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## Geosequestration John Kaldi<sup>1</sup>

### Introduction

Coal, oil and natural gas currently supply around 85% of the world's energy needs. Moreover, given the relatively low cost and abundance of fossil fuels together with the huge sunken investment in fossil-fuel based infrastructure, it is likely that fossil fuels will continue to be used for at least the next 25 to 50 years. The burning of fossil fuels is, however, the major source of anthropogenic (man-made) carbon dioxide (CO<sub>2</sub>). CO<sub>2</sub> is the main «greenhouse» gas released to the atmosphere. One promising means by which to reduce anthropogenic CO<sub>2</sub> emissions, and so the atmospheric buildup of CO<sub>2</sub>, is geosequestration. Geosequestration, also known as carbon capture and storage (CCS), involves the long-term storage of captured CO<sub>2</sub> emissions in deep subsurface geologic reservoirs. Carbon sequestration can be pursued as part of a portfolio of greenhouse gas abatement options, where this portfolio also includes improving the conservation and efficiency of energy use and utilising non-fossil energy forms such as renewable (solar, wind, tidal) and nuclear energy.

Geosequestration comprises a number of steps: first, the CO<sub>2</sub> is captured at the source, where this can be a power plant or other industrial facility; the captured CO<sub>2</sub> is then transported, typically via pipeline, from the source to the geologic storage site; next, the CO<sub>2</sub> is injected deep underground via wells into the geologic reservoir; and, finally, the CO<sub>2</sub> is stored in the geologic

reservoir, where its movement is carefully monitored and the quantity stored is regularly verified.

### CO<sub>2</sub> capture

CO<sub>2</sub> capture can be carried out at point (stationary) source of CO<sub>2</sub> such as a power plant. It involves trapping, or «capturing», the produced CO<sub>2</sub> rather than allowing it to be released to the atmosphere. This captured CO<sub>2</sub> is then compressed to make it more dense and so easier, and less costly, to transport to the geologic storage site.

Anthropogenic CO<sub>2</sub> that can be captured is produced by three main types of activity: industrial processes, electricity generation, and hydrogen (H<sub>2</sub>) production. Industrial processes that lend themselves to CO<sub>2</sub> capture include natural gas processing, ammonia production and cement manufacture. It is to be noted however that the total quantity of CO<sub>2</sub> produced by these processes is limited. A far larger source, accounting for one-third of total CO<sub>2</sub> emissions, is fossil-fuelled power production. The types of power plants that are best suited to CO<sub>2</sub> capture are pulverized coal (PC), natural gas combined cycle (NGCC) and integrated coal gasification combined cycle (IGCC) plants. Finally, a potentially large future source of CO<sub>2</sub> for capture will be H<sub>2</sub> production, where the produced H<sub>2</sub> is used to fuel a hydrogen economy i.e., is used in turbines to produce electricity and in fuel cells to power cars. Technologies for capturing CO<sub>2</sub> from electricity generation fall into two general categories: post-combustion and pre-combustion.

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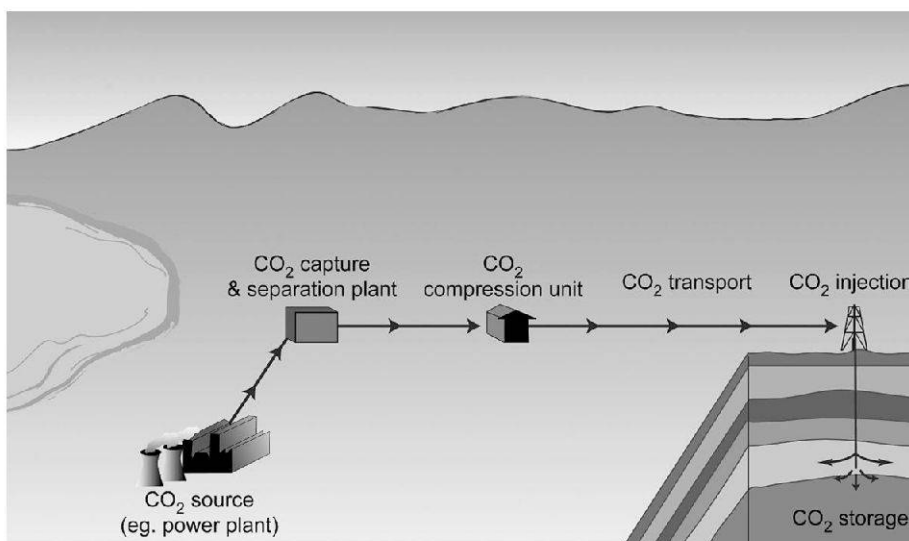
- **Post-combustion:** Currently, the most widely used post-combustion technology for CO<sub>2</sub> capture is chemical absorption. This capture process involves the flue gas being blown through a solvent such as monoethanolamine (MEA) in an absorption column and the CO<sub>2</sub> in the flue gas being absorbed in the MEA solvent by formation of a chemically bonded compound. A very similar process using MEA has been used for decades to remove acid gases, such as CO<sub>2</sub> and hydrogen sulphide (H<sub>2</sub>S), from natural gas streams. Chemical absorption is most likely to be used for pulverised coal (PC) and natural gas combined cycle (NGCC) power plants.
- **Pre-combustion:** In the case of integrated gasification combined cycle (IGCC) plants, it would be possible to utilise the pre-combustion CO<sub>2</sub> capture method of physical absorption. This capture method involves gasifying the coal to produce a synthetic gas (syngas) composed of carbon monoxide (CO) and hydrogen (H<sub>2</sub>). The CO is reacted with water to produce CO<sub>2</sub> and H<sub>2</sub>, and the H<sub>2</sub> is sent to a turbine to produce electricity. CO<sub>2</sub> is captured by means of dissolving it in a physical solvent such as methanol. A number of IGCC and coal gasification facilities exist world-wide to produce syngas and various other by-products. One such example of a gasification facility is an ammonia manufacturing plant.

While the capture of CO<sub>2</sub> for carbon geosequestration is a relatively new concept, CO<sub>2</sub> capture for commercial markets has been practised here in Australia as well as overseas for many years. In Australia, CO<sub>2</sub> capture for commercial markets occurs at natural gas wells and ammonia manufacturing plants. The captured CO<sub>2</sub> is used for various commercial processes including carbonation of beverages and dry ice production. In the United States, CO<sub>2</sub> capture at power plants using chemical absorption based on the monoethanolamine (MEA) solvent has been practised at some plants since the late 1970s, with the captured CO<sub>2</sub> being used for enhanced oil recovery (EOR).

There are also now plans in the United States to build the world's first IGCC plant that will not only produce electricity but also hydrogen fuel, with the CO<sub>2</sub> generated in the process being captured and sequestered underground.

### CO<sub>2</sub> transport

CO<sub>2</sub> transport involves moving, or «transporting», the captured CO<sub>2</sub> from the CO<sub>2</sub> point source to the geologic storage site. The CO<sub>2</sub> is typically transported in a compressed form via pipeline, although the CO<sub>2</sub> could also be transported by truck, rail or, in the case of a geologic storage site located offshore, ocean tanker.



**Fig. 1:** A simplified view of the steps involved in the geosequestration process. Image courtesy of CO<sub>2</sub>CRC.

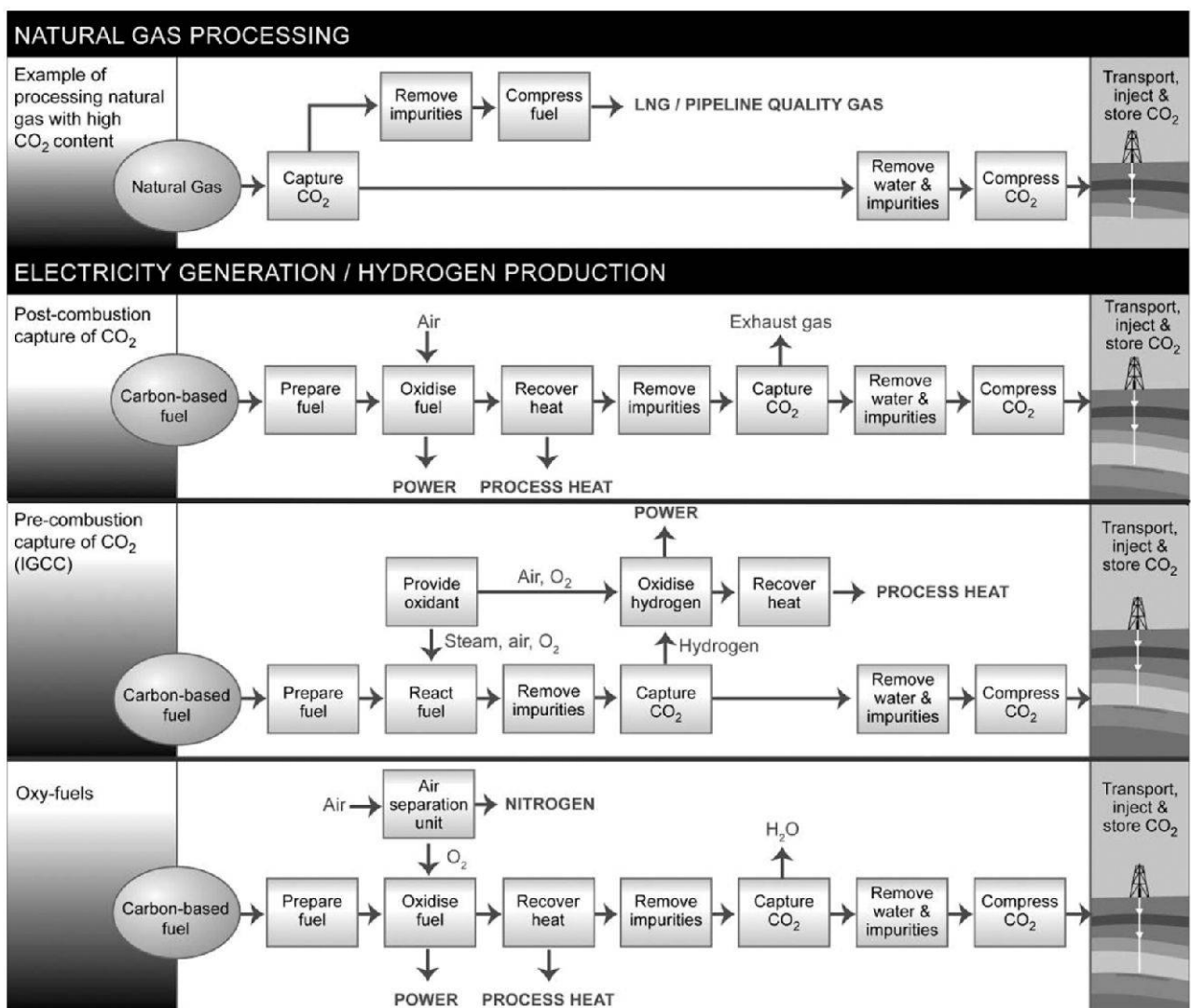


*Transport via pipeline:* CO<sub>2</sub> is transported via pipeline as a supercritical or dense phase fluid. Above the critical point, which occurs at a temperature of 31.4°C and a pressure of 7.38 MPa, CO<sub>2</sub> exists in the supercritical/dense phase. CO<sub>2</sub> in this phase has a significantly higher density than either gaseous or liquid CO<sub>2</sub>. Transporting the CO<sub>2</sub> in this phase, and also at higher density, has significant economic benefits. The transport of CO<sub>2</sub> by pipeline already occurs quite extensively in the United States as well as, to a smaller extent, in other countries where CO<sub>2</sub> is used for enhanced oil recovery (EOR) operations. In the United States, there are some 2,400 km of CO<sub>2</sub> pipelines to supply 72 EOR projects using CO<sub>2</sub> floods. Many of these pipelines have been in operation since the early 1980s. Most of the transported CO<sub>2</sub> is obtained from

high-pressure, high-purity natural underground deposits, with a small percentage of the CO<sub>2</sub> from anthropogenic sources. The longest and one of the most significant CO<sub>2</sub> pipelines currently in operation is the Weyburn Pipeline, which is 325 km in length and transports 2.7 million m<sup>3</sup> of CO<sub>2</sub> per day from the Great Plains Synfuels plant in North Dakota, USA, to the Weyburn CO<sub>2</sub>-enhanced oil recovery project in Saskatchewan, Canada.

### CO<sub>2</sub> injection

CO<sub>2</sub> injection involves taking the CO<sub>2</sub> from the surface and putting, or «injecting», it deep underground into a reservoir rock. The CO<sub>2</sub> is injected into the reservoir via a single well or array of wells. Both enhanced oil recovery (EOR) using CO<sub>2</sub> floods and acid



**Fig. 2:** Overview of carbon dioxide capture processes. Image courtesy of CO2CRC.

gas injection (AGI) are mature technologies that involve significant quantities of CO<sub>2</sub> being injected underground and are therefore very good analogues for CO<sub>2</sub> injection as part of geosequestration activities. The first project using CO<sub>2</sub> for EOR began in 1972 and by 2000, there were 84 operational projects worldwide (72 in the United States) injecting an estimated total of more than 15 million tonnes of CO<sub>2</sub> per year. In the case of AGI, the first project came online in 1989 and in 2001, over 360,000 tonnes of acid gas, around 90% of which is CO<sub>2</sub>, was injected into geologic reservoirs at more than 30 different locations across western Canada.

### CO<sub>2</sub> storage

CO<sub>2</sub> storage involves keeping the CO<sub>2</sub> secured deep underground in a geologic reservoir. In addition to the careful selection of the subsurface formation, a comprehensive monitoring system needs to be put in place to ensure that the CO<sub>2</sub> remains in the subsurface.

The main geological constraints for finding the «right» place to store CO<sub>2</sub> include: a reservoir rock, a trap, and an impermeable caprock. The reservoir rock needs to be porous and permeable. Porosity is a volumetric measurement of the percentage of pore space in a rock that is available for storage. Permeability is the fluid transmissibility of the rock, and is important to allow the injection of CO<sub>2</sub>, and its subsequent dissemination into the pore system of the reservoir rock.

Since the stored CO<sub>2</sub> is less dense than the formation water, it will naturally rise to the top of the reservoir, and a trap is needed to ensure that it does not reach the surface. CO<sub>2</sub> can be trapped by a number of different mechanisms, with the exact mechanism depending on the formation type. The most common traps are structural (anticlinal or fault juxtaposition), stratigraphic (pinchout of reservoir rock against non-reservoir) or hydrodynamic (CO<sub>2</sub> is entrained in the groundwater flow and is constrained above

and below by impermeable seal lithologies). Two other important trapping mechanisms are solubility and mineral trapping. Solubility trapping involves the dissolution of CO<sub>2</sub> into the reservoir fluids, while mineral trapping involves the reaction of CO<sub>2</sub> with minerals present in the host formation to form stable, solid compounds such as carbonates. As the CO<sub>2</sub> moves through the reservoir along the flow path, a proportion of the CO<sub>2</sub> dissolves in the formation water and some of this dissolved CO<sub>2</sub> becomes permanently fixed by reactions with minerals in the host rock. If the flow path is long enough, the CO<sub>2</sub> might dissolve completely or become fixed by mineral reactions before it reaches the basin margin, essentially becoming permanently trapped in the reservoir.

A caprock is required to seal the CO<sub>2</sub> within the trap. Caprocks are generally very fine grained rocks with low porosity and, even more importantly, low permeability. The caprock must be of sufficient thickness and ductility to prevent microfractures and through-going faults from developing as possible CO<sub>2</sub> leakage pathways.

Obviously, active and depleted oil and natural gas fields, which generally have proven geologic traps, reservoirs and seals are ideal sites for storage of injected CO<sub>2</sub>. In such fields, it is important to ensure that hydrocarbon resources do not occur or have already been produced from the specific target formation. Also, care must be taken that all existing wellbores are adequately cemented (to prevent CO<sub>2</sub> reflux) before sequestration operations begin.

### Monitoring

Monitoring of the activities of stored CO<sub>2</sub> includes petrophysical, seismic, and surface geochemical methodologies. Wellbore properties such as pressure, temperature, resistivity and sonic responses will be recorded in injection and observation wells. Seismic monitoring, using an array of methodologies, will allow tracking of movement of CO<sub>2</sub>



in the subsurface. Geochemical sampling at surface localities will allow rapid detection of any seepage or leakage in the unlikely circumstance that this should occur.

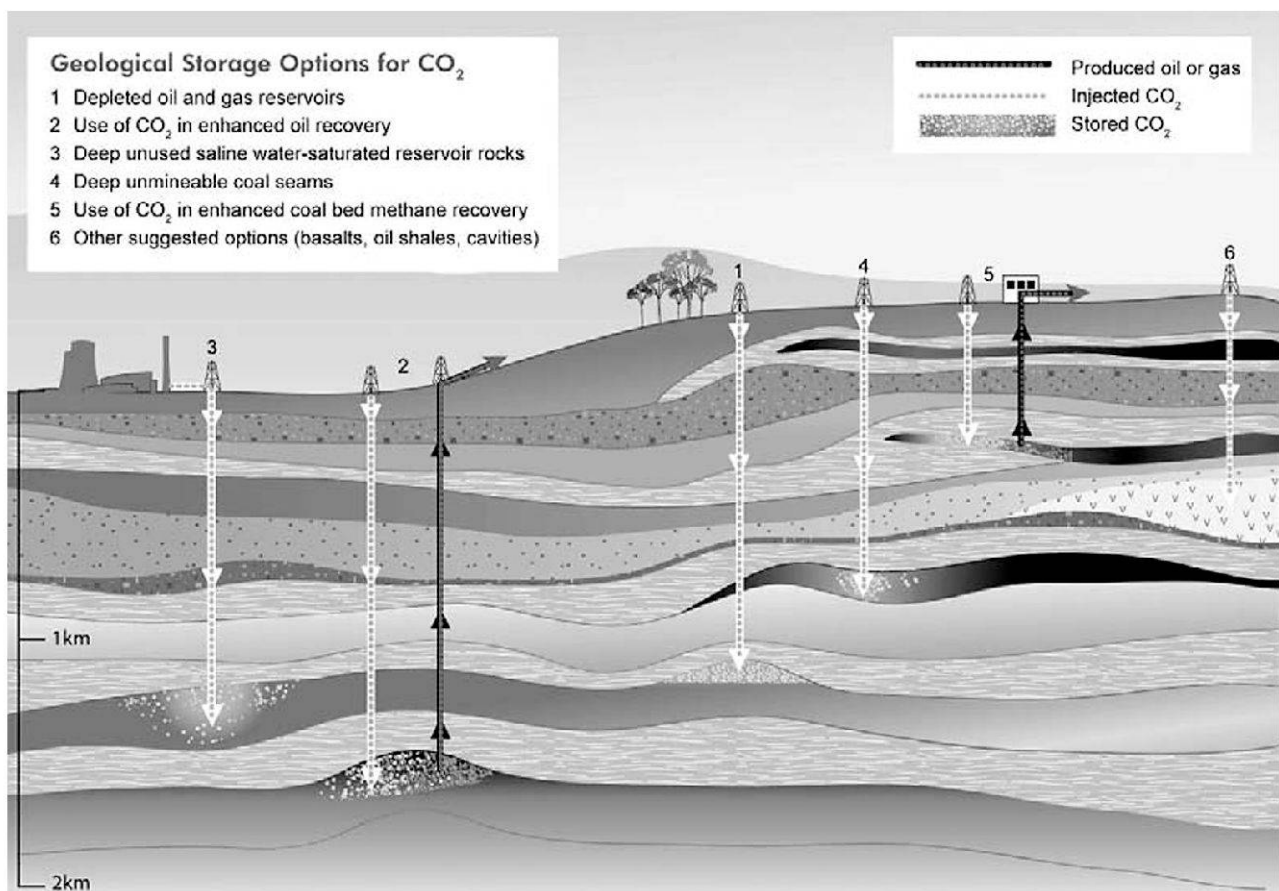
### Existing CO<sub>2</sub> Sequestration programs

The first commercial-scale project dedicated to CO<sub>2</sub> storage in a geologic reservoir has been in operation at the Sleipner West Field since 1996. Sleipner West is a natural gas field operated by Statoil and located in the North Sea about 250 km off the coast of Norway. The natural gas produced at the field has a CO<sub>2</sub> content of about 9% that, in order to meet commercial gas specifications, must be reduced to 2.5%. It has been standard practice in natural gas production for the by-product CO<sub>2</sub> to be vented to the atmosphere. At Sleipner, however, the CO<sub>2</sub> is compressed and injected via a single well into the Utsira Formation, a 250 m-thick, brine-saturated sandstone located at a depth of

800 m below the seabed. About one million tonnes of CO<sub>2</sub> has been injected annually at Sleipner since operations began in October 1996, with a total of 20 million tonnes of CO<sub>2</sub> expected to be sequestered over the lifetime of the project.

### CO<sub>2</sub> Sequestration Sites in Australia

An Australia-wide study of sedimentary basins conducted over the past five years has assessed 100 sites for the suitability for the safe, long-term storage of CO<sub>2</sub>. The majority of these sites were found to be potentially suitable. Ideally, these areas have reservoir rocks such as porous and permeable sandstones that are overlain by caprock seals of non-permeable rocks such as shale. A detailed evaluation at these and other sites to determine the most suitable areas for geosequestration is underway. Areas being evaluated in detail include the Sydney Basin in NSW; Central and South-



**Fig. 3:** CO<sub>2</sub> storage options. Image courtesy of CO2CRC.

East Queensland; the Perth Basin in Western Australia; and the Otway Basin spanning southern Victoria and into the Southern Ocean.

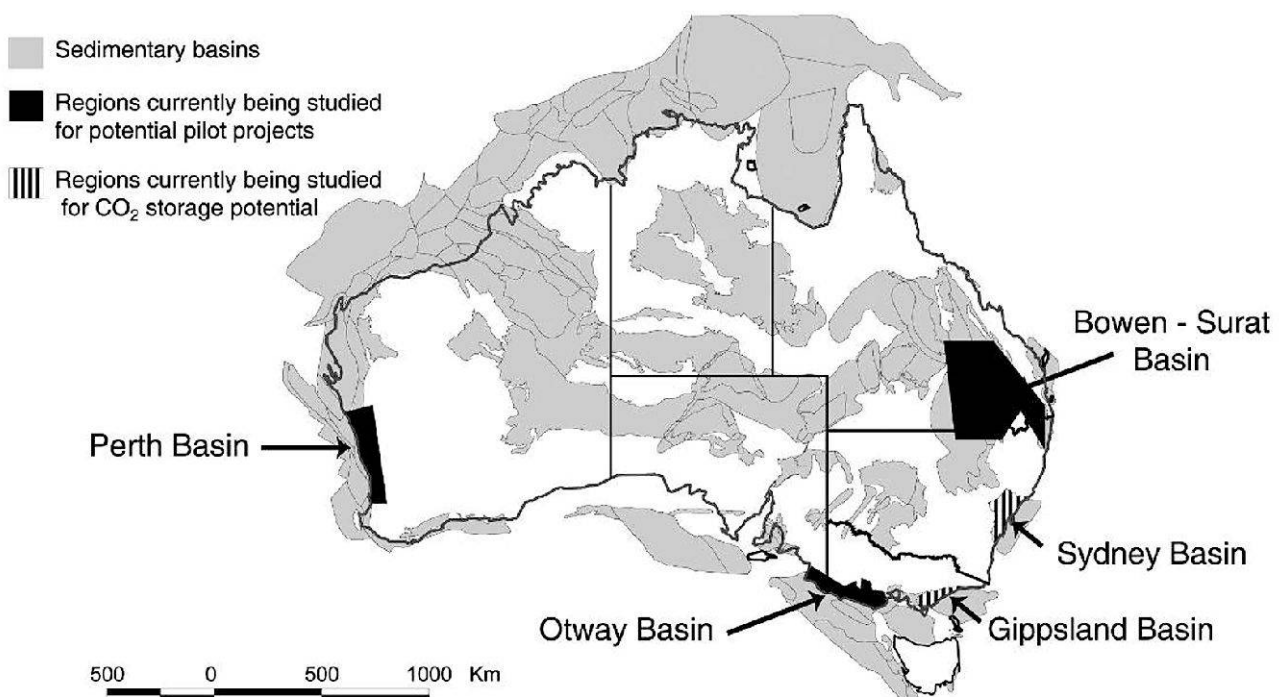
## Risks

Concerns surrounding CO<sub>2</sub> geosequestration relate to the potential for unanticipated CO<sub>2</sub> leakage as well as the possibility of induced seismicity and CO<sub>2</sub> migration. The risks associated with CO<sub>2</sub> storage, although considered very low, are characterised by a greater degree of uncertainty than those connected with CO<sub>2</sub> transport and injection. This is first due to the fact that once the CO<sub>2</sub> enters the geologic reservoir, its fate is transferred from largely human control to a natural system. Second, unlike for CO<sub>2</sub> transport and injection, enhanced oil recovery (EOR) using CO<sub>2</sub> floods and acid gas injection (AGI) do not provide a great level of understanding or expertise in safe and effective management of CO<sub>2</sub> storage; the quantities of CO<sub>2</sub> stored are smaller and the time periods involved are shorter than required for carbon geosequestration. Through the

development of improved models of the long-term behavior of CO<sub>2</sub> in reservoirs and the study of analogs such as natural CO<sub>2</sub> deposits, scientists are however gaining a better understanding and further minimizing the risks of CO<sub>2</sub> storage.

It is highly unlikely that any geologic CO<sub>2</sub> storage project would result in a catastrophic release of CO<sub>2</sub>. A common misconception is that an accidental leak from a CO<sub>2</sub> storage site could lead to an event analogous to the type that occurred in 1986 at Lake Nyos, Cameroon. The slow accumulation of CO<sub>2</sub> in this volcanic lake came to exceed the lake's finite capacity to contain the gaseous buildup and the vented CO<sub>2</sub> was not able to diffuse to safe levels before it reached nearby populated areas. There are two major reasons why this type of catastrophic release of CO<sub>2</sub> is unlikely to be repeated at a CO<sub>2</sub> storage site.

First, while the forces acting within Lake Nyos tended to cause a CO<sub>2</sub> pressure buildup, the pressure of CO<sub>2</sub> injected into a geologic reservoir should be reduced as it moves away from the injection well and is diffused over large areas of the formation. Second, Lake



**Fig. 4:** Regions currently being studied for potential pilot projects or for determination of likely CO<sub>2</sub> storage potential. Image courtesy of CO<sub>2</sub>CRC.



Nyos is located in mountainous terrain whereas any geographical setting that might allow CO<sub>2</sub> to accumulate in low-lying areas would in general be avoided for a CO<sub>2</sub> storage project. Finally, it is to be noted that there is no record of a catastrophic CO<sub>2</sub> release from a natural CO<sub>2</sub> deposit and such a release from a CO<sub>2</sub> storage project should be able to be prevented through careful site selection, operation and monitoring.

It is not expected that induced seismicity will be a significant problem at geologic CO<sub>2</sub> storage sites. Induced seismicity has been documented in enhanced oil recovery (EOR), acid gas injection (AGI), natural gas storage and waste injection operations. These induced seismic events have been caused by poor engineering practices such as the injection of the CO<sub>2</sub> at too high pressure, which in turn can result in microfracturing of the reservoir rock and/or small movement along existing fracture lines. It is to be noted however that most of the recorded events have been of a very small magnitude and have caused no harm. Moreover, the risk of induced seismicity can be reduced through careful siting and placement of injection wells, adherence to proper pressure guidelines and a sound understanding of the geomechanical properties of the storage reservoir.

## Summary

- Geosequestration could play a significant role in any portfolio of options for CO<sub>2</sub> emissions reduction.
- By reducing CO<sub>2</sub> emissions while still allowing for the continued use of fossil fuels, carbon geosequestration allows time for the transition to renewable energy sources from fossil fuels.

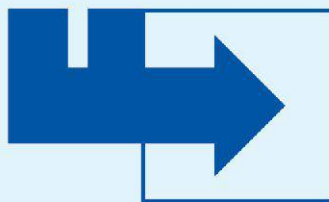
- Effective geosequestration of CO<sub>2</sub> involves: capture of CO<sub>2</sub> at stationary source locations; transportation of CO<sub>2</sub> from the source to the geological storage site; injection of CO<sub>2</sub> into subsurface reservoirs; storage of CO<sub>2</sub> in the subsurface; restoration of geosequestration sites; and effective monitoring and verification of CO<sub>2</sub> storage.
- Geosequestration sites ideally have simple geology. This means they should have no active faults, to avoid movement and leakage; the right sort of porous and permeable rocks to allow the injection and absorption of the CO<sub>2</sub> and the necessary rocks and geometries to trap the CO<sub>2</sub>.
- Given the large number of known geologic formations suitable for geosequestration, the opportunity exists for significant volumes of CO<sub>2</sub> storage in Australia.
- Much of the technology needed for carbon geosequestration projects is already at quite an advanced stage of development.
- Geosequestration research will lead to the establishment over the next four years of one or more geosequestration pilot projects in Australia.

## Acknowledgment

The point of this article is not to debate the issues of renewable energy versus fossil fuels, or the effects of greenhouse gases on global warming or climate or the environment. The reason for submitting this piece is to help provide geoscientists, who are likely as not to find themselves involved in public and/or private debates and discussions on the topic of geosequestration, with some basic information on the main issues involved in this timely and possibly poorly understood topic. In this piece I have blatantly and unabashedly used the work of many researchers from the CO<sub>2</sub>CRC and its precursor the GEODISC Program of the APCRC. To these able colleagues, I give full credit for the details of the science; any errors are, of course, mine.

For further information on geosequestration, please refer to [www.co2crc.com.au](http://www.co2crc.com.au)



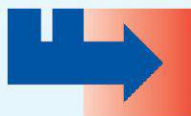


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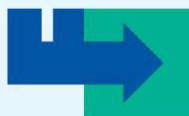
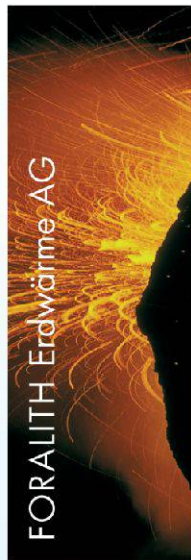
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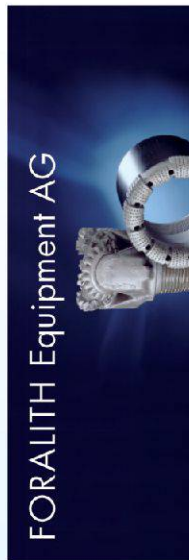
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