key areas of common programmatic interest recommended in the short term are to:

- Engage with, and review, existing pilot and demonstration PCC projects enabling the provision of sound advice to key stakeholders and project proponents.
- Understand the relevance of the demonstration programs and support the analysis of key data leading to results and findings for the industry, also taking a key part in the dissemination of these results and findings to a larger audience (research community, government and general public).
- Provide targeted support for potential Gen I-IV researchers while large scale projects are developing.
- Facilitate and engage with proponents and researchers as the new larger scale integrated demonstrations emerge. Ensure key research input is able to contribute through appropriate funding.
- Enable targeted novel technology trials to develop alongside emerging first stage demonstrations to underpin future improvements.
- Facilitate and provide enabling funding for R&D linkages with potential proponents and/or licensors, through e.g. utilisation of the existing Australian PCC pilot plants and other lab-based research capabilities, including the wide range of analytical support facilities developed through the ongoing R&D programmes.
- Facilitate the development of formal development pathways for the range of potential PCC applications in Australia.
- Confirm the screening methodologies for techno-economic assessments and utilise these on a location specific or project specific basis.

- Continued support to engagements with overseas demonstration projects and R&D programmes providing results of interest to the Australian situation.

Apart from costs, and the specific issues that might drive a given PCC research project, the key short-term research recommendation identified for Australian conditions are:

Continue PCC Pilot Plant Programs

Since PCC solvents are sensitive to flue gas impurities, all flue gases are to a greater or lesser extent different, and the cost of large solvent degradation rates are high, it is necessary to trial existing and new solvents in pilot plants on a range of power plant technologies and coal types. In order to reduce the risk and cost for demonstration and commercial operation of PCC, it is therefore necessary to develop and compile a comprehensive data base of solvent performance against flue gas properties for existing solvents that are currently proposed and new solvents that will be developed in the future.

Develop dedicated solutions to Australian flue gas quality issues

The flue gas impurity issues for Australian flue gases are well-documented. It still remains unclear how these can be better handled here than might be considered by vendors for overseas settings. Vendors will focus on the need for de-SO_x, de-NO_x and particulate removal prior to CO_2 capture, which are known to add excessively to the overall capture costs. A research focus on the investigation of interactions between SO_x, NO_x and the liquid absorbents is likely to provide an insight into lower cost solutions for handling of the flue gas impurities. This should include other known impurities in the flue gas such as HCl, HF, Hg and particulate matter. It is likely that the PCC process will constitute a multi-pollutant removal system.

Address the environmental impacts in their totality

Environmental issues, such as water usage, the dispersion of NO and in certain cases solvent and solvent breakdown product emissions need to be addressed from a rigorous scientific perspective. As well as developing new, superior capture formulations, the research program needs to continue the investigation of alkanolamine degradation and fate of emissions in the atmosphere. In addition existing environmental research capabilities (e.g. a smog chamber and chemistry based dispersion models) need to be targeted at understanding the fate of PCC process emissions to the atmosphere, in addition to developing prevention, handling and remediation methodologies for waste products and waste streams. The knowledge generated provides a starting point for emission guidelines for PCC plants under Australian conditions. It is anticipated that there will be additional environmental benefits as a result of the multi-pollutant removal aspect of a PCC process, which needs to be taken into account.

Support PCC implementation in Australian power plants

The implementation of PCC in Australian power plants requires a thorough understanding of retrofit applications, including controllability and plant integration issues. The integration entails both the extraction of steam for liquid absorbent regeneration and the integration of the gas absorbers into the flue gas path under site-specific conditions. Alternative methods to provide the heat of regeneration (e.g. solar thermal, geothermal) or an electricity operated system would limit the impact on the power plant steam cycle and need to be investigated. It is anticipated that the opportunities for heat integration for our low efficiency power plants might be larger than for overseas plants and these should be pursued.

Lower parasitic PCC process energy requirements

Research into options which limit the parasitic energy requirements of PCC continues to be at the forefront in many R&D programme, world-wide. In the Australian context, given the low cost of the fuel, the impact on the increased cost of generation might be less than elsewhere. Nevertheless, more energy efficient PCC processes need to be pursued, because of the need for more efficient resource utilisation, the large drop in power plant output after PCC (~150 MW_e reduction in plant output for a 600 MW_e power plant) and related environmental impacts. This covers e.g. more energy efficient liquid absorbents and process modifications. Also the integration of the CO_2 compression process with the liquid absorbent regeneration process provides opportunities for reduction of the energy usage of the capture process.

Reduce equipment size and costs

Capital costs are dominated by the equipment size, in particular those in the gas path. Increasing the absorption rates through the use of faster reacting liquid absorbents or the use of intensified contacting processes or devices using cheaper materials of construction will provide important cost benefits in the Australian and indeed the global situation.

Lower process cooling requirements

Cooling water constraints in Australia will almost certainly lead to the use of air cooling for PCC applications, which is more expensive than water cooling and also leads to a reduction in the generation efficiency. It is hence a critical issue. Alternative sources of water in the surroundings of power plants might be utilised. The combustion process itself produces water which can be used in the power plant. Combining the PCC process with water recovery processes, e.g. by fuel pre-drying or condensation from the flue gas has particular benefits in the Australian context.

Continue liquid absorbent process development and process validation

Reactive liquid absorption processes are technically and scale-wise the most advanced technology for PCC application. Their potential for improvement is still large, but as yet untapped. Realisation of the full potential of reactive liquid absorption processes is best done by an integrated programme of demonstration plants, pilot plants and laboratory research, using the analytical facilities and pilot plants already available within the research organisations. This covers the whole scope of liquid absorbent chemistry (reaction kinetics, oxidative and thermal degradation, corrosion, and additive formulation), process development (different flow sheets, thermodynamic data) and equipment development (contacting devices, integrated heat and mass transfer equipment). There should be room for the development of technology from Australian researchers in addition to the validation of overseas technology for Australian conditions. The proposed activity will underpin and support the demonstration activities.

Integrate the use of renewables into PCC

In order to reduce the parasitic energy load of PCC on the power plant, there is an opportunity in Australia to utilise renewables, particularly concentrated solar thermal, to provide heat for CO_2 stripping from the solvent. This will reduce the impact of the PCC process on the power plant steam cycle and thereby avoids a likely bottleneck in retrofitting power plants with PCC. In general more research is required to develop and demonstrate the integration of renewables into the PCC technology.

5.4 PCC research - long term

It is appropriate to recognise the emerging nature of the CCS area and that for significant continued reductions in cost to be delivered in 'the plant after next' (and those for commercial application) underpinning research is needed across a range of capture generations and this came out from stakeholders discussions.

A long term goal is to further develop and provide fundamental chemistry and engineering knowledge to underpin the use of existing CO_2 capture technologies. In addition to a fundamental understanding of existing PCC technologies, the development of improved CO_2 capture processes based on current reactive liquid absorption technologies is an important future direction. A crucial research direction remains the development of new CO_2 capture chemistry and the engineering processes that can provide step-change improvements over existing technologies. This entails considerable innovation and discovering completely new types of chemical systems for CO_2 capture. Going hand-in-hand with this is the optimal design of engineering processes to work with these new chemical systems. In essence, this means using reactive liquid absorbents and engineering processes that are similar to existing ones, but which yield better CO_2 capture performance when applied to power stations. Examples of such novel directions are: ionic liquids, hyper branched polymers, phase change liquid absorbents (slurries and emulsions), enzyme-enhanced processes. It is likely that each of these directions will also have its very specific requirements in terms of the process flow sheet and equipment to enable the realisation of the anticipated benefits.

The long term research should focus on a range of emerging technologies (membranes, adsorbents, cryogenic, biological). It should address the materials research aimed at improving the performance and lowering the costs of the separating agents, the development of scalable component such as membrane modules, novel reactors addressing issues like scale-up and methods of fabrication. However, also the efficiency improvement of supporting technologies such as vacuum pumps and compressors should be addressed. The research should contain the aspect process or component testing in a realistic environment.

6. Acknowledgements

The leading authors wish to acknowledge the input from their colleagues in the preparation of this scoping study, as well as the supportive comments received from power companies and technology suppliers.

7. References

1. Lowe, Allen, Noel Simento, 2009, Considerations for Research Supporting Low Emission Coal Technology Demonstration
2. Wibberley, Louis, et.al. 2006, State of the art review Post Combustion Capture, CSIRO/CO2CRC
3. Feron, P.H.M., 2007: A global perspective on post-combustion CO_2 capture, invited presentation at CO2CRC Research symposium, Perth, Australia, 6-8 November
4. Davison, J, 2007: Performance and costs of power plants with capture and storage of CO_2, Energy 32, 1163–1176
5. Hasan, R**,** Scholes, C**,** Stevens, G and Kentish, S, 2009. The effect of hydrocarbons on the separation of carbon dioxide from methane through a polyimide gas separation membrane. *Industrial and Engineering Chemistry Research,* vol. 48, pp. 5415-5419
6. Scholes, C**,** Kentish, S and Stevens, G, 2009. Minor component effects on membrane gas separation for carbon capture. *In: 8th World Congress of Chemical Engineering,* Montreal, Quebec, Canada, 23-27 August
7. Gassnova, 2009, International CCS technology survey, issue 5, July 2009 (www.gassnova.no)
8. Bak, H., 2009, E.ON's CCS activities: From pilot plants to demos to commercial scale, presentation at Dutch National CCS symposium, Driebergen, 15 April
9. Sander, M.T. and Mariz, C.L., 1992, Energy Conversion and Management, Volume 33, Issue 5-8, pp. 341-348
10. Reddy, S., 2008, Econamine FG Plus^{SM} for Post-Combustion CO_2 Capture, presentation at 11th meeting of the Post-Combustion CO_2 Capture Network, Vienna, Austria, May 20-21
11. Mimura, T., et.al., 1995: Research and Development on Energy Saving Technology for Flue Gas Carbon Dioxide Recovery and Steam System in Power Plant, Energy Conversion and Management, 36(6-9), 397-400.
12. Iijima, M, 2008, Post-combustion system, Coal Fired Plant and Multipollutant Control, presentation at 11th meeting of the Post-Combustion CO_2 Capture Network, Vienna, Austria, May 20-21
13. Ryan, C., 2009, Cansolv Technologies: CO_2 Capture Sequestration & Utilisation, China CCS Conference, Beijing, China, March
14. Paelinck, Ph., 2009, Carbon Capture and Storage update, Clean Power Today, Sydney, July 27
15. Cottrell, A. et al., 2008, Post-combustion capture R&D and pilot plant operation in Australia, Aaron Cottrell et.al., Energy Procedia, Volume 1, Issue 1, pp 1003-1010
16. Feron, P.H.M., 2008, Post-Combustion Capture (PCC) R&D at CSIRO, presentation at COAL21 Post Combustion CO_2 Capture Meeting, Canberra, Australia, 6 August
17. Harkin, T**,** Hoadley, A and Hooper, B, 2009. Reducing the Energy Penalty of CO2 Capture and Storage Using Pinch Analysis. *In: 12th International Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction,* Rome, Italy, 10-13 May. Available online at http://www.aidic.it/pres09/ [Accessed 30 July 2009].

18. Allinson, W G, Nguyen, D N and Bradshaw, J, 2003, The Economics of Geological Storage of CO_2 in Australia. The APPEA Journal, 2003, pp. 623-635
19. IPCC, 2005: IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer (eds.)] Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp
20. Brown, Ph., et al, 2007: LCA of the Australian Electricity Grids, Technology assessment report No. 62, Cooperative Research Centre for Coal in Sustainable Development
21. Dave, N., T. Do, D. Palfreyman, 2008, Assessing Post-Combustion Capture for Coal Fired Power Stations in APP Countries, CSIRO Energy Technology, Progress Report No. 1 - ET/IR – 1083
22. Dave, N., T. Do, D. Palfreyman, 2009, Assessing Post-Combustion Capture for Coal Fired Power Stations in APP Countries, CSIRO Energy Technology, Progress Report No. 2 - ET/IR – 1144
23. Bailey, D.W. and P.H.M. Feron, 2005, Post-combustion Decarbonisation Processes, Oil & Gas Science and Technology – Rev. IFP, Vol. 60, No. 3, pp. 461-474
24. Feeley, T.J. et al, 2007, Water: A critical resource in the thermoelectric power industry, Energy 33, pp. 1–11
25. Feron, P., 2009, The potential for improvement of the energy performance of pulverized coal fired power stations with post-combustion capture of carbon dioxide, Energy Procedia, Volume 1, Issue 1, pp. 1067-1074
26. Chapel, D., Ernst, J. and Mariz, C., 1999, "Recovery of CO_2 from Flue Gases: Commercial Trends", Paper No. 340 at Canadian Society of Chemical Engineers, October, Saskatoon, Canada
27. Holling, Bernd, 2009, Linde's PCC-Activities Construction of a Pilot Plant Concepts for a Large Scale Plant, Presentation at RWE PCC symposium, Duesseldorf, July, 30
28 CO2CRC patent (Application No. PCT/AU2008/000664)

Appendix 1: Questions to Power Generators

1. In a carbon constrained world what is your company's vision on how to provide low emissions power?

2. How does CCS and in particularly PCC fit into a low-emissions power strategy?

3. Do you have concrete plans to develop or implement low-emissions power requiring the use of PCC?

4. Which are the major issues and/or gaps that need to be addressed to have PCC commercially available by 2020 and more in particularly ready for first-of-a-kind demonstration by 2015?
Suggestions:

- FG quality
- Environmental impacts
- Cost (now and improvements)
- Training/Education
- Cost reduction (integration, equipment, technology)
- Retrofit possibilities
- Flexibility in operation
- Asset management

5. How can research & development support the successful demonstration of PCC?

6. What training and educational needs do you expect to arise from the adoption of PCC on a large scale in Australia?

7. What position do you see for novel and break-through PCC technologies?

Appendix 2: List of PCC pilot plants operating or planned to operate on actual flue gases

Who	Where	Fuel	Technology	Capacity	Status	Remarks
Kansai Power together with MHI	Kansai Power station	Gas	KS-1		In operation since 1991	Still in use for PCC development
International Test Centre supported by consortium	Saskpower power station Boundary Dam near Estevan, Saskatchewan	Lignite	Various amine solutions	170 kg/h CO_2	First built in 1987	Still in use for PCC development
E.ON, TNO supported by CATO programme	E.ON power plant on Maasvlakte, The Netherlands	Black coal	Amino-acid salt solutions; membrane contactors	Max. 250 kg/h CO_2	In operation since July 2008	
Dong Energy, EU-funded through CASTOR project	Esbjerg, Denmark	Black coal	Various amine solutions	1 ton/h CO_2	In operation since January 2006	
MHI with J-Power and supported through RITE	J-Power Matsushima power plant	Black coal	KM-CDR technology with KS-1 solvent	0.4 ton/h CO_2	In operation since July 2006	
E.ON, Siemens supported through Cooretec programme	E.ON Staudinger power station in Germany	Black coal	Amino-acid salt solutions developed by Siemens	Not known	Start-up in September 2009	
E.ON, Fluor	E.ON power station in Wilhelmshafen, Germany	Black coal	Econamine FG Plus	~ 3 ton/h CO_2		16000 m^3/h flue gas; 10 MEuro project cost
E.ON, MHI	E.ON power station in Germany	Black coal	KS-1	~ 4 ton/h CO_2	Start-up in 2010	20000 m^3/h flue gas; 10 Meuro project cost
E.ON Cansolv	E.ON Power station at	Black coal	CANSOLV	~ 4 ton/h	Start-up at the end	20000 m^3/h flue

Technologies	Heyden, near Minden, North Rhine Westphalia, Germany			CO_2	of 2009	gas; 10 Meuro project cost
E.ON, Alstom Power	E.ON power station in Sweden	Oil and gas	Chilled ammonia	~ 1 ton/h CO_2		Equivalent to 5 MW_{th}
E.ON together with Electrabel Hitachi Power	Transportable pilot plant to be used in Germany, Belgium, Netherlands		Amine solutions developed by Hitachi Power	~ 1 ton/h CO_2		5000 m^3/h flue gas
RWE npower, partnering with CANSOLV Technologies, BOC, IM Skaugen, The Shaw Group Inc., Tullow Oil Plc.	RWE npower power station Aberthaw, South Wales	Black coal	CANSOLV	~ 1 ton/h CO_2	Start-up in 2010	Equivalent to 1 MW; 8.4 M£ project cost Shell will also join as a partner
RWE Power with BASF, Linde	RWE Power Niederaussem power station at	Lignite	Amine solutions	~ 0.5 ton/h CO_2	Commissioning in mid-2009 with 30% MEA – SO_2 removal to 3 ppm	4 Meuro project cost
Alstom Power with EPRI and We Energies	WE Energies Pleasant Prairie Power plant, Wisconsin, USA	Black coal	Chilled ammonia	~ 1 ton/h CO_2	Start-up in 2008	Equivalent to 5 MW_{th}
Alstom Power with AEP	Mountaineer plant, New Haven W.Va.	Black coal	Chilled ammonia	~ 10 ton/h CO_2	Start up in 3 quartern 2009	Equivalent to 30 MW_{th} to be followed by 200 MW_{th} demonstration
Alstom Power with	Mongstadt	Gas	Chilled ammonia	~ 10 ton/h		Equivalent to 30

Statoil				CO_2		MW_{th}
Powerspan with Basin Electric	Basin Electric Antelope's Valley power station in North Dakota	Black coal	ECO2	1 Mton/a CO_2	Start up in 2012	Equivalent to 120 MW
Cansolv	Transportable pilot plant used in various locations worldwide	Gas, coal, cement flue gas, blast furnace flue gas	CANSOLV solvents	25 kg/h CO_2	Variable	
Aker Kvaerner	Karstø gas terminal facilities near Stavanger, Norway	Gas turbine exhaust	Various including membrane contactors	180 kg/h CO_2	Established in 1998; Not in operation anymore	Flue gas: m3/h; 4-6% CO2
ENEL	Brindisi, Italy	Black coal	Amine solutions	~ 2.5 ton/h CO_2	Start up in autumn 2009	
EDF	Not known	Black coal				
Korean Institute of Energy Research		Black coal	20% MEA – ABB Lummus technology	~ 250 kg/h CO_2	Established in 2004; Not in operation anymore	
PG Elektrownia Belchatow	Belchatow, Poland	Lignite	Alstom amine technology		In operation in Mid 2011	
Sigma Power Ariake Co. Ltd	Mikawa Power Plant, Omuta City, Fukuoka, Japan	Black Coal	Toshiba' amine technology	10 ton/day CO_2	In operation by August 2009	
Alstom Power with DOW Chemical	DOW Chemical Manufacturing facility Charleston W.Va.	Black Coal	Alstom amine and ammonia technology	1800 ton/a CO_2	In operation in second half 2009	
Aker Clean Carbon	Scottish Power, Longannet, Scotland	Black Coal	Amine solutions	200 kg/h CO_2	May 2009	Flue gas 1000 m^3/h

China Huaneng Group	Huaneng Beijing Cogeneration plant	Black Coal	Amine solutions	500 kg/ h CO_2	In operation since July 2008	CO_2 sold into local market
China Huaneng Group	Power plant in Shanghai	Black Coal	Amine solutions	100,000 ton/a CO_2	Start up in January 2009	CO_2 to be sold into local market
Loy Yang Power with CSIRO	Loy Yang A Power station	Lignite	Amine solutions	100 kg/h CO_2	Start up in June 2008	Part of Latrobe Valley PCC project
International Power with CO2CRC/ CO2CRC H3 Capture Project	Hazelwood power station	Lignite	Amino Acid salts from BASF / Potassium Carbonate solutions	2 ton/h CO_2	Start up in May 2009	CO_2 used for ash-water neutralisation
Delta Electricity with CSIRO	Munmorah Power station	Black Coal	Aqueous ammonia	375 ton/h CO_2	Start-up in January 2009	
Tarong Energy	Tarong power plant	Black Coal	Amine solutions	100 kg/h CO_2	Start-up in August 2010	
CO2CRC H3 Capture Project with International Power	Hazelwood power station	Lignite	Membrane processes- Gas separation and Gas Absorption membranes	2 kg/h CO_2	Start up in July 2009	
CO2CRC H3 Capture Project with International Power	Hazelwood power station	Lignite	Vacuum Swing Adsorption	25 kg/h CO_2	Start up in July 2009	