CARBON DIOXIDE CAPTURE AND STORAGE

RESEARCH DEVELOPMENT & DEMONSTRATION IN AUSTRALIA

A Technology Roadmap
2004

DRAFT

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Reference CO2CRC 2004 Carbon dioxide capture and storage: Research development and demonstration in Australia - A technology Roadmap 2004. Cooperative Research Centre for Greenhouse Gas Technologies, Canberra, Publication No 2004/01 January 2004. 60pp.

Foreword

The carbon capture and storage technology roadmapping exercise was coordinated by CO2CRC during the second half of 2003. It proved to be important on several counts. First, the process was valuable for fostering collaboration in that it brought together around 10 people from industry, government and the research community, mainly from Australia, but also including overseas participants. Second, it also brought together a wide range of organizations. Third, whilst the original impetus for developing the roadmap came from the need for CO2CRC to identify its own research and innovation priorities, it quickly acquired a much broader significance. Specifically it highlighted the need to place capture and storage technologies into a broader context of options for low emission technologies and a clean energy pathway to a hydrogen economy.

This technology roadmapping exercise has been a lengthy exercise. Indeed in many ways it commenced in 1999 when we started the GEODISC program. This ensured that when developing the roadmap for storage technologies we did not start with a blank sheet of paper We already had a fund of knowledge on geosequestration opportunities in Australia and obviously this in turn had a major impact on the outcome of our gap analysis and the form of the roadmap.

The 2003 technology roadmapping exercise recognized the very great importance of ensuring that the outcomes be placed within the international R&D scene. Capture and storage technologies are expensive to develop and demonstration geosequestration projects involve a very high cost indeed. Therefore, in Australia we are seeking to build on the experience of other countries and vice versa. This report serves to indicate areas where Australia can contribute to addressing the global issue of reductions in greenhouse gases and also areas where it will seek to collaborate with other countries.

Due to the enormity of the exercise and inevitable deadlines, it has not been possible to provide all participants with the opportunity to review the material in this paper nor present it as an official Australian policy position; indeed this exercise was never embarked on with that in mind. However it does provide a solid foundation for influencing the direction of R&D for CO2CRC and collaborating organizations, in Australia and internationally, which was its primary purpose.

Australia has offered to make the results of the exercise available to the wider international community involved in the Carbon Sequestration Leadership Forum (CSLF). Some of the CSLF countries who may seek to benefit from our experience will need to consider not only the Australian roadmap but also the years of work undertaken by Australia prior to the roadmap. It is also important to stress that each nation will have its particular needs and priorities and the roadmap presented here is not presented as a universal technology roadmap but merely as an example of the way that one country, Australia, went about establishing priorities in capture and storage technologies and placing those priorities into the longer term targets of low emission energy and the hydrogen economy.

Let me acknowledge the efforts of a large number of people in developing this roadmap. Will Fraizer and Colin Scott of ChevronTexaco Australia facilitated the workshops and provided access to their methodology for roadmap development. They were assisted by Karl Gerdes and Scott Imbus, also of ChevronTexaco Energy Technology Co. Vello Kuuskraa of ARI in Washington provided valuable input into the workshops. Particular thanks are due to Andy Rigg (CO2CRC) who was responsible for coordinating the CO_2 storage roadmap, and Barry Hooper (CO2CRC) who was responsible for the CO_2 capture roadmap. John Bradshaw (CO2CRC and Geoscience Australia) played a major role in compiling results from the various workshops. Comments on the draft of this report were provided by Will Fraizer, Andy Rigg, Barry Hooper, David Collins, the research community, the public sector and the CO2CRC Board.

Finally I would like to acknowledge the contribution of all the CO2CRC research participants and industry sponsors, and also of CSIRO, the "Coal CRCs", COAL21, the Centre for Functional Nanomaterials, the AUstralian Academy of Technical Sciences and Engineering and the Australian Greenhouse Office.

Peter J Cook

Chief Executive
CO2CRC
Canberra, Australia
10 December 2003

1. Executive Summary

Four levels of technology roadmaps are defined for Australia in this report: Level Zero provided the foundation; Level 1, with a time scale of 5-10 years, is the most detailed component and is concerned with research and development; Level 2 with a time scale of 10-20 years is focused on demonstration of CO_2 capture and storage; Level 3, with a time scale of 20-30 years is concerned with the place of CO_2 capture and storage technologies in the evolving hydrogen economy.

A series of Level 1 technology roadmap workshops were held in 2003 to establish an Australian and CO2CRC position in CO_2 capture and storage technologies and to identify the core issues for capture and storage, from an Australian perspective and place these into an international perspective.

Researchers and industry representatives brainstormed ideas for improving the technology across the complete spectrum of capture to storage. Broad technology themes were identified and an assessment made of the strengths of Australian research in delivering these advances.

Findings from the capture and storage workshops led into a discussion on Australian research directions, the implications for current research programs and specific program initiatives. The workshops focused on cost reductions in capture and the safe, secure and appropriately monitored storage of CO_2.

Capture research will require close liaison with commercial providers and engineering groups, ensuring Australia has a fast follower approach. International collaboration will be very important, but new research initiatives will also be pursued by Australia in niche areas. In the case of capture, a discussion of technology horizons was introduced to give a perspective of likely developments and how these linked into potential demonstration projects.

In the case of the CO_2 storage workshop, there was a focus on the more important storage options for Australia, such as saline formations, although issues relating to CO_2-enhanced petroleum recovery were recognized, but in view of the limited opportunities and low volumes expected to be involved, were not pursued in detail. However the topic will be the subject of a future technology roadmapping exercise. Similarly technologies relating to use of CO_2 were not fully covered due to time constraints but will be addressed at a later date. The priorities identified will be an important driver for CO2CRC programs, but are likely to be of significance to the broader research community in Australia and elsewhere.

The specific outcomes of the Level 1 capture and storage workshops were then placed within a broader technology roadmap context, using separate but related initiatives. These included the outcomes of the international Hydrogen Conference sponsored by the Australian Government in Broome, Western Australia in May 2003. It also included the outcomes of a joint industry-government partnership, known as COAL21. This then provided a temporal framework for aspects of the Level 2 roadmap out to 2015. A preliminary technology roadmap, focused on potential pilot, demonstration and commercialisation opportunities, is provided and these opportunities will influence R&D program milestones in the future.

This was then followed by a Level 3 roadmap to 2030 which attempts to place capture and storage into the path to the more speculative hydrogen economy. This technology roadmap is not presented as a formally endorsed Australian Government roadmap and indeed this exercise was not embarked on with that intention. It was developed for the guidance of CO2CRC and collaborating organizations in their future approach to R&D.

2. Background

2.1 Australia's CO_2 Emissions

The problem of increasing levels of atmospheric CO_2 is a global issue and Governments have agreed that steps must be taken to stabilize and, in the longer term, decrease CO_2 emissions. There is less agreement on how best to achieve this. The Australian Government has decided not to ratify the Kyoto protocol at present but is committed to meeting Australia's Kyoto target of limiting emissions to 108 percent of 1990 levels between 2008 and 2012.

Approximately 50% of Australia's CO_2 emissions are derived from a variety of stationary sources (Figure 1). These are sources of CO_2 that have the potential to be captured and stored, provided appropriate and economically effective technologies can be developed and introduced at the time that new assets are developed or existing assets are replaced or retrofitted. Significantly, the 50 top emitters of CO_2 in Australia, located in 7 or 8 regional centres or nodes, produce 95% of Australia's total stationary CO_2 emissions.

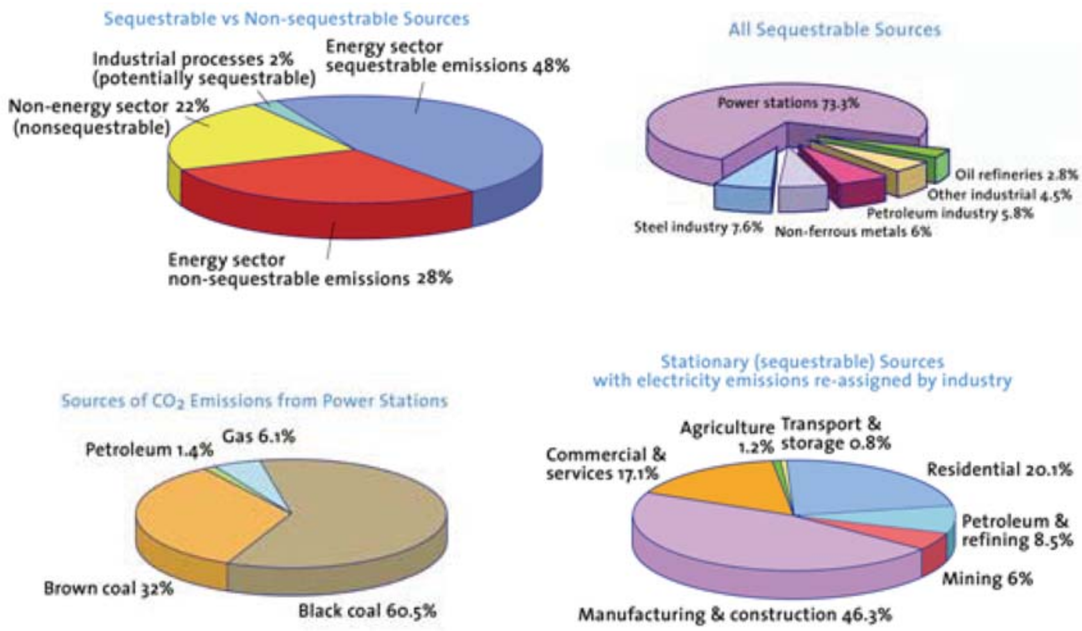


Fig. 1. Industries where greenhouse gas technologies might potentially be applied in Australia to stationary sources of CO_2.

A range of measures will be needed to enable Australia to attain its emission targets including increased energy efficiency, decreased carbon intensity and more effective sequestration. Stationary CO_2 emissions are predicted to grow strongly for the next 20 years and beyond, with increasing use of fossil fuels, notably coal and natural gas. During this time frame renewable energy is also expected to grow significantly although its total market share will probably continue to be modest. Consequently, additional options must be developed, particularly those that will address the issue of CO_2 emissions from major stationary sources. One promising areas of investigation for Australia is greenhouse gas technologies that separate and capture CO_2 from process and flue gases and then store that CO_2 in geological or mineral environments. These technologies however must compare favourably with other options in terms of costs and environmental and social acceptability.

The challenge is to develop cost effective technologies and systems that will make it possible over time to capture a significant proportion of 'stationary CO_2' and store it in geological locations safely and securely for thousands of years or more.

But, the potential significance of these technologies is much greater than merely providing an option for decreasing emissions from conventional stationary energy and process systems. It also opens up the possibility of integrating capture and storage technologies with advanced energy systems such as IGCC or oxyfuels (see later) to low emission electricity, syngas and hydrogen. Advanced fossil fuel-based energy systems with capture and storage therefore provides one pathway to the hydrogen economy with current projections suggesting that it will be the cheapest pathway for some years to come. With this in mind it was decided to address the role of capture and storage technologies in a fossil fuel-based hydrogen economy through a multi-level roadmapping process.

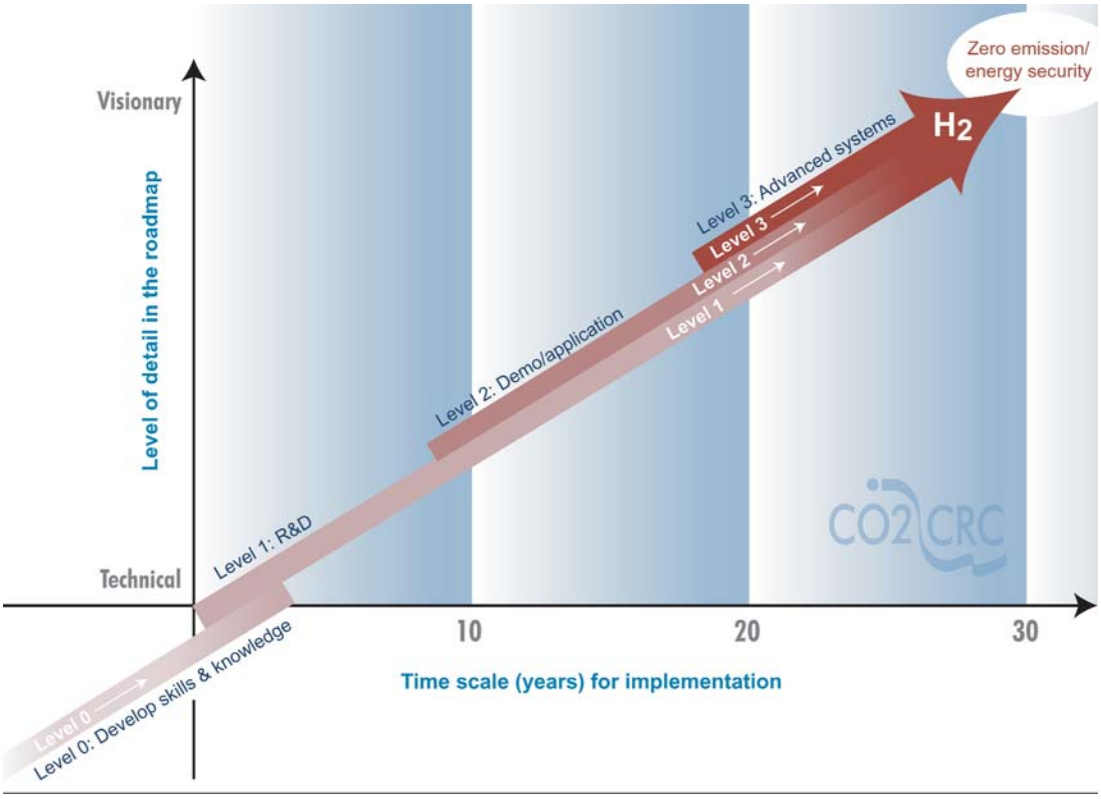


Fig 2. Schema for the Australian Technology Roadmap illustrating the four levels of mapping related to degree of detail and timing and commercialisation.

The technology roadmap process used for Australia effectively has four levels (Fig 2):

Level 0 - Assessment of preliminary activities over the previous 5 years that have contributed to development of technical capability and knowledge

Level 1 - This is the main focus of this report. It is aimed at defining research and technology directions for Australia over the next 5-10 years through a detailed roadmap

Level 2 - Definition of proposed pilot, demonstration and commercial projects that could contribute to R&D over the next 10 - 20 years, particularly through application of R&D

Level 3 - Definition of the place of capture and storage in a hydrogen roadmap over the next 20-30 years.

3. Preliminary Activities (Level 0)

3.1. GEODISC

This level of roadmap covers the development of knowledge infrastructure prior to detailed roadmapping undertaken in 2003.

In the period July 1999 - July 2003, a large number of Australian researchers participated in the GEODISC program of the Australian Petroleum Cooperative Research Centre (APCRC). The primary purpose of GEODISC was to examine Australia's geosequestration potential at a broad level and to undertake related research to facilitate that assessment. That study had its own generalized roadmap, first developed in 1998 and modified as necessary over the subsequent four years. The schedule of technical activities undertaken under GEODISC is shown in Figure 3.

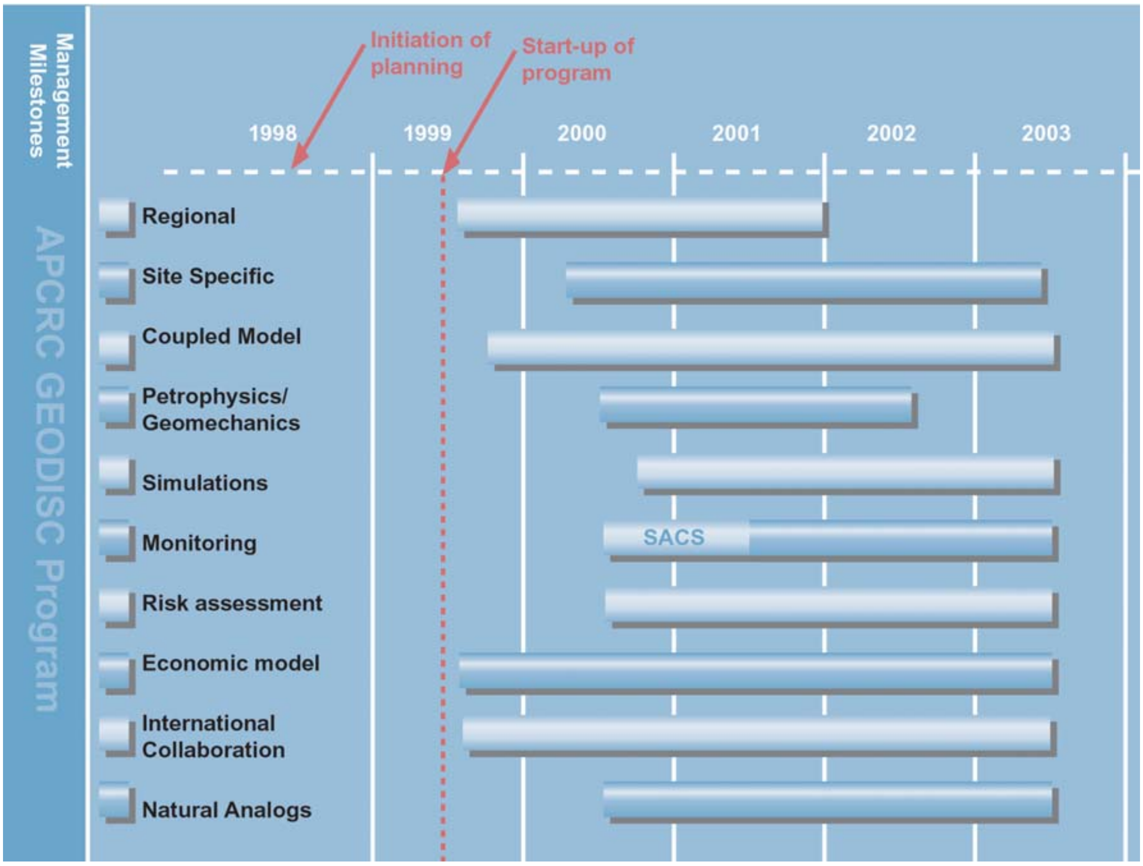


Fig 3. Level 0 roadmap developed for GEODISC (after Cook et al, 2000)

This provides some indication of the work undertaken up to the start of the current technology roadmapping exercise and clearly demonstrates the importance of developing a knowledge base and an adequate level of expertise and infrastructure prior to embarking on the next phase of research and development covered by the detailed Level 1 roadmap.

As a result of four years of GEODISC research Australia has achieved a great deal in terms of developing its skill base and its knowledge base in geological storage of CO_2. Specifically, the preliminary work has:

- Developed an understanding of CO_2 storage amongst a large group of geologists, geophysicists, modelers, reservoir engineers and economists.
- Established a methodology for defining Environmentally Sustainable Sites for CO_2 injection (ESSCIs) and assessed more than 100 sites for their storage potential (Fig 4)
- Determined that Australia does have very significant potential for geological storage of CO_2, particularly in saline formations in the western half of the continent; more work is required on potential storage sites in eastern Australia.
- Established that the number and distribution of many major stationary sources of CO_2 was likely to be amenable to geological storage.
- Indicated that, in some circumstances, geological storage may be an economically viable option in Australia for mitigating CO_2 emissions
- Showed that geological storage is likely to be technically viable as a long term option
- Carried out a preliminary matching of CO_2 sources and sinks
- Suggested that there are a number of methods for monitoring subsurface CO_2
- Established that CO_2 leakage to the surface requires consideration but that it is unlikely to be a major issue at most Australian sites considered suitable.

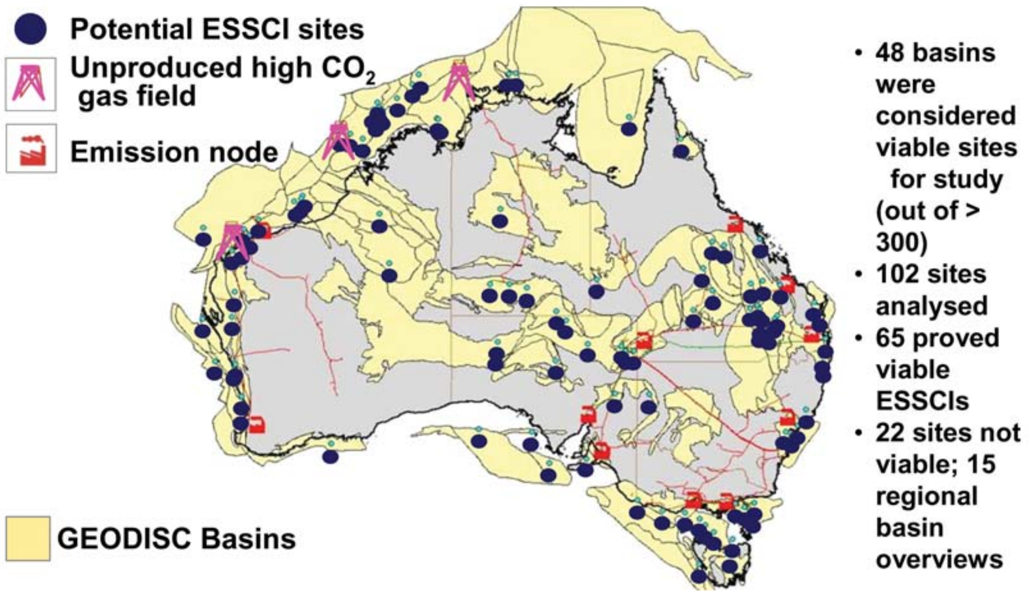


Fig 4. Location of Australian sites (ESSCIs - Environmentally sustainable sites for CO_2 injection) assessed for the CO_2 storage potential (after Bradshaw et al, 2001)

What GEODISC did not address were any issues relating to the capture and separation of CO_2 from flue gases or other emissions. However it was recognized that there was a significant skill base in Australia in relevant technologies such as solvents, membranes, pressure swing adsorption and cryogenic separation. Nor did it address the use of CO_2 as a mitigation option, or mineral storage in the formation of useful minerals.

It was recognized that to take matters further and fully assess capture and storage options for Australia, there was a need to now start more detailed studies. Given there was inevitably a limit to the funds and other resources available to undertake further research, it was necessary to prioritize activities and it was decided that developing a technology roadmap was the way to most effectively prioritize. At the same time, it was also recognized that we were not starting off with "a blank sheet of paper". Through GEODISC, real expertise and knowledge had been developed which must be recognized in the roadmap if the maximum benefit is to be derived from the prior investment by Australia in geological storage research and development.

Together, this experience and these issues provided the backdrop against which it was decided to embark on a major new Australian program of research and demonstration of CO_2 capture and storage technologies.

3.2. CO2CRC

The Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) - a joint venture between industry, government and research institutions - was formed in October 2003 following its success in obtaining Australian Government funding.

CO2CRC will contribute to efforts to address climate change through participation in international research programs and also through involvement in the international arena in bodies such as the Carbon Sequestration Leadership Forum (CSLF), the Special Working Group III of the Intergovernmental Panel on Climate Change (IPCC), and the Climate Action Partnership (CAP) with the United States and other countries.

Vision and Mission

The **vision** is to develop cost effective transitional technologies that will help Australia decrease CO_2 emissions to the atmosphere from major stationary CO_2 sources, whilst at the same time continuing to derive benefit from its abundant fossil fuels and existing industrial base.

The **mission** of the Cooperative Research Centre for Greenhouse Gas Technologies and collaborating research organizations is to:

- undertake outstanding collaborative research into new CO_2 sequestration technologies, to demonstrate that CO_2 capture and storage is economically and environmentally sustainable;
- enable Australia to decrease its CO_2 emissions to the atmosphere, maintain the competitiveness of its industries and exports and develop new commercial opportunities;
- offer outstanding education and training in greenhouse gas technologies and contribute to the resolution of a significant global environmental problem through participation in international programs and initiatives and through collaboration with the world's leading research groups. and other international initiatives and linkages.

CO2CRC combines the research-user focus of ten major petroleum, oil and power companies covering several industry sectors and the research provider (geoscientific, engineering, chemical, economic etc) strengths of universities, research organizations and the private sector. It has strong links with leading overseas research institutions in Europe, the United States, Canada, New Zealand, and Japan.

Fact-finding visits were made by CO2CRC to industry, government officials and researchers in the UK, Netherlands, USA, Canada and Japan to assess international capabilities and needs. The resulting preliminary gap analysis and technology assessment showed:

- Technology options for limiting CO_2 emissions are seen as increasingly important by many industry sectors and governments.
- Any technology solution must embrace ongoing dependency on fossil fuels for the foreseeable future.
- The cost of CO_2 capture must decrease considerably
- The characteristics of Australian emissions represent local challenges and opportunities for users of capture technologies.
- Potential users see geological storage as 'promising' but yet to be proven.
- Australian geology is favourable for users of CO_2 storage technologies.
- The emerging hydrogen economy will initially be based on fossil fuels and effective geological sequestration will be an essential component.

Based on these assessments and the substantial technology base of the previous GEODISC program, a business plan was developed and agreed by all participants in CO2CRC.

The strategy adopted for CO2CRC was to:

- Assemble an outstanding multi-disciplinary-interdisciplinary team of researchers to work on technology based research with industry, whilst ensuring integration of other stakeholder issues especially socio-economic matters
- Take a 'whole of industry' approach to CO_2 encompassing a variety of emissions from a range of sources.
- Work with leading national and international research teams to maximize technology transfer and research leverage.
- Focus on the identification, development and application of the most cost-effective system(s) for the capture of CO_2 from major stationary sources
- Identify suitable geological locations for long term CO_2 storage
- Undertake Pilot and Demonstration Projects to prove capture and storage feasibility.
- Look for early opportunities to store CO_2 and obtain additional beneficial outcomes to offset sequestration costs (enhanced petroleum recovery; mineral products).
- Develop regional options for capture and storage, and in so doing, lay down the basis for a future hydrogen economy based on fossil fuels.

Specific programs were developed around five areas:

1. Geologically storing CO_2

2. Demonstration program for geological storage

3. Using CO_2 and obtaining valuable products

4. Capturing CO_2 through the use of a range of technologies

5. Developing regional strategies for decreasing CO_2 emissions

Based on the prior GEODISC work and the new programs of CO2CRC, Australia now has a major focus for CO_2 capture and storage research and technologies. However it does not have a monopoly on research and since CO2CRC was established, it has been seeking to strengthen its links with other key Australian and international groups in order to ensure a coordinated and supportive approach is taken to capture and storage research and technology development in Australian and internationally. As part of this strategy of partnership, CO2CRC catalysed and coordinated meetings involving all major research groups active in the CO_2 sequestration field in Australia. It also decided to develop a detailed technology roadmapping exercise not just for CO2CRC programs but for Australian capture and storage. This is described in the next section.

4. Detailed Technology Roadmap (Level 1)

4.1 General

The Australian technology road mapping exercise session was set up to define the direction of Australian R&D into carbon capture and storage (CCS). It brought together a broad range of stakeholders in the area including industry, government and researcher personnel. Additional invitees from groups outside the CO2CRC ensured broad input to the exercise. Several overseas experts involved in international carbon capture and storage programs were valuable contributors.

The sessions were facilitated by personnel from ChevronTexaco using one of their technology review techniques and supplemented by other R&D portfolio methodologies. It was intended that the roadmapping exercise would define the CO2CRC program and the broader Australian R&D context for greenhouse gas technology directions. Specifically that it was intended to ensure that R&D proposals were:-

- realistic and timely
- utilized the Australian skill base
- took into account research activities elsewhere in the world
- effectively incorporated into the CO2CRC program
- were compatible with national research priorities

The detailed (Level 1) road mapping exercise was initiated through two separate workshops - one in Perth on 14th August 2003 covering CO_2 Storage with a large group of researchers and one in Melbourne on 21st August 2003 covering CO_2 Capture with a smaller group of participants.

Mr. Will Fraizer and Mr. Colin Scott of ChevronTexaco Australia facilitated the roadmap. International participants added significant value to these sessions namely, Karl Gerdes and Scott Imbus (ChevronTexaco Energy Technology Co), Vello Kuuskraa (ARI) and Alex Malahoff (GNS-NZ).

4.2 Roadmapping Process

4.2.1 Functional Steps

The facilitators employed a Functional Analysis technique to break down the key steps in each stage of CCS. FAST (Functional Analysis System Technique) diagrams were developed by the attendees and served as the basis for showing relative cost of each functional step.

Separate FAST diagrams were developed for each stage and/or technology application area with Figure 5 offering an overview of capture plus storage.

4.2.2 Idea Generation

Having established the core functional steps in each technology area, the groups brainstormed ideas and/or technologies that would enable significant improvements in the field of CCS, e.g. improvements in the integrity and security of storage or reductions in the cost of capture.

Large numbers of ideas were documented in spreadsheets and diagrams, samples of which are included in Appendix 1. It was recognized that not all of the ideas raised in the Storage group meeting were specific technologies, but it was felt that the chance to sample input from a wide range of people from different disciplines and backgrounds was too good an opportunity to miss. Some of these non-technology items have been tagged as issues or processes for separate consideration.

4.2.3 Categorization

In order to realistically process the large number of ideas, it was necessary to group or aggregate the individual ideas into common themes or technology areas. Once this reduction was complete, a review of technology impact, research positioning and an assessment of technology maturity was performed.

The relative importance of technologies was initially assessed qualitatively, but wherever possible, this was supported by subsequent quantitative assessments. The competitive positioning of local research was somewhat subjective, but given the broad bands used and some post-August reviews, it was considered fit for the purpose of this exercise.

Categorization was completed during the capture exercise but, due to the number of participants in the storage workshop, it was necessary to do much of this after the session and with a much smaller group.

Samples of the aggregation and mapping outputs are included in Appendix 1.

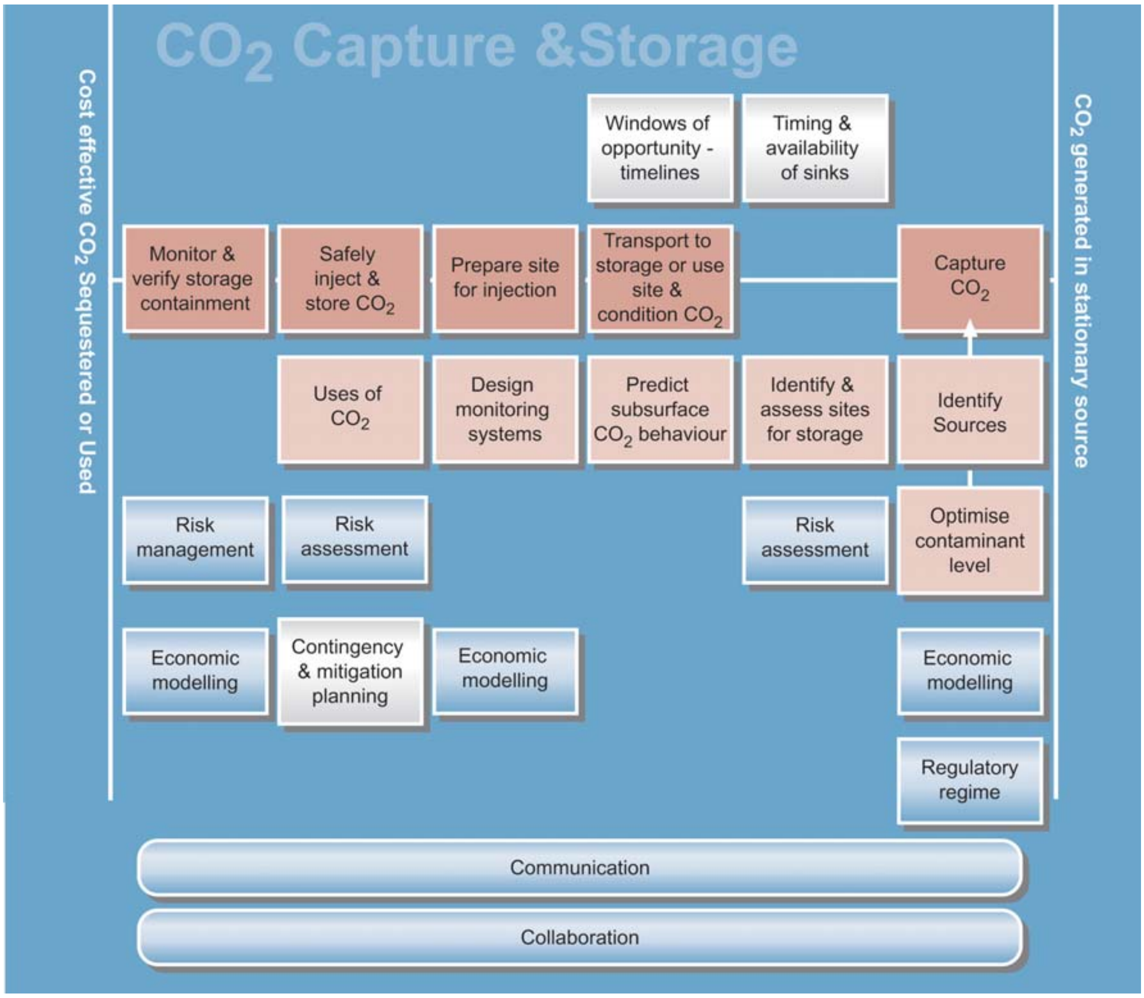


Fig 5. High level Functional Analysis Technique FAST diagram for CO_2 capture and storage

4.2.4 Post Processing

Having completed the formal sessions, post processing was needed to confirm the program detail. This varied between the main program areas of Capture and Storage and included doing a reality check on CO2CRC and other outputs with a range of external sources from industry, government and research organizations.

The outcomes of the initial technology roadmapping are discussed in detail within the two broad headings of CO_2 Capture (4.3) and CO_2 Storage (4.4). It was recognized at the workshop time that as most projects under the heading "Using CO_2" program would not commence until late-2004, these would be considered in detail later. However the Idea Generation phase was undertaken for "use of CO_2 for value added products" and "use of CO_2 to ameliorate environmental concerns." Neither of these are reviewed further here, although some early ideas are provided in Appendix 1, and these will be further addressed at the time of the first update to this technology road map.

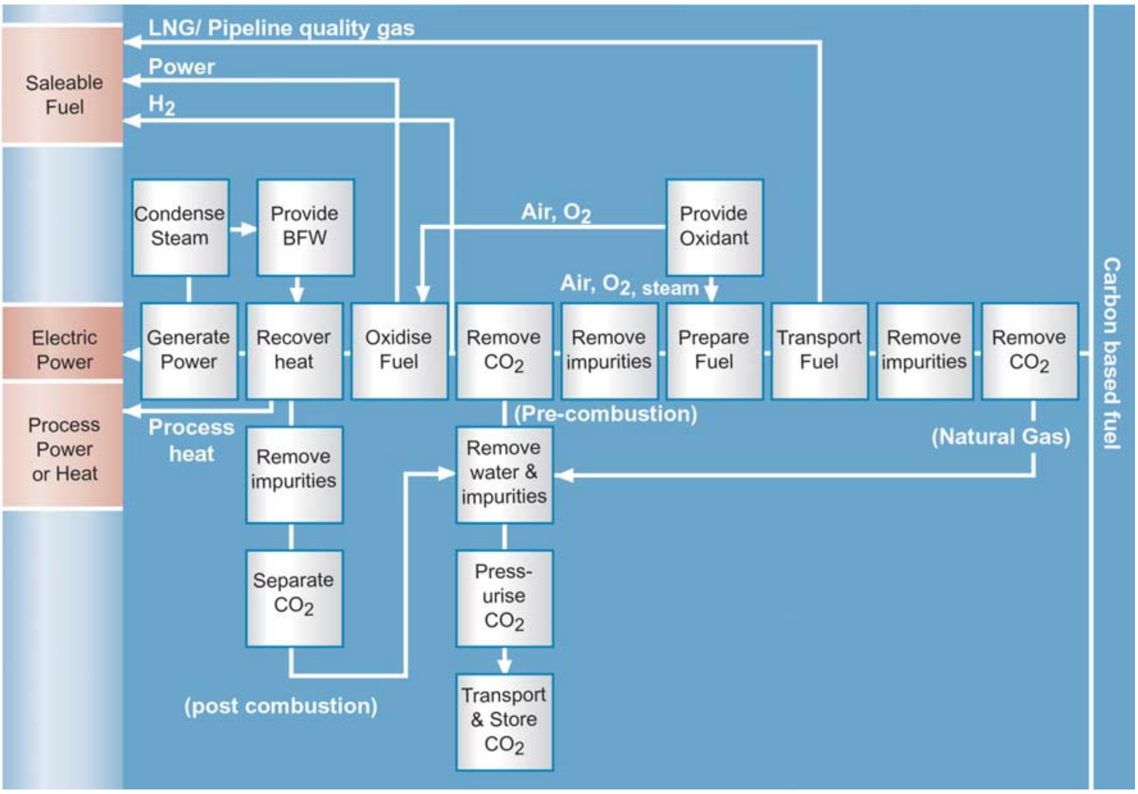


Fig 6. General System Technique FAST diagram for CO_2 capture

4.3 CO_2 Capture Roadmap

A broad mix of personnel attended the capture technology road mapping exercise from industry and research (see attendance list - Appendix 2). A FAST diagram was developed for CO_2 capture (Fig 6). The session was structured to focus on the key areas of:

Post Combustion:

- The removal of CO_2 from combustion exhaust gases at power stations and/or industrial facilities. The CO_2 is at low concentration and the gases are at low pressure

Pre-Combustion:

- Pre-combustion is the approach of converting fossil fuels into hydrogen, which is then used as a fuel in combustion operations (turbines, heaters and the like), in direct power generation via fuel cells or as a chemical feedstock. Carbon in the fuel is converted to CO_2. Since H_2 production is typically done at elevated pressure, and the CO_2 is present in relatively high concentration, the selective removal of CO_2 for sequestration is more easily accomplished, compared to removing it from normal flue gas. Operations involving coal or heavy liquid hydrocarbons use a Gasification technique while natural gas or light liquid hydrocarbons use Steam or Autothermal reforming.

CO_2 removal from natural gas:

- CO_2 is often a constituent of raw natural gas and must be removed to acceptable levels for transportation, use, or futher processing.

Oxyfuels:

- A process whereby fuels are combusted with oxygen, thus avoiding the handling of large volumes of nitrogen in exhaust gases.

Limited time was spent on the Oxyfuels issues due to the relatively simple CO_2 capture requirements. It was identified that there was considerable expertise available through the CCSD. Combustion technology issues were not considered to be in the remit of the current exercise and are the subject of consideration as part of Coal 21 (see later), the CRC for Coal in Sustainable Development (CCSD) and the CRC for Clean Power from Lignite (CRCCPL) as well as CSIRO's Energy Transformed initiative. Personnel from these organizations attended the workshop and the need for ongoing consideration of the interface issues between CO2CRC and these organizations will be a continuing feature of greenhouse gas technology research in Australia.

Following the idea generation and aggregation into technology themes, a categorization and gap identification exercise was completed on the position of Australian research in these areas. The outcome of this stage is discussed below.

Technology	Natural Gas	Post-Combustion	Pre-Combustion	Oxyfuels
Solvent Absorption[1]	✓	✓	✓	
Membranes[2]	✓	✓	✓	✓
Adsorption[3]		✓	✓*	✓*
Cryogenics[4]	✓		✓	✓
Hydrates[4]			✓	
Chemical Looping[5]			✓	✓

Notes:

1. Solvent absorption includes work on new solvents and improved contactors
2. Membranes include polymeric and inorganic units used for either gas separation or as a gas absorption device. Inorganic units lend themselves to high temperature applications and modification as reactive separators
3. Adsorption includes work on new adsorbents structures and modified cycles. *More particularly for O2 separation though possible application in pre-combustion
4. Cryogenics /Hydrates are applicable in higher pressure situations or as a hybrid linking to sequestration ready CO2
5. Chemical Looping is an integrated method of removing N2, most likely applicable to gas fired applications

Table 1. Capture Technologies versus Application

4.3.1 Technology Themes

The initial qualitative view of the importance of particular technology areas (Table 1), in the Australian context, was unsurprisingly consistent with the views of other international organizations. It should be noted that the researchers participating in the roadmap session had expertise and interests in specific technologies, so there was some focus on familiar subject areas, with the core opportunity areas being:

- Solvents
- Membranes (polymeric and inorganic)
- Adsorbents
- Cryogenics/Hydrates
- Other novel areas e.g. chemical looping

The data from the road mapping was later cross referenced with prospective research areas from major international CO_2 capture programs, i.e. Carbon Capture Project (CCP), IEA GHG R&D program and the US Department of Energy. Combining these assessments with consistent capture cost data for the technologies in the various applications results in a matrix of prospective Technology/Application matches (Table 1).

From a technology perspective, the review suggests a number of technology horizons for CO_2 capture (Fig. 7).

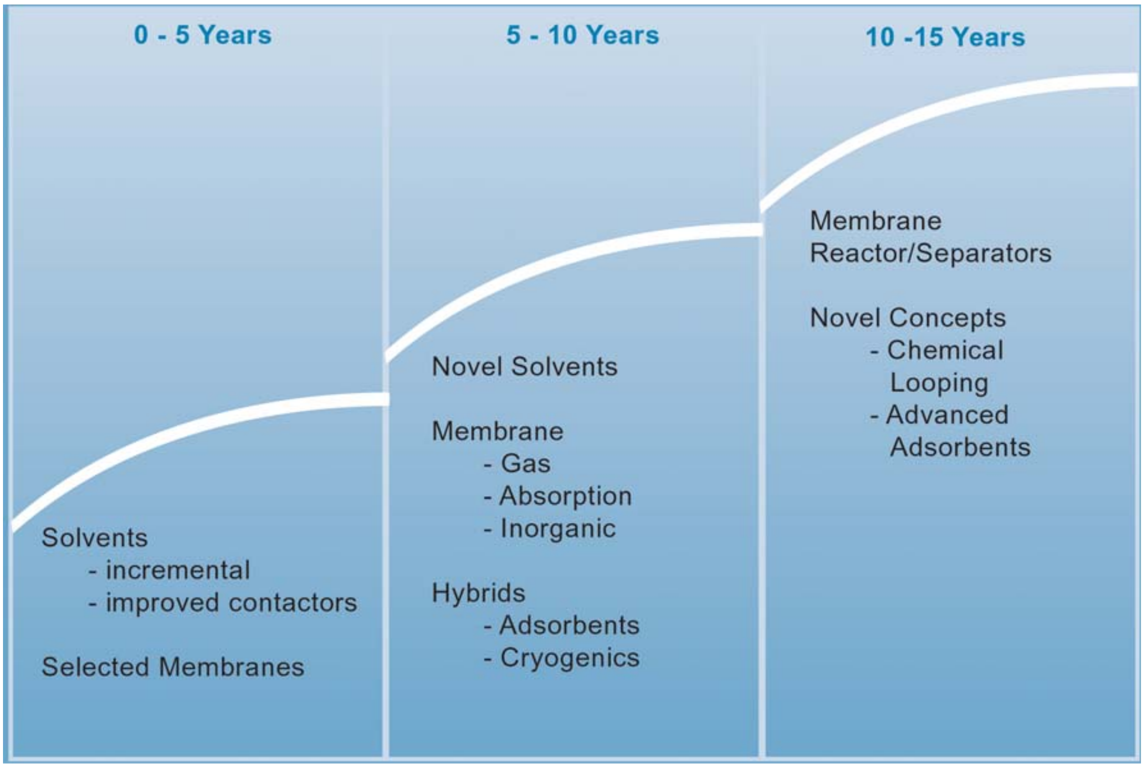


Fig 7. Technology horizon for CO_2 capture

In the immediate future, solvents will dominate, with possible cost effective applications for membranes. The next bands of improvements are likely through novel solvents, improvements in membrane system capability and possible hybrids applications. Longer term gains will come through commercialization of novel concepts, such as membrane reactor/separators.

4.3.2. Australian Perspective

CO_2 capture and separation has been deployed in the Australian gas and petrochemical industry for many years, but specific research to store CO_2 after capture, has been limited. This is changing with significant interest in support of the emerging greenhouse issues for the fossil fuel industry. CO2CRC and other Australian groups are focusing efforts in this area, building on the world-class research coming out of the GEODISC program, and solvent, membrane and related research undertaken previously by cooperating research organizations and universities.

Australian research funding in the area of greenhouse gas research has increased significantly in recent times and greenhouse science has been identified as a national priority. Nonetheless by comparison with major OECD countries funding is limited and therefore must be targeted to specific Australian issues. Furthermore, given the large amount of work performed in overseas programs, strengthening links with international research and commercial interests is critical in order to leverage opportunities for local industry.

Core issues identified in the CO_2 capture technology road mapping were:

- Providing an economic overview of technology options
- Capture cost driver
- An ability to choose the best options for Australian conditions
- Gas Treatment
- Appropriate technology for application
- Hybrid systems
- Processing Plant
- Establishing appropriate interfaces between capture and storage
- Compression
- Gas mixtures

While minimal work has been performed in Australia directly in the area of CO_2 capture, research in related areas positions the local R&D community favourably. Only the area of Chemical Looping indicated a weak position - this will be followed up with other researchers (Table 2). A full list of technology categorisation is given in Table 3.

Technology Area/Theme	Competitive Positioning
Solvents	Favourable
Membranes - polymeric and inorganic	Favourable/Strong
Adsorbents	Favourable
Cryogenics/Hydrates	Favourable/Strong
Chemical Looping	Weak

Table 2. Relative positioning of Australian CO_2 capture R&D

4.3.3. Implications for Australian Capture R & D

Based on the emerging capture cost reduction opportunities, the relative strengths of the Australian research base and the needs to introduce and demonstrate these technologies in the local energy sectors, the framework for the CO2CRC programs in particular can be shaped, but obviously there is an impact on other R&D programs.

The technology horizon diagram (Fig. 7) indicates the technology of choice for near term CO_2 capture demonstration will be a form of solvent absorption or possibly selected membrane applications. The greatest opportunities for significant reductions in CO_2 capture costs are likely to come from the horizon two or three technologies.

Core issues for Australian researchers will be to:

- Maintain an overview of the emerging CO_2 capture area
- Enable the selection of appropriate options for the local conditions
- Drive research efforts based on capture cost
- Focus efforts on the most promising technologies for specific applications

A balanced R&D portfolio in the capture area should maintain a watching brief on all horizon one technologies while pursuing specific emerging /pacing technologies.

The preferred approach is to evolve strong links with commercial and research entities in these emerging areas and to develop research projects that will enhance the local deployment of these technologies. The more mature technologies will be monitored and activities such as literature review and use of technology networks undertaken to maintain the necessary overview of the technology options. Significant international liaison will be required both on the current research agenda and to keep abreast of other advances.

Australian groups are not active in all areas across the entire capture sector nor is it intended at this stage to include all capture areas in Australia's R&D priorities. Skills for the core issues of gas treating, processing issues such as gasification, advanced energy cycles and equipment issues necessary for Oxyfuels application reside within the coal CRCs, CSIRO and the Queensland Low Emission Technology Centre for Clean Power.

It is, and will continue to be, important that all the groups working in this area maintain strong working relationships, in order to ensure a strategic overview for Australian industry and to maximize the value of publicly funded R&D and to ensure that storage and capture issues are addressed concurrently.

4.3.4. Implications for CO2CRC Capture Program

Other Australian organizations may wish to consider their response to the priorities outlined. Here, CO2CRC outlines its response to these priorities. One of the key drivers for the initial roadmapping exercise was to define specific directions within the CO2CRC Capture program and this report outlines that direction. At the same time, it is important to emphasize that CO2CRC projects will not be given "life of CRC" status. All activities will be subject to regular review with strict criteria requiring demonstration continuing cost reduction potential. Directions for the program are described below.

4.3.4.1 Techno-economics of CO_2 Capture

While not a specific technology theme, techno-economic considerations are important to provide a common basis by which projects and technologies are measured.

Considerable work has been done in international programs and that work will be leveraged and integrated into the work already done under GEODISC. The interfacing between capture and storage will be standardized and work done on the impact of mixed gases on the end-to-end costs. CO2CRC will also work with the coal CRCs to develop a common platform for energy economics modelling.

Technology	Relative Importance Now	Relative Importance Future	Technology Impact	Relative position of Australian R&D	Maturity
Novel absorbent solvents	Low	Med	Emerging	Favourable	Growth
Improved solvents	Med	Low	Key	Favourable	Mature
Improved solvent-gas contactor systems	Low	Med	Base	Tenable	Mature
Optimised solvent system integration (heat transfer)	Low	Med	Key-Pacing	Favourable-Strong	Mature
Gas-liquid membrane systems	Med	Med-High	Pacing	Strong	Growth
Novel membrane polymers / manufacturing / fabrication	Med	Med	Emerging	Strong	Growth
Novel inorganic membrane materials / manufacturing	Med	Med	Emerging	Favourable-Strong	Embryonic
Ion transport based CO_2 separation / reactor systems (similar to fuel cells)	??	??	Emerging	Tenable	Embryonic
Improvements to existing membrane materials	Med	Med	Key	Strong	Growth
Improved membrane module design	Med	Med	Key	Strong	Growth
Optimised system integration - membranes/hybrids	Low	Med	Emerging	Favourable	Growth
Membrane based reactors	Med	High	Emerging	Favourable-Strong	Embryonic
Facilitated transport systems	Low	Med	Emerging	Favourable-Strong	Embryonic
Gas adsorbant contacting systems	Low	Med	Emerging	Strong	Embryonic
Novel adsorbants (low temperature mesoporous adsorbants)	Low	Med	Emerging	Strong	Embryonic
Novel adsorbants (high temperature applications)	Low	Med	Emerging	Tenable	Embryonic
Optimised process cycles for adsorption/regeneration	Low	Med	Pacing	Strong	Growth
Combined adsorption/reaction (PSR)	Low	Med	Emerging	Tenable	Embryonic
Chemical looping concepts	Med	Med	Emerging	Weak	Embryonic
Low temperature / cryogenic CO_2 separation	Med	Med	Key	Favourable-Strong	Growth
Hydrate formation/separation	Med	Med	Emerging	Tenable?	Embryonic
Improved / integrated flue gas/ syngas treatment (pre-CO_2 capture)	Low	Low	Base	Weak-Tenable	Mature
Cost /process optimisation models	N/A	N/A	Base	Favourable	Mature

Table 3. Categorization of technology themes in CO_2 capture.

4.3.4.2. Solvents

A watching brief will be maintained by CO2CRC on the solvent absorption area, particularly focusing on the IEA GHG initiatives and solvent providers. Solvent absorption is applicable to all CO_2 capture applications and is likely to provide the ongoing benchmark for capture costs. Further, it is not intended to further develop new solvents at this stage of the program but to leverage the established range of solvents and their respective improvements into work in gas absorption membranes.

4.3.4.3 Membranes

The CO2CRC will focus on polymeric membranes in the area of gas separation and gas absorption membranes, whilst the ARC Centre for Nanomaterials Research will focus on inorganic membranes.

Gas separation membranes

Gas separation membranes are strong candidates for improved natural gas separation, post combustion coal applications, and hybrid systems. Research on modified polymer systems is directed toward improving the robustness of equipment and improving the flux of these systems.

Gas absorption membranes

Gas absorption membranes are strong candidates in all but high temperature applications of CO_2 capture and are expected to be useful in hybrid systems. Research by CO2CRC will be undertaken with the emerging range of solvents and commercial membrane systems to support preferred applications in the Australian scene.

4.3.4.4. Adsorption

Adsorption is currently not preferred in CO_2 capture but improvements in adsorbent capacity and optimized cycles may lead to substantial reductions in costs.

CO2CRC will investigate novel mesoporous materials which are showing promise while reviewing the broad potential for cost reductions through improved CO_2 adsorption cycles. A watching brief will monitor oxygen adsorption opportunities that may arise from this work.

4.3.4.5. Cryogenic/Hydrate Processes

Cryogenics processes are established in natural gas applications. They offer potential in several core CO_2 removal applications directly, as part of hybrid systems and as an interface to storage ready CO_2. The CO2CRC will continue to support this work with added focus on broader CO_2 applications.

4.3.4.6. Other Interests

The positioning and structure of the capture program within the CO2CRC enables the potential optimization of capture and storage costs by bringing together the geological and chemical engineering features required for the end-to-end process. Consequently the capture program will look at issues of mixed gases, hybrid configurations and other potential cost reduction techniques. CO2CRC will actively collaborate with research and industrial organizations in the field while seeking opportunities to demonstrate and commercialize carbon capture and storage as a cost effective means to drastically reduce greenhouse emissions in Australian industry.

4.4 CO_2 Storage Roadmap

A large group and a broad mix of personnel from industry, government and research attended the storage technology road mapping exercise. Because of the work conducted in the GEODISC program, CO_2 storage technologies are at a somewhat more mature stage in Australia, than the capture technologies.

The Functional Analysis process outlined in Section 4.2.1 identified four core functional steps for CO_2 storage (Fig. 8.) These are,

- Transportation and conditioning of CO_2
- Safely and effectively injecting CO_2
- Safely and effectively storing CO_2, and
- Monitoring and verification of the stored CO_2.

The workshop also briefly considered the use of CO_2 to produce valuable products and to produce beneficial environmental outcomes (Appendix 1.4) based on a FAST diagram developed to address these dual benefits (Fig. 9)

Storage Option	Feasibility	Potential Capacity	Data Availability	Expertise	Priority
Saline reservoir rocks	Very high	Very high	High	Very high	1
Depleted oil reservoirs	High	Low	High	High	2
Depleted gas reservoirs	Very high	Now - Low Future - High	High	High	2
Deep coal seems	Medium - low	Medium?	Low	Medium	2-3
Voids and cavities	High	Low	Low	Low	4
Basalts	?	?	Low	Medium	3
Serpentinites	Low	?	Low	Medium	4
Enhanced oil recovery	Low	Low	Medium	Low	2
Enhanced gas recovery	?	Low - medium	Low	Medium	2
Enhanced coal bed methane	?	Medium	Low	Low	2
Reaction with brines	High	Low?	Low?	High	3
Use of carbonate minerals	High	Low	High	High	3

Table 4. Australia's position in technologies CO_2 storage
(Priority 1 - highest, priority 4 - lowest)

4.4.1. Technology Themes

Discrete Idea Generation sessions were held for each of the core functional steps and a very large number of ideas were later categorized and further consolidated by a smaller group into technology theme categories as shown below. As mentioned previously, this also included some ideas better represented as "issues" and "processes" rather than technology themes.

- Transportation and conditioning of CO_2
  - Pipeline technology
  - Effects of contaminants
  - Trucking, shipping and temporary storage technologies
  - Issues relating to understanding the physical state of pipeline fluids
  - Operational issues
  - Environment, regulation and safety issues
  - Compressor technology
- Safely and effectively injecting CO_2
  - Injection well technology
  - Geomechanical issues
  - Use of pre-existing well bores
  - Injection process technology
- Safely and effectively storing CO_2,
  - Containment issues
  - Geological storage options
  - CO_2 properties and behaviour
  - Subsurface impacts of CO_2 storage
  - Modelling and simulation issues
  - Near well-bore rock-fluid interaction
  - Regional rock-fluid interaction
- Monitoring and verification of the stored CO_2.
  - Remote sensing technology
  - Verification requirements and technology
  - Surface and near-surface monitoring requirements and technology
  - Detection of unexpected leakage
  - Geophysical monitoring technology
  - Geomechanical monitoring technology
  - Well-based monitoring technology

4.4.2 Technology Prioritization

In order to rank those technologies to be researched in the near term, all of the technologies, issues and processes were evaluated as to their relative importance now and in the near future (important because of the rapidly emerging application of many pre-existing hydrocarbon industry technologies to the issue of carbon dioxide storage), their technical maturity and where the expertise for such research and study is located.

A simple matrix identified those technologies that were considered high or medium importance now, that were not aging technologies, and where expertise resided in Australia. This, in turn, determined those technologies on which Australian research could most profitably be focused in the early stages.

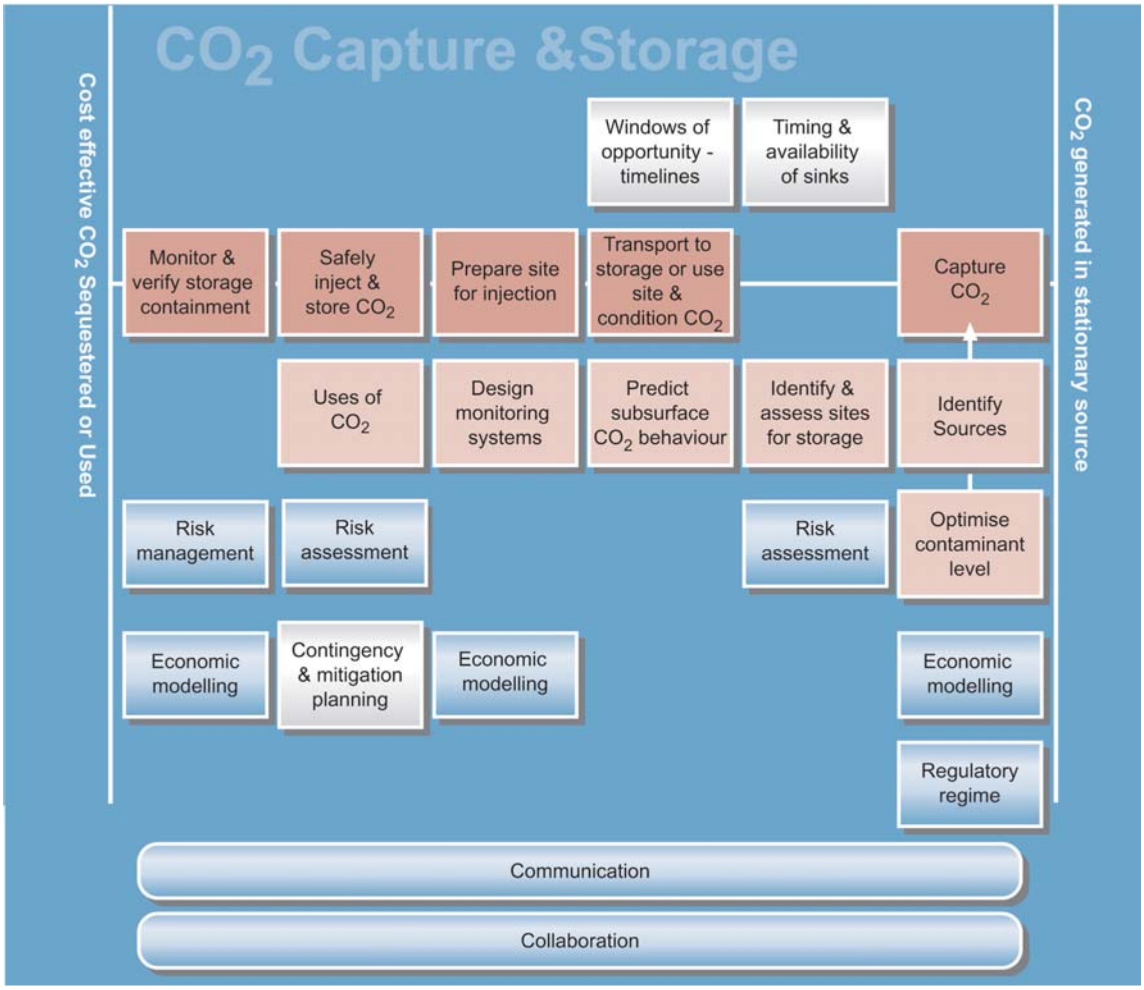


Fig. 8. General FAST diagram for CO_2 capture and storage

4.4.3. Implications for Australian Storage R&D

Much of the necessary storage expertise is drawn together as part of CO2CRC. However, a range of relevant underlying skills are also developed within other programs and organizations. For example, the coal CRCs have outstanding expertise in coal analysis composition and properties and that expertise would be drawn on for storage projects relating to coal. The Federal and State Geological Survey organizations have unrivalled knowledge of regional geology. Reservoir modelling R&D is underway in both the public and private sectors and would be utilized wherever possible in the storage program, it is also recognized that there are considerable benefits in adopting industry standards in order to allow project comparisons.

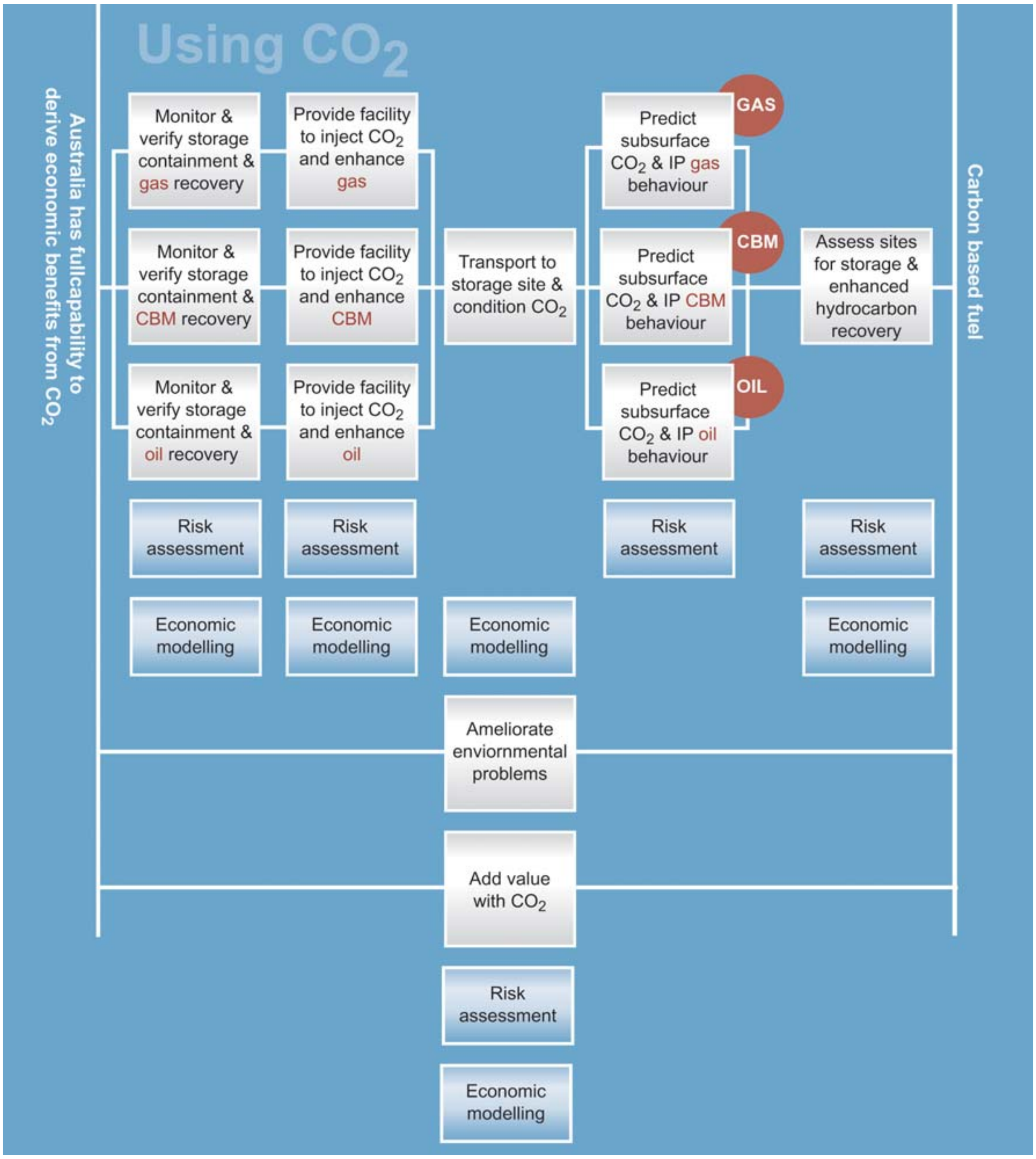


Fig. 9. General FAST diagram for using CO_2

The range of storage options are shown schematically in Figure 10 and, to some extent, because of its strong earth science base, Australia is potentially able to undertake R&D into all of these options. However it is also evident from previous research undertaken by GEODISC that the most significant storage opportunities are likely to lie in saline formations, coals and coal basins and perhaps enhanced petroleum recovery (oil, gas, CBM). Other options are more likely to be pursued through international collaboration.

Based on a combination of factors relating to Australian geology and, to a lesser extent, likely storage capacity, it is possible to prioritize broad storage areas (Table 4). Where the opportunity exists to exploit "low hanging fruit", least cost, or even no cost storage options can be potentially developed at an early stage. For example while Australian storage potential incorporating enhanced oil recovery is seen as modest it is still likely to be accorded a priority for R&D because of its least cost status.

For some options the necessary expertise and data bases are available (e.g. saline formations). In other cases they are not available and will need to be developed if the topic is a priority for Australia (e.g. enhanced coal bed methane) or alternatively the necessary data and collaboration can perhaps be accessed through international collaboration.

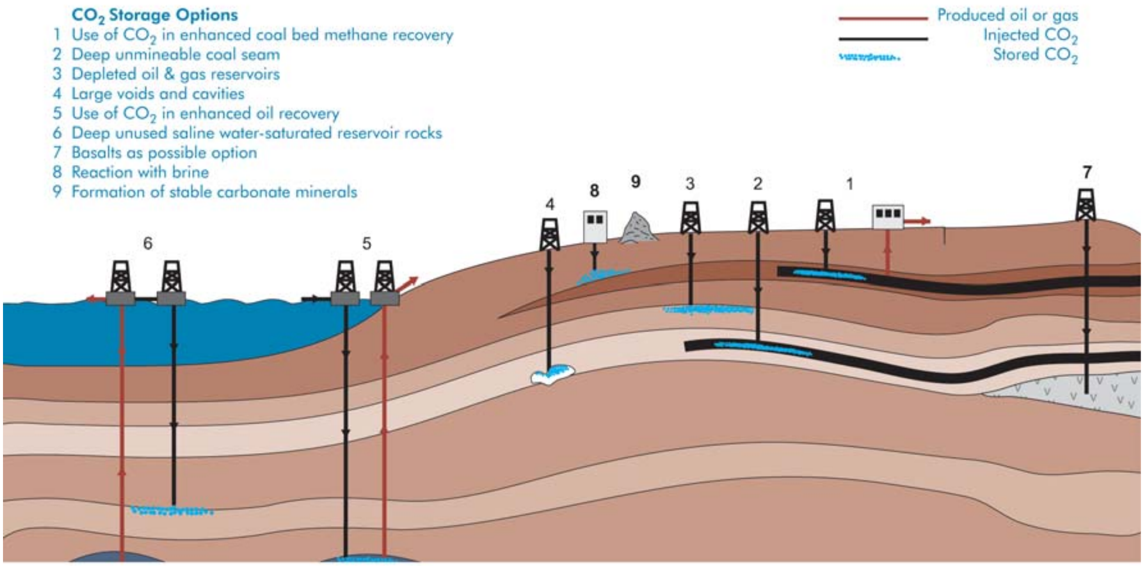


Fig. 10. CO_2 Storage Options

4.4.4 Implications for CO2CRC Storage Program

Within the storage priorities outlined in Table 4, it is necessary to define the generic and the specific technologies required to exploit the various storage options. These are outlined below and summarized in Table 5 and form the basis of CO2CRC Storage R&D priorities.

- Injection of CO_2
    - Technologies for assessing, modelling and predicting geomechanical effects during CO2 injection; areas for research are pore pressure prediction, stress regime analysis and modelling, rock strength measurement and prediction, and fault reactivation modelling
    - Technologies for assessing, modelling and predicting other near-well bore formation damage during injection
    - Technologies for assessing, modelling and prediction of near well bore chemical changes, especially conditions for hydrate formation
- Storing CO_2
    - As for injection, research technologies to be used for assessing, measuring and predicting geomechanical effects in the storage reservoir and seal units distant from the well bore, focusing on fault reactivation and fracture propagation.
    - Use of natural analog studies to support recommendations for various storage options and the technologies to be most effectively used in searching for, evaluating and assessing CO_2 storage options
    - Given the preliminary assessment of the substantial and dominant storage potential for Australia's saline formations, to develop the most appropriate technologies for searching for, evaluating and assessing the potential of saline formations in Australia.
    - Continue research work started in GEODISC on the technologies required to evaluate PVT behaviour of CO_2 in water and of CO_2 and other gas mixtures in water
    - Development and adaptation of existing technologies for assessing and avoiding possible

interaction of CO_2 storage projects with other resources such as coal, oil/gas, aquifers, surface amenities, soils, deep ecosystems etc. In particular to research interaction of CO_2 with microbial organisms.

- Developing technologies to allow construction of fully coupled models integrating geological, geomechanical, geochemical, hydrodynamic and chemical processes. In particular adapting pre-existing technologies for modelling short and long-term displacement and mixing of fluids

- Monitoring and Verification
    - Develop technologies for airborne monitoring especially CO_2-specific scanners
    - Utilization of natural analogs for development and implementation of surface and near-surface leak detection technologies
    - Develop seismic-based technologies to assist in monitoring and verification. This will include continuous seismic monitoring technology, gravity technologies, VSP technologies, multi-component and cross-well seismic technologies

These areas of research will continuously be evaluated for progress and in particular technology breakthroughs; those topics which are not providing satisfactory progress will be potentially replaced and supplemented by projects currently ranked lower in the Technology Road mapping prioritization exercise.

Functional Step	Technology Theme	Technology	Impact Now	Impact Future	Technical Maturity	Expertise Location	Rank
Safely and effectively inject CO_2	Geomechanics	Formation damage	Med.	High	Growth	CO2CRC	1
		Pore pressure; stress regime; rock strength; fault reactivation	Med.	High	Growth	CO2CRC	1
	Injection process	Near well bore changes, hydrates	Med.	Low	Embryonic	CO2CRC / Internat.	1
Safely and effectively store CO_2	Containment	Geomechanical modelling	High	High	Growth	CO2CRC	1
	Geological storage options	Analogue Study	High	Low	Growth	CO2CRC	1
		Saline Formations	High	High	Growth	CO2CRC	1
	CO_2 properties and behaviour	CO_2 mixtures	High	Low	Growth	CO2CRC	1
		CO_2 /H_2O PVT behaviour	Med.	Low	Growth	CO2CRC	1
	Subsurface impacts	Compromising existing resources - coal, oil, gas, aquifer, surface amenities, soils, deep ecosystems, groundwater	High	High	Embryonic	CO2CRC / Internat.	1
		Fault reactivation	High	High	Growth	CO2CRC	1
	Modelling	Integration, cross verification and predictive models: geological / geomechanical / hydrodynamic / geochemical	High	Med.	Embryonic	CO2CRC / Internat.	1
	Regional rock fluid interaction	Displacement mechanisms (short and long term)	High	Med.	Growth	CO2CRC /	1
		Interaction of microbes with CO_2 and H_2O	Med.	Low	Embryonic	CO2CRC / Internat.	1
Monitor and verify the stored CO_2	Remote sensing	CO_2 specific scanner for airborne use	Med.	High	Embryonic	CO2CRC	1
	Verification	Modern analogues including leaky systems	High	Low	Growth	CO2CRC	1
	Geophysical methods	Gravity	Med.	Low	Embryonic	CO2CRC / Internat.	1
		Vertical seismic profiling	Med.		Growth	CO2CRC / Internat.	1
		Multi-component 4D seismic	Med.		Growth	CO2CRC / Internat.	1
		Cross well seismic	Med.		Growth	CO2CRC / Internat.	1
Transport and condition CO_2	Pipelines	Materials	Low	High	Mature	Internat.	2
		Design	Low	High	Mature	Internat.	2
		Corrosion of pipeline	Low	Med.	Mature	Internat.	2
		Leak monitoring	Low	High	Growth	Internat.	2
		Corrosion of equipment	Low	Med.	Mature	Internat.	2
	Trucking/ shipping & temporary storage	Shipping using LNG technology	Low	High	Growth	Internat.	2
		Interim storage / holding tanks	Low	High	Growth	Internat.	2

Table. 5. Categorization of technology themes relevant to CO_2 storage. *(Continued on next page)*

Functional Step	Technology Theme	Technology	Impact Now	Impact Future	Technical Maturity	Expertise Location	Rank
Transport and condition CO_2 (continued)	Operations	Downhole separation	Low	Internat.	Growth	Internat.	2
		Use of current infrastructure	Low	High	Growth	Internat.	2
		Regulation / tax regime for CO_2 transport	Low	Internat.	Embryonic	CO2CRC, Australia, Internat.	
	Compressors	Performance	High	High	Mature	Internat.	2
		Metering	Low	High	Mature	Internat.	2
Safely and efficiently inject CO_2	Injection wells	Use of existing wells	Med.	Med.	Mature	Internat.	2
	Geomechanics	Injection well modelling	Med.	Med.	Mature	CO2CRC	2
		Fracture modelling	Low	Med.	Growth	Internat.	2
	Use of pre-existing wells	Integrity of old wells	Low	High	Growth	Internat.	2
	Injection process	Injectivity prediction	Low	Med.	Mature	CO2CRC	2
		Modelling injection process & interruption	Low	Med.	Growth	Internat.	2
		Relative permeability issues	High	Internat.	Mature	CO2CRC	2
Safely and efficiently store CO_2	Containment	Existing well work-overs	High	High	Mature	Internat.	2
		Seal integrity	High	High	Mature	CO2CRC	2
		Leaking well bores	High	High	Mature	Internat.	2
		Trap integrity	High	High	Mature	CO2CRC	2
	Geological storage options	Depleted fields	High	Internat.	Mature	CO2CRC / Internat.	2
		Enhanced Petroleum Recovery	High	Internat.	Mature	CO2CRC	2
	Modelling	Seismic derived petrophysics	Med.	Med.	Mature	CO2CRC / Internat.	2
		Predictive volume estimates	Low	Internat.	Growth	CO2CRC / Internat.	2
	Regional rock fluid interaction	Mineral alteration	Low	Internat.	Growth	Co2CRC	2
Monitor and verify stored CO_2	Remote sensing	Satellite / aerial remote sensing	Low	Med.	Embryonic	CO2CRC / Internat.	2
		Hyerspectral radar	Low	Med.	Growth	Internat.	2
	Verification	Auditing stored CO_2	Low	High	Mature	Internat.	2
	Subsurface monitoring	Baseline atmospheric soil survey	High	Med.	Mature	Internat.	2
		Local & regional environmental impact	High	Med.	Mature	Internat.	2
	Geophysical methods	Continuous seismic sources	Low	Med.	Embryonic	C02CRC	2
		AVO	Med.	Med.	Mature	CO2CRC / Internat.	2
		High resolution seismic	High	Med.	Mature	Internat.	2
		Use of casing systems for well monitoring	Low	Med.	Embryonic	Internat.	2
		Surface online real-time analysis	Low	High	Mature	Internat.	2

Table. 5. Categorization of technology themes relevant to CO_2 storage. (Continued)

5. CO_2 Capture and Storage Technology Application Roadmap (Level 2)

5.1. General

Detailed research needs have been outlined in Section 4 in the discussion on Level 1 of the technology roadmap.

Level 2 of the roadmap (Fig 2) is concerned with identifying the opportunities for applying Level 1 R&D and for "learning through doing". Developing this Level 2 roadmap was done by a small subgroup who considered the scope for linking with small, medium and large scale projects involving geosequestration in Australia and internationally. It is recognized that it is essential that for the Australian and the international research and industry communities to utilize all available opportunities to work together in major geosequestration projects. Bodies such as the CSLF will help to facilitate collaboration in some instances. In some cases, commercial requirements may limit the scope for multilateral collaboration, but in many cases there is benefit in making information available as widely as possible.

The Level 2 mapping drew on industry-supplied information on timing of their proposed geosequestration projects in Australia and elsewhere. The most significant commercial scale project proposed for Australia at the present time is the Gorgon CO_2 reinjection project. It is part of the Gorgon Gas development, which is operated by ChevronTexaco, Shell and ExxonMobil. Assuming that the CO_2 reinjection project receives all the necessary government approvals and it is technically and economically viable, the Gorgon Joint Venture expects that the project will be commissioned in late 2008 (fig 11), with CO_2 injection into the Dupuy Formation commencing in early 2009. The proposed project will involve injection and storage of 4-5 million tonnes of CO_2 per annum and is expected to be the world's largest geosequestration project at that time. The geosequestration project is part of a large scale gas development and offshore LNG export located in the northwest of Western Australia, based on massive offshore natural gas reserves containing approximately 14 mole percent CO_2.

The Gorgon CO_2 reinjection project will involve a wide range of surface and subsurface investigations that are likely to add enormously to our knowledge of deep storage conditions. It therefore provides outstanding potential opportunities for R D&D within the constraints of a commercial operation.

At the same time, based on current plans, it is unlikely that there will be a major commercial project in Australia, involving geosequestration before 2009. Consequently, opportunities should be examined for undertaking R&D projects at the demonstration (medium scale) and pilot (small scale) range, in Australia and internationally prior to 2009.

The Level 2 roadmap attempts to link potential small scale (pilot) and medium scale (demonstration) projects to early geosequestration opportunities (Fig 12).

At a smaller scale, pilot projects are seen to offer scope for addressing specific issues such as CO_2 injectivity, validation of models, testing of monitoring capability and assessment of impact of CO_2 on the deep environment. Additionally, pilot projects were seen as an important component in communicating geosequestration issues (especially storage) to the public.

Under the COAL 21 Program, opportunities are being assessed for developing projects to demonstrate low emissions technology, based on coal. This program, convened by the Australian Coal Association (ACA), brought together the relevant CRCs, CSIRO, major power and coal companies and Australian federal and state government. The scope of this exercise was broader than the CO_2 capture and storage focus of this report but nonetheless capture and storage technologies were seen as occupying "centre stage" in moving towards low emission energy, based on fossil fuels.

COAL 21 identified integrated Gasification Combined Cycle (IGCC) for black and brown coal and oxygen-firing of conventional pulverized fuel type systems (Oxy-fuel combustion) as two key enabling technologies for linking coal-based power generation with CO_2 capture and storage. Immediate priorities in relation to these technologies were identified as being the construction of a black coal (and perhaps also a brown coal) IGCC demonstration offering scope for CO_2 capture and storage as well as hydrogen generation to be commissioned around 2008 and an investigation of the potential of oxyfuel combustion and associated post combustion CO_2 capture option.

COAL 21 supported a series of small scale (pilot) CO_2 storage projects to be followed by a medium scale project associated with an IGCC demonstration plant with the pilot projects possibly commencing in 2005/2006. Each of these types of project will offer opportunities to validate key parameters prior to proceeding to the next development stage.

Fig. 11. Timetable for the proposed Gorgon Project (after the ESE review of the Gorgon Gas Development Project on Barrow Island, submitted to the WA Government by ChevronTexaco February 2003)

5.2. Proposed Pilot Projects

Opportunities to undertake or participate in small scale field trials to validate parameters and conditions related to CO_2 storage and monitoring are being reviewed. These would be based around specific research needs and confirm issues such as injectivity, sealing and other geological criteria. The concept at this stage is to use an existing source of CO_2 (such as a fertilizer plant or a gas separation plant and inject 5-10,000 tonnes of CO_2 over a relatively short period of time (6 months?)

While there is a need to demonstrate these features locally, Australian researchers are associated with international projects and plans are in progress to become involved in a small-scale pilot CO2 injection project in Frio, Texas. Therefore this United States project is is also incorporated into this roadmap. Other overseas projects may also be included in the future as opportunities arise to participate.

The key issues for any pilot project are to have highly focused objectives, be well resourced and operate under a high degree of quality control. The project must be managed in an exemplary fashion. Failure due to poor process might severely impact the acceptability of capture and storage technology. At this stage of concept planning it is proposed that there will be two pilot projects in Australia: one in a West or Central Australian basin; the other in an East Australian basin related to coal.

CO_2 capture pilot projects, per se, are unlikely for the capture area in Australia in the short term with small scale work is being validated in existing facilities overseas; so integration into a demonstration plant may be more pertinent.

5.3. Proposed Demonstration Projects

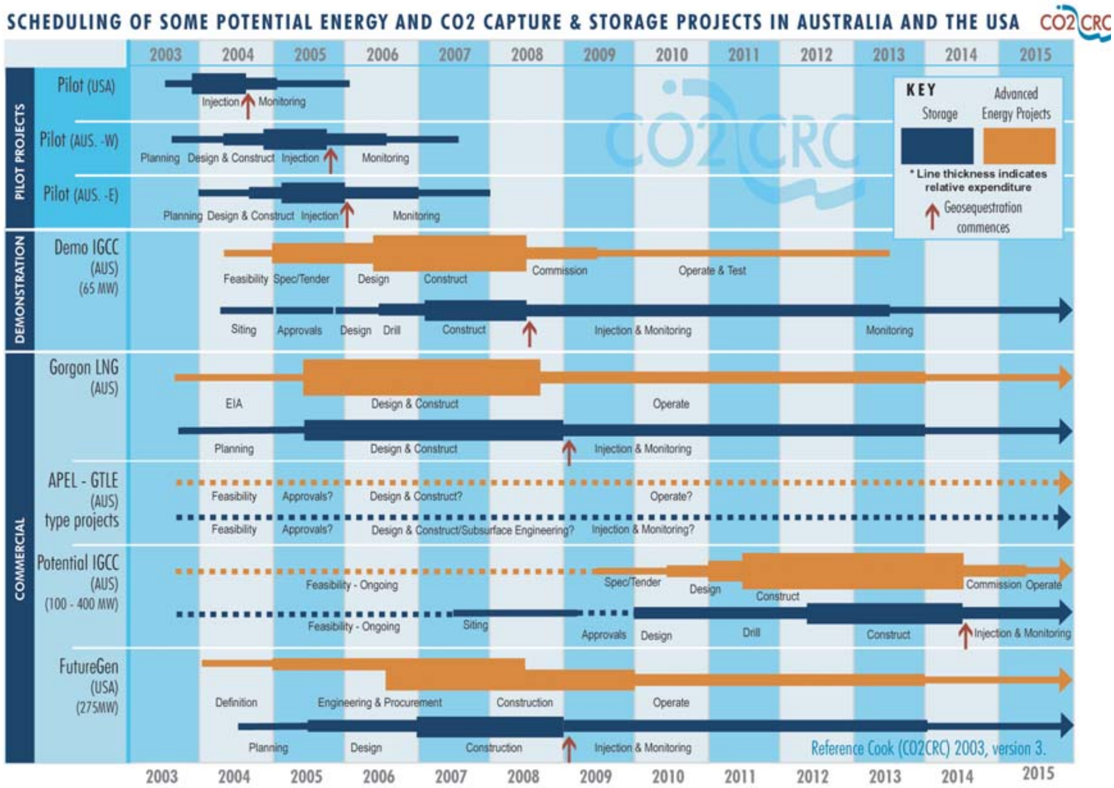


Fig 12. Technology roadmap (Level 2) showing opportunities for RD&D related to pilot (5-10,000 tonnes injected CO_2), demonstration (50-100,000 tonnes CO_2) and commercial projects involving CO_2 capture and storage.

The next potential project scale involves demonstration of larger scale processing components and integrated capture and storage. While being integrated the suggested demonstration plant would be capable of operation with or without the more novel technology components. It is likely that some capability to test alternative emerging technologies would be incorporated either as an in line feature or, more likely, as a side stream. The design of the plant and storage location may not be the most economical and pragmatic criteria such as integration with existing plant operations may prevail.

As indicated earlier, an IGCC demonstration plant and R D&D facility has been suggested by COAL 21 with a notional commissioning date of mid 2008. This facility would potentially provide the opportunity to store 50-100,000 tonnes of CO_2 per annum, initially for a period of perhaps 5 years, with the prospect of extending the life of the plant well beyond that. This concept is similar to the much larger FutureGen project being progressed by the US Department of Energy (DOE), which allows for various core and non-core technologies to be assessed.

A demonstration plant of the type suggested would seek to successfully assimilate technology that is more commonly found in chemical processing than power generation. Whereas natural gas operations are extensions of core technology for the gas production and processing industry the diffusion of IGCC technology and reservoir management to the power and/or coal industry will require detailed consideration, which may in turn result in some changes to time schedules as shown in Figure 12.

Throughout demonstration and pilot phases, considerable work would be needed in the important areas of public education, location (site) selection and regulatory regimes.

5.4. Proposed Commercial Operations

Confirmation of core technology and economic features and regulatory and community issues will provide companies with the confidence to proceed to commercial operation. The most cost effective options for all technologies will have to be well understood and the most economically viable technology chosen for all aspects of the plant. This does not mean that commercial projects must therefore of necessity be preceded by pilot then demonstration projects. For example the Sleipner project went directly to the commercial stage. Future projects will no doubt do the same where operators and regulators are confident of reservoir behaviour, storage capacity, etc. Planning for the Gorgon project is well advanced on this basis.

It should be recognized that different technologies may be preferred in different applications and that only after a number of capture and storage applications are commissioned, will significant standardization become possible.

As the processing technology develops and matures, the major variant for projects is likely to be the storage site selection and location, and the associated transportation, storage and monitoring of the CO_2. Considerable care will be needed to ensure this selection process and the subsequent management of the reservoir are expertly managed.

In Australia, as mentioned earlier, the proposed Gorgon Project potentially provides an outstanding opportunity for R D&D commencing with CO_2 injection around 2009, but of course with potential research opportunities before that time, contingent on the commercial needs of the project and the agreement of the companies involved.

In addition, although at a somewhat less advanced planning stage, gas to liquids projects based on brown coal, are proposed for Victoria by the two companies, APEL and GTLE. If either of these projects were to go ahead they could involve storage of up to 10 million tonnes of CO_2 per annum. However for the present, the scheduling of the GTLE and APEL projects is unclear.

Similarly, whilst there is some very early consideration to the development of a fully commercial IGCC plant, with a capacity ranging from 100-400 megawatts, it is unlikely that a generation facility on this scale could be commissioned before 2014 (Fig. 12). Consequently for the purposes of this Level 2 roadmap this prospect is included as an R D&D opportunity but with a high degree of uncertainty attached to it.

Internationally, the USDoE FutureGen project offers an excellent opportunity for Level 2 collaboration in R D&D and very preliminary discussions have been held on this. However other international R D&D opportunities may also open up, using commercial projects but of course these are very much dependent on the agreement of the companies involved. Potential opportunities may include In Salah (Algeria) and Snohvit

(Norway).

The burgeoning coal bed methane industry may also offer R D&D opportunities related to commercial projects in Australia, North America and Europe. However this is dependant on a number of issues. Most notably proof that CO_2 related enhanced coal bed methane is commercially viable. Additionally CO_2 related enhanced oil recovery and enhanced gas recovery may also provide new Level 2 R D&D opportunities. However these are not for the present included in the Level 2 Roadmap (Fig. 12).

6. CO_2 Capture & Storage and a Roadmap to the Hydrogen Economy (Level 3)

6.1. General

Level 3 of the roadmapping process (Fig 2) is concerned with the longer term objective of placing future direction in capture and storage into developing the hydrogen economy. Obviously attainment of this long term target involves many research components, a large number of organizations and the successful resolution of key technical and commercial issues. The CSIRO Energy Flagship has a particular focus on the hydrogen economy and this program will be developing a more comprehensive hydrogen technology roadmap. For the present, the Australian Government's recently released hydrogen study, (see www.industry.gov.au) provides a good starting point at the national level.

The roadmap for capture and storage technologies needs to extend to Level 3 roadmapping and consider some of the enabling technologies, and the research development and demonstration required for moving towards the hydrogen economy. As part of this, it is also important to take into account the concept of large scale low emission hubs as a step towards the hydrogen economy (Fig. 13).

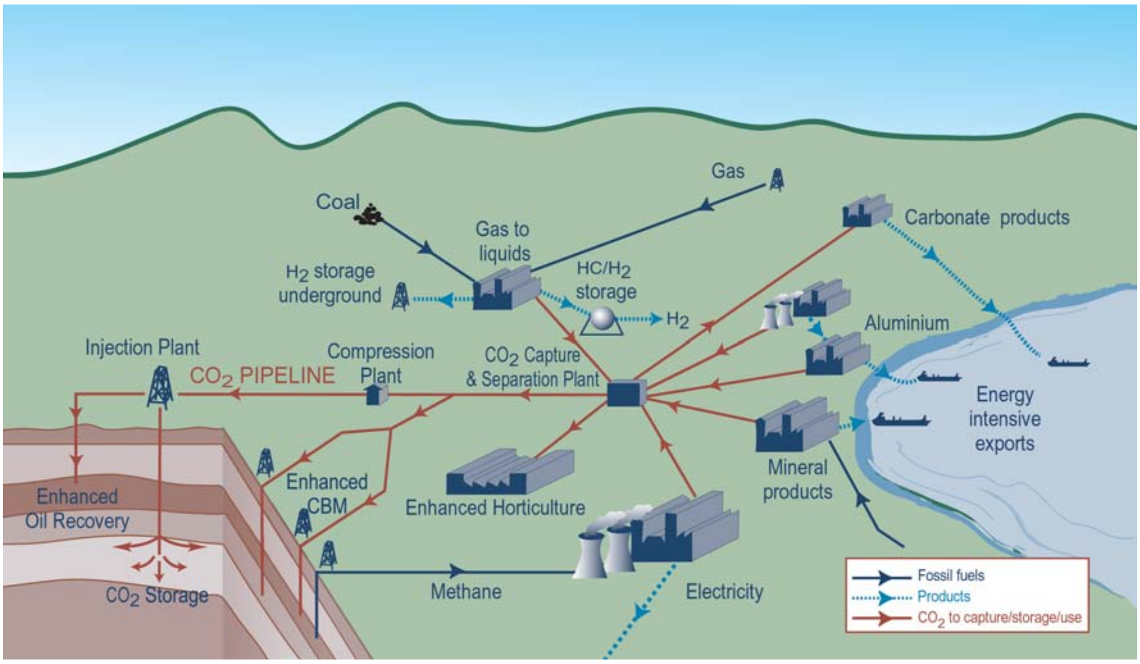


Fig. 13. An emission-free vision for the future

Hydrogen has the potential to provide clean energy at the point of use but there are many technical and economic challenges to be overcome before it becomes a practical alternative to fossil fuels particularly for transport. Fossil fuels, notably coal and natural gas, coupled with carbon capture and storage could provide the transitional pathway to the longer term objective of a hydrogen economy based on renewable energy.

Australia has some natural advantages in the lead-up to the hydrogen economy, notably its abundant fossil fuels and its massive CO_2 storage capacity. However much of the technological development and most of the market pull will come from the larger OECD countries and the United States of America in particular. Therefore Australia must position itself to work closely with other countries in the development of the hydrogen economy.

There are technological challenges and barriers in hydrogen storage and distribution. The pathway to the hydrogen economy is not fully defined but fossil fuels will initially play a key role in the production of hydrogen and in the transition to the hydrogen economy. A hydrogen economy requires significant investment in new infrastructure (pipelines, storage facilities, fuelling stations, etc). This may present opportunities for Australia to participate in the development of technologies for the production, conversion, storage and distribution of hydrogen.

Low emission energy able to meet rapidly growing energy needs is increasingly seen as being of critical importance to the future development of Australia's energy intensive economy whilst at the same time contributing to Australia having a lower greenhouse signature. Sequestration technologies will also be important in securing future markets for Australia's LNG, coal and energy intensive imports. The long term objective must be to move to a hydrogen economy in which the hydrogen is obtained for example from electrolysis of water using electricity derived from renewable energy (wind, solar, biomass) or from artificial photosynthesis. Before this can be achieved, there are a number of hurdles to be overcome, but we are already able to define some of the key steps on the roadmap to the hydrogen economy that will be necessary between now and 2030. These include for Australia and other countries:

1. Acceptance of CO_2 capture and storage technologies

2. Application of CO_2 capture and storage technologies and low emission electricity generation from fossil fuels with

3. Production of commercial quantities of hydrogen from fossil fuels, with widespread application of capture and storage technologies, followed by:-

4. Development of hydrogen infrastructure

5. Wide scale application of hydrogen as an energy carrier for power and transport.

6. Production of commercial quantities of hydrogen from renewable energy

These steps are shown schematically in Figure 14.

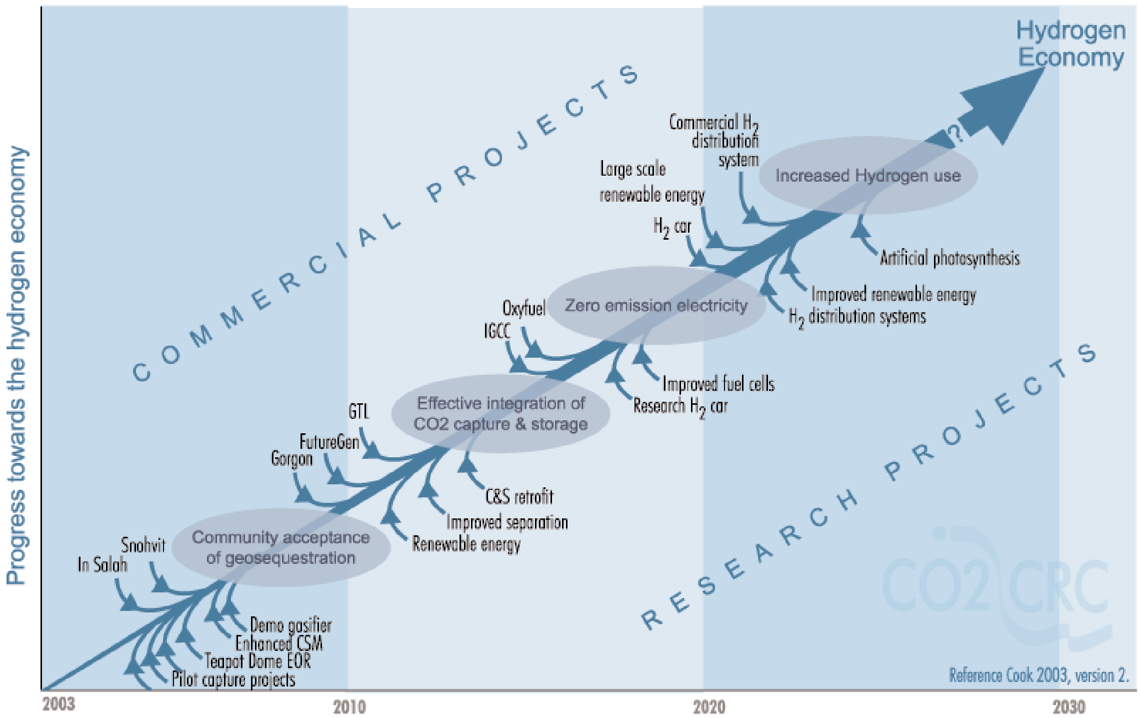


Fig. 14. Level 3 technology roadmap showing likely progress towards the hydrogen economy

6.2. CO_2 Capture and Storage

This topic is of course the prime focus of this roadmapping exercise (Section 4). Carbon sequestration can be the first step towards the hydrogen economy; the nexus arises from the fact that at the present time the cheapest and easiest way of generating low emission energy and hydrogen in significant quantities is through reforming or gasification of hydrocarbons followed by the so-called shift reaction. This produces H_2 from petroleum or coal, but it also produces CO_2. Therefore if we are to develop a hydrogen economy, based on fossil fuels, we must link this with the development and application of geosequestration technologies. Australia is linking with the USA and other countries in current and proposed geosequestration projects through the Climate Action Partnership (CAP) and Carbon Sequestration Leadership Forum (CSLF), which are being pursued in collaboration with organizations such as the USDoE and the Australian Department of Industry, Tourism and Resources (DITR).

The development of improved (and cheaper) technologies for CO_2 capture and separation represents a considerable challenge at this time and this topic is discussed in detail earlier in this Report.

6.3. Low Emission Electricity Generation

Australia currently generates almost half its total CO_2 emissions from electricity production, with annual growth in electricity use set to continue to rise steeply. If Australia's CO_2 emissions are to be curbed then it must use various measures, including fuel switching, renewables and low emission technologies including CO_2 capture and storage. Australia may need to retrofit CO_2 capture and storage systems to existing plants (likely to be expensive) or move to advanced energy systems such as IGCC or oxyfuel systems, linked to geosequestration. This in turn provides an important link to hydrogen generation opportunities. The prospect of developing a demonstration IGCC project in Australia, with "sequestration ready" emissions, is mentioned elsewhere in this Report (Section 5). The United States proposes to undertake the much larger FutureGen program which involves a 275 MWatt generator and hydrogen production coupled with geosequestration (Fig 12).

6.4. Hydrogen Production from Fossil Fuels

Hydrogen is currently produced (mainly from natural gas) on a fairly significant scale for the chemical and refining industries. The large scale production of hydrogen from fossil fuels and its use in energy production is likely to be a step on the path to the hydrogen economy. This is the basis for the DoE FutureGen initiative (Section 5). The use of fossil fuels (specifically coal) as the source of hydrogen is significant to Australia and the many other countries that have massive coal reserves; Australia also has very large "stranded" natural gas reserves that could be readily used as the feedstock for a hydrogen economy.

6.5. Development of a Hydrogen Infrastructure

Development of a hydrogen infrastructure requires effective technologies for using hydrogen as an energy carrier, including for vehicular transportation and sufficient demand for hydrogen. The Australian economy is too small to act as a leader in the widespread development of a hydrogen economy involving the generation, transportation, retailing and use of hydrogen. However there is scope for Australia to develop opportunities and contribute to technology breakthroughs. The CSIRO Energy Flagship program has a particular focus on hydrogen.

Australia's high potential for geosequestration of the CO_2 generated could make it attractive for inward investment relating to the development of a hydrogen economy. A model that links all of the necessary ingredients to form an emission free node is illustrated in Figure 13. Under this model, industries would co-locate and collaborate to share costs of CO_2 capture and storage, access cost efficient emission-free energy and be part of a system for generating, storing and distributing hydrogen.

6.6. Widespread Use of Hydrogen

This phase of the hydrogen pathway depends on the development and application of hydrogen fuel cells and the use of hydrogen for vehicular transport. The US$1 billion US presidential initiative, known as Freedom Car, is likely to provide a major boost to the development of the hydrogen car over the next decade but again a distribution and retailing system is critical to the widespread use of hydrogen-based transport systems. Given its small economy, Australia will not be the leader in this area but as pointed out earlier, Australia could become a high technology provider of "greenhouse friendly hydrogen" from fossil fuels. Using its fossil fuel-sequestration capacity to exploit that potential will require a massive financial investment.

6.7. Hydrogen from Renewables

Whilst obviously well outside the scope of the current roadmapping exercise the "ultimate" hydrogen economy could well be based on renewable energy derived from solar, wind or geothermal power or artificial photosynthesis or a combination of all these. However there are many technical challenges ahead and it will take time, perhaps many decades before we can produce hydrogen from renewable energy on the scale and at a cost that makes it commercially feasible. Fossil fuel-based low emission energy, leading to the hydrogen economy could provide the interim step; it could also help to ensure that the new distribution and retailing infrastructure required for hydrogen will already be in place and will not be a barrier to the takeup of renewable-based energy. Innovative hydrogen fuel cells, new types of membranes for separating H_2 and CO_2, more efficient solar cells will all be part of the necessary mix of technology innovations.

6.8. A Hydrogen Roadmap

Obviously the technology that will eventually take us to the hydrogen economy is far more comprehensive than just the CO_2 capture and storage technologies that are the main focus of this roadmapping exercise. Key requirements include improved advanced energy systems that will more effectively co-produce low cost hydrogen, improved hydrogen fuel cells, cost effective and efficient hydrogen transportation and storage, and commercially viable distribution systems.

Nonetheless the development of capture and storage technologies that are cost effective, safe, sustainable and acceptable to the community, could represent an important step on the technology roadmap that will progress the world's energy system to low emission systems , including hydrogen-based energy systems.

This roadmap is illustrated in Figure 14. The first ten years are focused on capture and storage because this must be fully resolved if we are to have community acceptance of geosequestration, effective integration of CO_2 capture and storage and low emission electricity. Importantly research projects and commercial projects run in parallel and together take us along the hydrogen pathway. Already commercial projects such as Sleipner and Weyburn have taken us part of the way down that pathway. The In Salah, and the proposed Snohvit and Gorgon projects will take us further along the pathway to FutureGen and the larger scale and more widespread application of low emission technology in developed and developing countries.

7. Summary and Conclusions

1. The Australian technology roadmapping exercise described in this document is valuable to Australian research, industry and government in that it:

   - Indicates technology gaps and priorities
   - Identifies expertise
   - Strengthens national R&D collaboration
   - Enhances opportunities for international RD&D cooperation
   - Defines a strategy for carbon sequestration technologies - and places that strategy in a national and international context.

2. There are other national technology roadmaps available that provide an excellent starting point for other such exercise. Those available from the US Department of Energy are particularly useful.

3. The Australian technology roadmap outlined here is structured on the following basis

   - Level 0, which involved developing the national knowledge infrastructure and skill base in the four years prior to formulation of this roadmap
   - Level 1, which has a 5-10 year time scale requires detailed technology assessments and gap analyses for R&D related to:
     - CO_2 capture
     - CO_2 storage
     - Use of CO_2
   - Level 2, with a 10-20 year timescale, involves broad scale assessments of potential demonstration and application opportunities through:
     - Pilot (small scale) R&D projects
     - Demonstration (medium scale) R&D projects
     - Commercial (Large scale) projects also offering R&D opportunities
   - Level 3, with a 20-30 year time scale, involves development of a roadmap for the hydrogen economy, stressing in particular the key role of CO_2 capture and storage, assuming that the hydrogen economy will initially be fossil-fuel-based, but with the longer term objective of moving to renewable energy.

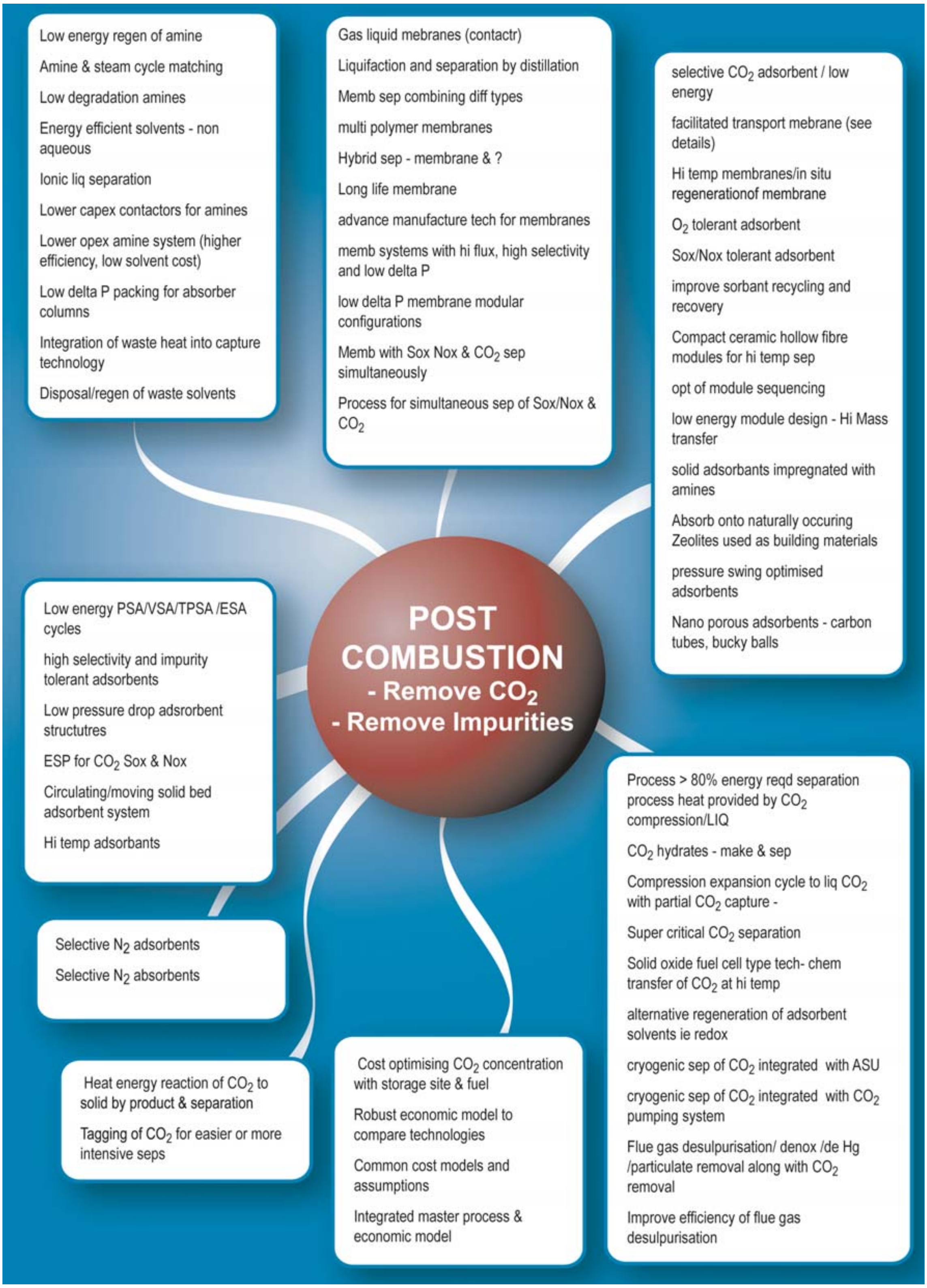
4. The Australian technology roadmap outlined here will require refining in the years ahead, but it represents a very useful start. In particular, it defines the way forward at 10, 20 and 30 year timescales using a range of inputs but with CO_2 capture and storage as a key enabling technology. The roadmap identifies key national and international projects.

5. It is only through collective national and international action that we will be able to undertake essential R&D, achieve necessary breakthroughs and implement new carbon sequestration technologies on the massive scale required to significantly decrease CO_2 emissions to the atmosphere whilst retaining the benefits of ready access to fossil fuels and low cost energy.

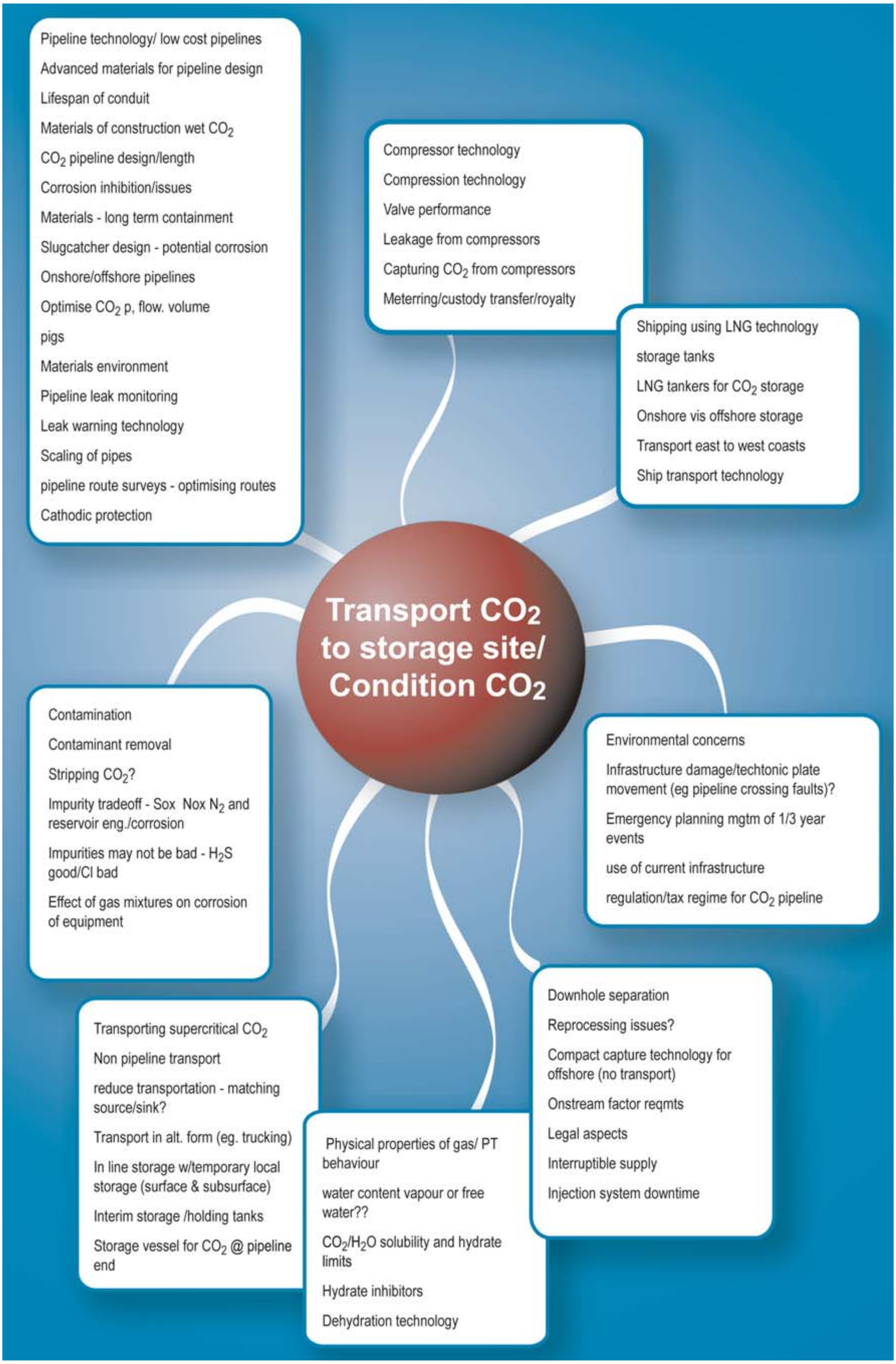
Appendices

Appendix 1.

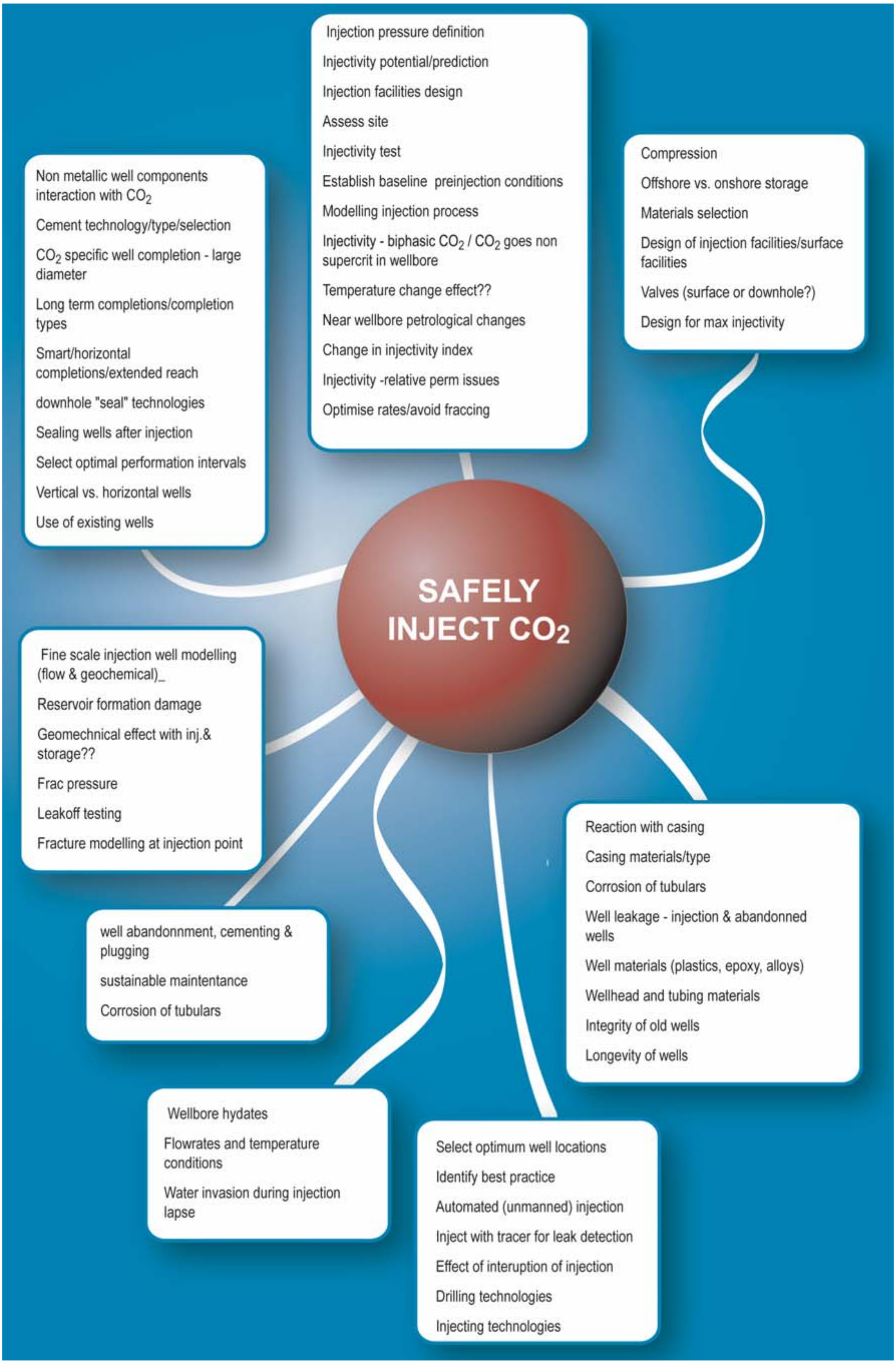
Examples of technology roadmapping outputs from the FAST methodology.



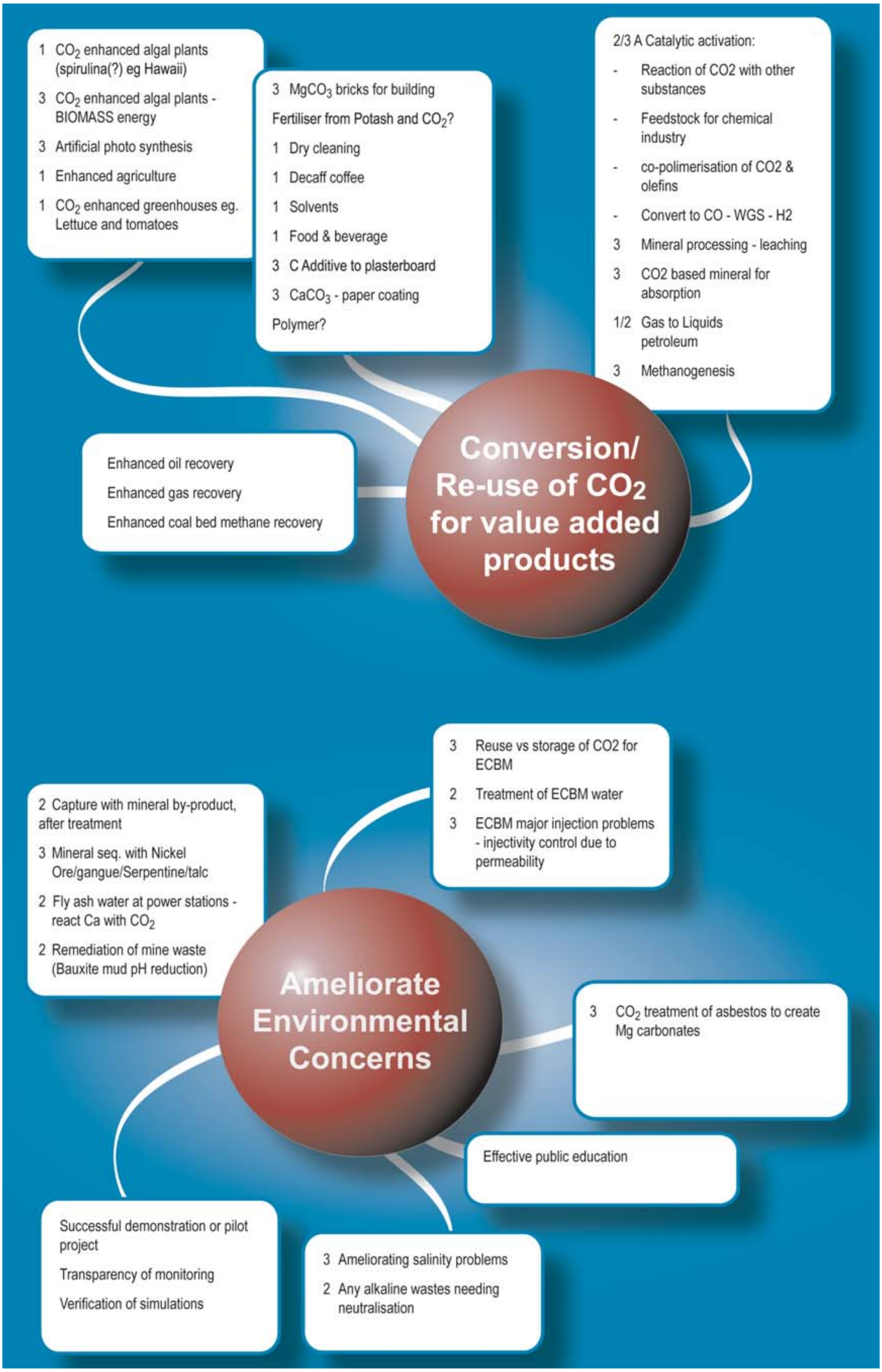
Appendix 1.1.


Transport CO_2 to storage site/ Condition CO_2
Pipeline technology/ low cost pipelines
Advanced materials for pipeline design
Lifespan of conduit
Materials of construction wet CO_2
CO_2 pipeline design/length
Corrosion inhibition/issues
Materials - long term containment
Slugcatcher design - potential corrosion
Onshore/offshore pipelines
Optimise CO_2 p, flow. volume
pigs
Materials environment
Pipeline leak monitoring
Leak warning technology
Scaling of pipes
pipeline route surveys - optimising routes
Cathodic protection
Compressor technology
Compression technology
Valve performance
Leakage from compressors
Capturing CO_2 from compressors
Meterring/custody transfer/royalty
Shipping using LNG technology
storage tanks
LNG tankers for CO_2 storage
Onshore vis offshore storage
Transport east to west coasts
Ship transport technology
Contamination
Contaminant removal
Stripping CO_2?
Impurity tradeoff - Sox Nox N_2 and reservoir eng./corrosion
Impurities may not be bad - H_2S good/Cl bad
Effect of gas mixtures on corrosion of equipment
Environmental concerns
Infrastructure damage/techtonic plate movement (eg pipeline crossing faults)?
Emergency planning mgtm of 1/3 year events
use of current infrastructure
regulation/tax regime for CO_2 pipeline
Transporting supercritical CO_2
Non pipeline transport
reduce transportation - matching source/sink?
Transport in alt. form (eg. trucking)
In line storage w/temporary local storage (surface & subsurface)
Interim storage /holding tanks
Storage vessel for CO_2 @ pipeline end
Physical properties of gas/ PT behaviour
water content vapour or free water??
CO_2/H_2O solubility and hydrate limits
Hydrate inhibitors
Dehydration technology
Downhole separation
Reprocessing issues?
Compact capture technology for offshore (no transport)
Onstream factor reqmts
Legal aspects
Interruptible supply
Injection system downtime

Appendix 1.2.


SAFELY INJECT CO_2
Injection pressure definition
Injectivity potential/prediction
Injection facilities design
Assess site
Injectivity test
Establish baseline preinjection conditions
Modelling injection process
Injectivity - biphasic CO_2 / CO_2 goes non supercrit in wellbore
Temperature change effect??
Near wellbore petrological changes
Change in injectivity index
Injectivity -relative perm issues
Optimise rates/avoid fraccing
Compression
Offshore vs. onshore storage
Materials selection
Design of injection facilities/surface facilities
Valves (surface or downhole?)
Design for max injectivity
Non metallic well components interaction with CO_2
Cement technology/type/selection
CO_2 specific well completion - large diameter
Long term completions/completion types
Smart/horizontal completions/extended reach
downhole "seal" technologies
Sealing wells after injection
Select optimal performation intervals
Vertical vs. horizontal wells
Use of existing wells
Fine scale injection well modelling (flow & geochemical)_
Reservoir formation damage
Geomechnical effect with inj.& storage??
Frac pressure
Leakoff testing
Fracture modelling at injection point
Reaction with casing
Casing materials/type
Corrosion of tubulars
Well leakage - injection & abandonned wells
Well materials (plastics, epoxy, alloys)
Wellhead and tubing materials
Integrity of old wells
Longevity of wells
well abandonnment, cementing & plugging
sustainable maintentance
Corrosion of tubulars
Wellbore hydates
Flowrates and temperature conditions
Water invasion during injection lapse
Select optimum well locations
Identify best practice
Automated (unmanned) injection
Inject with tracer for leak detection
Effect of interuption of injection
Drilling technologies
Injecting technologies

Appendix 1.3.


1 CO_2 enhanced algal plants (spirulina(?) eg Hawaii)
3 CO_2 enhanced algal plants - BIOMASS energy
3 Artificial photo synthesis
1 Enhanced agriculture
1 CO_2 enhanced greenhouses eg. Lettuce and tomatoes
3 $MgCO_3$ bricks for building
Fertiliser from Potash and CO_2?
1 Dry cleaning
1 Decaff coffee
1 Solvents
1 Food & beverage
3 C Additive to plasterboard
3 $CaCO_3$ - paper coating
Polymer?
2/3 A Catalytic activation:
- Reaction of CO2 with other substances
- Feedstock for chemical industry
- co-polimerisation of CO2 & olefins
- Convert to CO - WGS - H2
3 Mineral processing - leaching
3 CO2 based mineral for absorption
1/2 Gas to Liquids petroleum
3 Methanogenesis
Enhanced oil recovery
Enhanced gas recovery
Enhanced coal bed methane recovery
Conversion/ Re-use of CO_2 for value added products
3 Reuse vs storage of CO2 for ECBM
2 Treatment of ECBM water
3 ECBM major injection problems - injectivity control due to permeability
2 Capture with mineral by-product, after treatment
3 Mineral seq. with Nickel Ore/gangue/Serpentine/talc
2 Fly ash water at power stations - react Ca with CO_2
2 Remediation of mine waste (Bauxite mud pH reduction)
Ameliorate Environmental Concerns
3 CO_2 treatment of asbestos to create Mg carbonates
Effective public education
Successful demonstration or pilot project
Transparency of monitoring
Verification of simulations
3 Ameliorating salinity problems
2 Any alkaline wastes needing neutralisation

Appendix 1.4.

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RioTinto
Shell
Stanwell Corporation
Schlumberger
Woodside
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CO2CRC is also collaborating with many of the world's leading research organisations in the Asia-Pacific area, Europe and North America.

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