Engineering 3 (2017) 477–484

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Research
Clean Energy—Review

CCS Research Development and Deployment in a Clean Energy Future: Lessons from Australia over the Past Two Decades

Peter J. Cook

CO2CRC Ltd. & Peter Cook Centre for Carbon Capture and Storage Research, The University of Melbourne, Melbourne, VIC 3010, Australia

ARTICLE INFO

Article history:
Received 15 May 2017
Revised 24 June 2017
Accepted 9 July 2017
Available online 16 August 2017

Keywords:
Carbon dioxide
Carbon capture and storage
Otway
Australia

ABSTRACT

There is widespread, though by no means universal, recognition of the importance of carbon capture and storage (CCS) as a carbon mitigation technology. However, the rate of deployment does not match what is required for global temperatures to stay well below 2 °C. Although some consider the hurdles to achieving the widespread application of CCS to be almost insurmountable, a more optimistic view is that a great deal is now known about CCS through research, demonstration, and deployment. We know how to do it; we are confident it can be done safely and effectively; we know what it costs; and we know that costs are decreasing and will continue to do so. We also know that the world will need CCS as long as countries, companies, and communities continue to use fossil fuels for energy and industrial processes. What is lacking are the necessary policy drivers, along with a technology-neutral approach to decrease carbon emissions in a cost-effective and timely manner while retaining the undoubted benefits of ready access to reliable and secure electricity and energy-intensive industrial products. In this paper, Australia is used as an example of what has been undertaken in CCS over the past 20 years, particularly in research and demonstration, but also in international collaboration. Progress in the large-scale deployment of CCS in Australia has been too slow. However, the world's largest storage project will soon be operational in Australia as part of the Gorgon liquefied natural gas (LNG) project, and investigations are underway into several large-scale CCS Flagship program opportunities. The organization and progress of the Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) Otway Project, which is currently Australia's only operational storage project, is discussed in some detail because of its relevance to the commercial deployment of CCS. The point is made that there is scope for building on this Otway activity to investigate more broadly (through the proposed Otway Stage 3 and Deep Earth Energy and Environment Programme (AusDEEP)) the role of the subsurface in carbon reduction. There are challenges ahead if CCS is to be deployed as widely as bodies such as the International Energy Agency (IEA) and the Intergovernmental Panel on Climate Change (IPCC) consider to be necessary. Closer international collaboration in CCS will be essential to meeting that challenge.

1. Introduction

Overwhelming evidence indicates that the increase of anthropogenic greenhouse gases, and particularly carbon dioxide (CO_2), in the atmosphere is resulting in climate change and global warming. There is also a compelling case for saying that in order to keep the rise in global temperatures to well below 2 °C, there must be deep cuts in emissions, especially those resulting from the use of fossil fuels. Greater energy efficiency, greatly improved energy storage, large-scale deployment of renewable energy, more nuclear power, and more carbon capture and storage (CCS) or carbon capture, utilization, and storage (CCUS) will all be globally needed. At the same time, it is necessary to take a more holistic approach to the trilemma of having access to affordable, secure, and low-emission energy.

E-mail address: pjcook@co2crc.com.au

http://dx.doi.org/10.1016/J.ENG.2017.04.014
2095-8099/

Many countries and regions are reviewing how best to achieve these three objectives, and each country and region will obviously choose the technology mix that suits its particular circumstances.

Why, then, does this paper focus on CCS alone? A major reason is because, as the Intergovernmental Panel on Climate Change (IPCC), the International Energy Agency (IEA), and other bodies have shown, the cost of staying well below a 2 °C temperature rise will more than double if CCS is not deployed [1]. Indeed, it is unlikely that the global rise in temperature can be kept below 2 °C in the absence of CCS. Despite this, the speed of deployment of CCS technology is far below what is required. The Global Carbon Capture and Storage Institute (GCCSI) documents 16 commercial CCS facilities operating today and storing approximately 30 million tonnes of CO_2 per annum, with another six under construction. Together, these 22 facilities will store a total of 40 million tonnes of CO_2 per annum by about 2020. This amount is not insignificant. Nevertheless, it is far below what will be required if CCS is to play its necessary role in mitigating global emissions and meeting agreed-upon emission targets.

In the IEA's 2 °C Scenario (2DS), CCS delivers 12% of the necessary cumulative emission reductions up to 2050, meaning that approximately 94 Gt of CO_2 will need to be captured and stored. Of this, almost 14 Gt is in the form of negative emissions through bioenergy with CCS (BECCS), leaving 80 Gt to be applied to large-scale emission sources in the power and industrial sectors. At the current rate of CCS mitigation, we will store little more than 1 Gt of CO_2 by 2050. In other words, an increase of two orders of magnitude in the deployment of CCS will be required over today's figures, in order to keep the rise in temperature to well below 2 °C. This is a massive task.

However, is it possible that the picture is not as bleak as it appears, given some of the developments in CCS or CCUS that are happening in various parts of the world? In the past 20 years, a great deal has been achieved in our understanding of CCS through commercial projects such as the Statoil's Sleipner (Norway) project, which commenced the injection of CO_2 in 1996, and which has now successfully injected and stored 20 million tonnes of CO_2 over the subsequent 20 years. The Boundary Dam (Canada) and Petra Nova (the United States) projects have successfully integrated CCS with power generation. In addition, many pilot and demonstration projects that have been undertaken in recent years around the world, such as those in Australia (Otway), China (Yanchang), Japan (Tomakomai), Germany (Ketzin), and the Regional Carbon Sequestration Partnerships in the United States and Canada, have contributed to a firm base of knowledge for the acceleration of CCS. These projects, along with laboratory-based studies, provide confidence that there are no insurmountable technical barriers to CCS deployment. Nonetheless, hurdles exist, such as bringing down costs and increasing confidence in the technology. Underlying all this is the need to address the concerns of politicians, industry leaders, bureaucrats, non-governmental organizations, and the public at large, who have yet to be persuaded that CCS is safe, practical, and necessary [2]. Given this background, this paper briefly outlines the Australian energy context, within which CCS and related issues are being considered; it also reviews some of Australia's activities in CCS over the past 20 years, and looks at future options for research and clean energy opportunities, such as the conjunctive use of the subsurface for clean energy.

2. Australia's energy portfolio and mitigation options

Australia contributes less than 2% of global greenhouse gas emissions, yet has one of the world's highest per capita emission rates. It has signed the Conference of the Parties (COP) 21 Paris Agreement and will significantly decrease its absolute and per capita emissions over the next few years to meet its international greenhouse gas obligations. Australia will do this through a number of measures including an increase in the percentage of renewable energy, a decrease in its energy-intensive industrial base, and the closure of coal-fired power stations. Legislation and regulations have been major drivers for change, including a mandatory Renewable Energy Target (RET) that has resulted in the accelerated uptake of wind and rooftop solar energy systems. Because of Australia's federal system, the proportion of renewables varies greatly from state to state; for example, South Australia relies on wind and solar energy for 40% of its power. However, a major flaw in Australia's climate policy is the priority that is accorded to introducing more renewables, over a policy that focuses on decreasing emissions.

Australia is richly endowed with energy resources including coal, gas, and uranium (it has no nuclear power). It is the world's largest exporter of coal and will be the world's largest exporter of liquefied natural gas (LNG) by 2020. At the same time, it is facing the increasingly contentious issue of how to ensure that electricity in Australia is affordable, reliable, and has low emissions. This issue has been brought into focus in the past year or so by soaring electricity and gas prices, increased uncertainty in the supply of natural gas to the domestic market, and major power outages. This and related issues are comprehensively canvassed in the recently concluded review of the National Electricity Market (NEM) [3]. Among other conclusions, the review states that a more technology-neutral approach should be taken toward reducing emissions.

Australia's NEM was established in the 1990s to deliver cheap and reliable electricity, not emission reductions. However, over the past decade, energy and climate strategy in Australia has been dominated less by a policy of decreasing emissions and more by a policy of introducing increasing amounts of renewable energy into the energy mix without full regard for the consequences. Renewable energy backed up by battery storage will contribute to energy security at the household and district level, but is unlikely to do so to any great extent at the grid level for some time to come. Hydro power, including pumped hydro, will contribute to greater energy security, although opportunities in Australia are limited. Therefore, other modes of dependable, cost-effective, low-emission electricity that can work alongside renewables and can address energy security concerns must be considered in a technology-neutral manner. Coal-fired power generation currently provides much of Australia's grid stability, but it also results in Australia's relatively high rate of CO_2 emissions. In response to the need to decrease emissions, the proportion of Australia's coal-based power generation has decreased in recent years, while the proportion of intermittent wind and solar power has increased, resulting in the unintended but inevitable consequence of a less secure grid.

High-efficiency low-emission (HELE) coal-fired generation would be preferable to current largely critical or sub-critical coal-fired generation for providing lower emission grid stability. However, if used alone, HELE coal-fired generation would still produce per-megawatt hour emissions in excess of emission standards for power stations, such as those recently suggested by Victoria, and in excess of emissions from gas-fired power generation. Furthermore, although gas is cleaner than coal, it still produces significant greenhouse gas emissions. Biomass can be used to provide base-load power and can potentially be carbon neutral or even carbon negative. However, if coal, gas, or biomass continue to be used to provide cost-effective and secure power, only CCS can produce the required deep cuts in emissions for a future low-emission and secure energy mix.

As outlined by Finkel's report [3], Australia's energy security is provided by a range of measures, with varying degrees of success. Unabated coal- or gas-fired power generation still dominates electricity production and provides necessary inertia to the grid; however, it does so with a high carbon intensity that is inconsistent with the government's greenhouse policy and with community expectations. Renewable energy, smarter grids, demand management, batteries, and other forms of energy storage such as pump storage will be used more widely. However, there is still some way to go before batteries can provide grid-wide backup, and there is little prospect of batteries being used as backup for large-scale industrial users. In addition, although costs will decrease, adding storage costs to intermittent sources will have a major impact on the economics of renewables.

3. The potential role of CCS

Deploying CCS has the potential to maintain the energy security benefits of coal or gas (or biomass), while avoiding the environmental impact of their current use and doing so in a cost-effective manner. Current data suggests that retrofit CCS could be significantly cheaper than new-build CCS (submissions by Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) [4] and by Hooper [5] to Finkel's report). CCS is already being commercially deployed for coal-based electricity generation in the United States (Petra Nova) and in Canada (Boundary Dam), where it removes 90% of CO_2 emissions along with SO_x, NO_x, and particulates. It is applied to biofuels at Decatur (Illinois, the United States), and there are no insurmountable technical barriers to its deployment in Australia (see discussion later in this paper).

CCS is often criticized as being "too expensive" and "not commercially viable," in response to which the question must be asked: "Compared to what?" The levelized cost of electricity (LCOE) for new-build CCS is greater than that of wind power; it is within the same range as rooftop solar, but cheaper than solar thermal with storage [6]. If the cost of energy storage (e.g., batteries) is included for intermittent renewables, then coal-/gas-/biomass-based electricity generation with CCS is likely to be cheaper than wind and solar electricity generation. Furthermore, costings from the CCS retrofitted at Boundary Dam and, most recently, at Petra Nova indicate that for several reasons, retrofit CCS can be significantly cheaper than new-build CCS, with the prospect of costs decreasing further (the 2016 cost per megawatt of Petra Nova was about half that of the 2014 Boundary Dam). Although retrofitting CCS to existing power plants is highly site/project specific, recent costings of CCS retrofitting by Bongers et al. [4], the GCCSI (2017) [7], and Hooper [5] are all in much the same cost range (Table 1). It is important to note that these are in much the same cost range as intermittent wind and solar generation (Table 1), thus supporting the view that retrofit CCS has a potential cost-effective role to play in providing low-emission and secure electricity. Various pathways to retrofitting can be taken; among other approaches, the use of partial capture (as shown in Table 2) offers a way of balancing LCOE against emission reductions as circumstances dictate[†].

Table 1
LCOEs for a range of low-emission technologies from various Australian studies (compiled by Hooper, UNOTech personal communication).

Technology	LCOE $·(MW·h)$^{-1}$	Source
Coal—New-build with CCS (PCC)	150–200	Ref. [6]
Coal—Existing with retrofit CCS (PCC)		
GCCSI (2017)	80–130	Ref. [7]
UNO Technology (2017)	90–130	Ref. [5]
CO2CRC—Limited FGD/DeNO$_x$ (black and brown coal)	105–140	Ref. [4]
CO2CRC—Full FGD/DeNO$_x$ (black and brown coal)	105–165	Ref. [4]
Natural gas—New-build with CCS (PCC)	125–150	Ref. [6]
Natural gas—Existing with retrofit CCS (PCC)	75–115	Ref. [5]
Wind—Intermittent	90–120	Ref. [6]
Solar—Intermittent	125–175	Ref. [6]

FGD: flue gas desulfurization; PCC: post-combustion capture.

CCS has an added significance to Australia because of the importance of coal and LNG exports to the national economy. In the case of LNG, the importing country benefits from a decrease in its emission intensity if gas replaces coal; however, Australia's energy-intensive gas processing will result in a marked increase in related CO_2 emissions if CCS is not applied. Coal emissions are a consequence of its use in the importing country and therefore do not appear on Australia's greenhouse gas inventory (although fugitive emissions arising from coal mining activities do); of course, these emissions still contribute to global emissions. In an increasingly carbon-constrained world, countries will choose to decrease their use of coal and gas unless there is a viable, cost-effective carbon-reduction technology—that is, CCS. In addition, Australia is the world's largest exporter of metallurgical coal and iron ore for steel-making, a process that generates a significant proportion of the world's anthropogenic emissions. There is no alternative to CCS in decreasing the emissions from such industrial processes. Australia has much to gain economically from the global deployment of CCS. It is therefore no surprise that Australia is a major player in CCS research development and demonstration, and will shortly become host to the world's largest CO_2 storage project.

4. CCS R&D in Australia

Research into CCS began in Australia in 1998, with the first assessment of the CO_2 storage potential of the Australian continent (Fig. 1), which occurred through the Geological Disposal of CO_2 (GEODISC) Project [8]. This project brought together a talented team of geologists, geophysicists, geochemists, and hydrogeologists from a range

Table 2
Partial capture, using an option of initially installing a full-capture plant, will reduce the LCOEs in Table 1 in proportion to the level of emission reduction.

Partial capture	LCOE $·(MW·h)$^{-1}$
No capture	58
25% capture	64
50% capture	74
75% capture	86
90% capture	94

Using data on a brown coal retrofit from a submission to the National Electricity Market review [5].

Fig. 1. Australia's sedimentary basins and the location of CCS activities.

† Hooper personal communication.

of universities and research bodies, under the umbrella of the Australian Petroleum Cooperative Research Centre (APCRC). The primary question posed for this project was: “Does the geological storage of CO_2 have the potential to make deep cuts in Australia’s emissions?” By 2002, the answer was clearly “Yes!”. With this in mind, the APCRC remit was revised in 2003 and the CO2CRC was established, with a research priority focused solely on carbon capture and geological storage (i.e., CCS or CCUS). CO2CRC became, and continues to be, Australia’s most significant collaborative CCS R&D initiative.

Subsequent Australian CCS initiatives included individual research activities by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Geoscience Australia, and universities. Government support was provided for the early-stage assessment of three demonstration-scale CCS projects through the federal government’s CCS Flagship program, and joint industry and government funding was provided for Flagship-related research through Australian National Low-Emissions Coal Research and Development (ANLEC R&D). The GCCSI was established in 2008. In 2012, the University of Melbourne established the Peter Cook Center for CCS Research, with support from Rio Tinto, the Victorian Government, and CO2CRC. For a number of years, the industry separately funded (through a levy on coal) a number of CCS activities, via Australian Coal Association Low-Emissions Technologies (ACALET), such as the Callide Oxyfuel Project and storage activities in the Surat Basin. In recognition of the importance of CCS and of the need to take a global perspective, BHP recently established and funded a number of global CCS initiatives. These include the establishment of the CCS Knowledge Center in Saskatchewan, Canada; research at Peking University into the application of CCS in the steel industry; and, most recently, international collaborative research into CO_2 trapping mechanisms by the University of Melbourne, Stanford University, and the University of Cambridge.

Australia does not yet have an advanced commercial proposal for a power-related CCS project, but the CarbonNet Project in Victoria, the Carbon Transport and Storage Corporation (CTSCo) Project in Queensland, and the Southwest Project in Western Australia are at various stages of assessment. By far the most significant commercial CCS development in Australia to date is the world’s largest storage project, which is being implemented on Barrow Island as part of the Gorgon LNG project; this project will start injecting 3 million–4 million tonnes of CO_2 per annum in 2018, and will continue to do so for the next 25 years.

To date, the focus of CCS R&D in Australia has been on storage in saline formations, which is appropriate given the nature of Australia’s geology and the abundance of storage capacity in saline formations, not only in Australia but around the world [2]. What scope is there for the beneficial use of CO_2? As recently pointed out by MacDowell et al. [9], the potential for the use of CO_2 as a means of limiting climate change is quite modest, with CO_2 enhanced oil recovery (EOR) the only opportunity to beneficially use CO_2 at a significant scale, mainly in North America. Unfortunately, the opportunities for EOR in the Asia-Pacific area appear to be limited [9]; nonetheless, they do exist in Southeast Asia. Such opportunities have received little attention in Australia. In general, the nature of Australia’s oil- and gas-producing basins appears to offer limited scope for EOR, although further consideration is required. Storage in depleted oil and gas fields and enhanced gas recovery may offer Australia more opportunities in producing basins such as the Gippsland Basin. The production of useful carbonate minerals from silicate minerals has also received some commercial attention and may provide a useful niche opportunity, but again is unlikely to be possible at a scale that would make it a significant mitigation option. BECCS-related negative emissions are an integral part of many global mitigation models that aim to stay well below a 2 °C rise in temperature. Some work is underway on BECCS in Australia [10], but the topic deserves more attention.

5. The delivery of CCS R&D through CO2CRC

5.1. Structure

Through GEODISC and the APCRC, foundation studies into CO_2 storage were underway as early as 1998. Building on this work, CO2CRC was formally established in 2003 as an unincorporated joint venture with around 30 Australian and international members from industry, governments, universities, and research organizations. Its remit was to undertake commercially significant R&D into both capture and storage. One of the early pioneering studies it undertook was an assessment of the scope for a CCS hub in the Latrobe Valley and the adjacent Gippsland Basin. This work provided the basis for a range of subsequent detailed assessments of the CCS potential of the region by Shell, Anglo, and, most recently, CarbonNet (see Section 4).

Since its establishment, the primary aim of CO2CRC was to undertake a pilot-scale storage project in Australia at a commercially significant scale. A few similar projects existed in 2003, mostly in North America, from which lessons could be learned. For example, it was evident that undertaking a storage research project was complicated if performed in conjunction with a commercial EOR project, not least because commercial and research aims did not always match. It was also evident, if somewhat paradoxical, that securing an adequate supply of CO_2 had been problematic and expensive for a number of previous projects. Finally, it was clear that although it would be ideal to have a fully integrated CCS project with CO_2 derived from, for example, a coal-fired power station with CO_2 capture, such a situation did not exist at scale in Australia and was unlikely to do so for at least a decade. As it was not possible to wait that long, it was decided that CO2CRC needed its own facilities, its own site, and its own source of CO_2.

In 2003, it was decided that an essential starting point for a CO2CRC field experiment was to have a secure and affordable supply of CO_2. CO2CRC therefore purchased a high-CO_2 gas well (Buttress 1) in the Otway Basin in southwest Victoria. At the same time, the opportunity arose for CO2CRC to purchase a related petroleum tenement with depleted gas fields, excellent reservoir rocks, satisfactory seals, structural and stratigraphic traps, and a valuable database derived from previous oil and gas exploration activities. Although there is no such thing as a perfect research site, the Otway opportunity came very close to the ideal. In a situation that may have been unique among research organizations [11], CO2CRC now had its own producing CO_2 well and depleted gas fields.

An early decision was made to focus the efforts of CO2CRC at the Otway site; however, it was necessary to first set up a formal liability and risk management system that was acceptable to the board of CO2CRC. This was no easy matter; CO2CRC comprised many member organizations, each with a different attitude toward risk and liability, which are the sort of issues that are routinely dealt with by exploration companies but are unusual for research organizations. Therefore, it was necessary to form a separate incorporated company composed of 10 resource companies that agreed to come together as shareholders, in order to take on the financial and other liabilities that may arise in any subsurface operations. This close engagement with resource companies provided CO2CRC with access to exploration and production expertise that ensured that the highest standards of health, safety, and environmental management were followed, and that regulations and licensing conditions were adhered to. CO2CRC also established a separate company to hold and exploit intellectual property (IP).

This arrangement provided a clear administrative structure for the successful management of a series of CCS field and plant experiments to be carried out over a number of years. However, as the research needs changed and as operations became more capital intensive, it was necessary for CO2CRC to make a number of changes that allowed it to enhance its operational activities at the Otway site. Since 2012, CO2CRC has conducted progressively more of its capture research through the University of Melbourne. In addition, its IP related to capture cost reduction (including solvent processes, equipment design, and process/heat integration) was transferred in 2014 to an Australian company, UNO Technologies Pty. Ltd. In 2015, any remaining responsibilities for finance, field operations, research coordination, and property ownership were transferred from the unincorporated joint venture (which was then closed) to the incorporated company CO2CRC Ltd., its independent board, and its chief executive, Ms. Tania Constable. CO2CRC Ltd. continues to be supported by Australian and overseas governments, the industry, universities, and research organizations[†].

5.2. The CO2CRC Otway Project

Along with its collaborating organizations, CO2CRC commenced carbon capture research in 2003, with a focus on bringing down the cost of carbon capture through the development of improved solvents and membranes for both pre- and post-combustion capture. For several years, CO2CRC successfully operated a pilot-scale post-combustion capture plant at the Hazelwood coal-fired power station, which provided important insights into opportunities for plant integration and retrofitting CCS to existing power plants, and into the economics of doing so. The use of carbonate solvents received particular attention, and a closed-loop absorption-stripping system was developed that removes CO_2 from industrial gas streams using high-efficiency precipitating potassium carbonate scrubbing. The IP associated with this process was transferred to UNO Technologies Pty. Ltd. in 2014, as mentioned earlier. In 2017, CO2CRC established a pilot plant at the Otway site to test new technologies for the separation of CO_2 from natural gas, using high-CO_2 Buttress gas as a starting point.

For the past 14 years, however, CO2CRC's research emphasis has been on storage, with a primary focus on testing and monitoring storage at a commercially significant scale through the CO2CRC Otway Project, located in Western Victoria. During this time, CO2CRC and its collaborating organizations have spent more than $100 million on developing, drilling, and instrumenting the Otway site and on undertaking major scientific programs. It is anticipated that CO2CRC will spend an additional $41 million between now and 2019 to further instrument and monitor the site and to undertake more leading-edge CCS science.

The priority at CO2CRC was to demonstrate that CCS "works," and that the organization could competently and safely undertake a CCS operation. By 2005, the necessary approvals had been obtained. CO2CRC then set about putting in a gas pipeline and drilling an injection well to a depth of approximately 2000 m; in other words, CO2CRC began the sort of activities that a fully commercial CCS project required, even though Otway Stage 1 (as it was now called) was purely a research project.

Between March 2008 and September 2009, 65 445 tonnes of super critical CO_2 (gas rich in CO_2) were injected at a depth of 2053 m into the Waarre C Formation of the new CRC-1 well; this formation was a homogeneous sandstone reservoir within a depleted gas field. During this period, the following issues arose and were resolved: Certain pieces of downhole equipment did not function properly; the injectivity was low at first; and it was necessary to adjust surveying and sampling schedules so as not to disturb the activities of local farms. At the end of this time, activity at the CRC-1 well was suspended to await subsequent stages of the project, although maintenance and monitoring continued at the site. (Stages 2 and 3 of the project are described below.) Although this project has not been closed down, future projects will include successful abandonment and closure procedures.

The Otway Stage 1 project was a major success and produced significant findings, as described below:

> *The CO2CRC Otway Project has demonstrated that the storage of CO_2 in a depleted gas field can be designed and safely achieved. Monitoring showed that there has been no measurable effect of stored CO_2 on soil, groundwater, or atmosphere.... Seismic imagery and fluid sampling confirmed dynamic and geochemical models. Sensitivity of monitoring techniques to surface leakage rates at the few kilotons yr^{-1} … was demonstrated. Achieving this sensitivity shows that commercial-scale storage programs could be effectively monitored to ensure climate abatement was being achieved.* (Jenkins et al. [12])

Other key scientific outcomes of the project were reported by Stalker et al. [13], Underschultz et al. [14], and Cook [15].

In 2008, CO2CRC started to plan a new series of experiments (Otway Stages 2A, 2B, and 2C), to be undertaken at the site over several years, again with a focus on commercial CCS. Saline formations are the most abundant and extensive global potential storage opportunity; however, in order to ensure regulatory and community acceptance, the various trapping mechanisms (Fig. 2) [2] that operate during CO_2 plume migration must be better understood, the CO_2 plume must be successfully monitored, and the plume stabilization must be verified. Otway Stage 1 was undertaken in order to test storage in the Waarre C Formation. Otway Stage 2 was targeted at storage in a saline aquifer without structural closure—the Paaratte Formation, at a depth of 1500 m. The aim of Otway Stage 2 was to assess residual and dissolution trapping mechanisms during the migration of the CO_2 plume, successfully monitor the plume, and develop the ability to predict when plume stabilization would occur.

As part of Otway Stage 2A, a new injection well (CRC-2) was drilled and extensively cored, and geological characterization of the Paaratte Formation was undertaken. A static model was developed that was populated with petrophysical properties for flow modeling and elastic properties for seismic modeling [16].

The Otway Stage 2B residual saturation and dissolution test

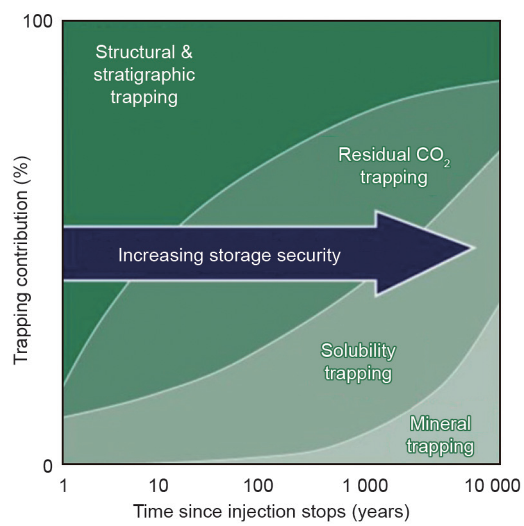

Fig. 2. Trapping mechanisms of CO_2 [2].

[†] More information on CO2CRC can be found at www.co2crc.com.au.

sequence, which was undertaken in 2011 and repeated in 2013, involved the injection of 140 tonnes of pure CO_2 into the Paaratte Formation. This CO_2 plume was driven to residual saturation by the injection of CO_2-saturated formation water (up to 450 tonnes) into the same interval. It used a single-well approach that can be deployed in industrial projects to expand and improve the near-well characterization methodologies in a cost-effective manner. A related experiment involving just 10 tonnes of CO_2 was also used in order to determine with greater confidence the range of rock-fluid geochemical reactions that occur during the geological storage of CCS, including storage in the presence of trace contaminants [17–19].

The Otway Stage 2C test was undertaken in 2015–2016 in the Paaratte saline aquifer. The aim of this test was:

> *To accurately predict the movement of CO_2, giving confidence to the users of carbon capture and storage technologies and regulators how CO_2 will behave when permanently stored, and the technical capabilities of seismic monitoring to validate this plume movement.* (Tania Constable, 2016)[†]

To test seismic resolvability, 15 000 tonnes of CO_2-rich gas was injected. It was important for the plume to be sufficiently thick and continuous for its development to be visualized with four-dimensional (4D) seismic monitoring; it was also necessary for it to be sufficiently laterally restricted such that the seismically resolvable plume was within a reasonable monitoring region (approximately 1 km^2). Finally, it was important for stabilization to occur within a finite (short) time. The prediction by CO2CRC is that CO_2 will be effectively immobile at seismic resolution approximately 2 years after injection, that is, late in 2017. Stage 2C monitoring is still underway to test this prediction (www.co2crc.com.au). Cost-effective fiber-optic cables and a high-resolution buried receiver were fitted with automated communications facilities to allow researchers to remotely access and operate this advanced surface and subsurface monitoring system [20–22].

Expanding on the learnings from Stage 2, CO2CRC initiated Otway Stage 3 at an anticipated cost of $40 million in late March 2017, with the drilling of a new appraisal well, CRC-3, undertaken in April 2017.

> *The project will focus primarily on developing a cost-effective "smart field" where up to 40 000 tonnes of CO_2 will be injected underground and monitored using various new tools and techniques in real time. This injection amount is necessary to model a commercial storage project of 4 million tonnes per annum of CO_2. The project has been designed to be transferrable to different environments both onshore and offshore making it a valuable investment for a range of industries.*
>
> *Tania Constable, CEO of CO2CRC, said, "A smart field gives regulators and the community confidence that the CO_2 can be constantly monitored at lower cost."*
>
> *"Once installed in the subsurface, the technology will pinpoint the areas of risk faster and be cheaper to operate than traditional methods of CO_2 monitoring. Our instruments sit below ground, potentially doing away the need for expensive and disruptive above-ground seismic surveys,"…* (Tania Constable (CEO), CO2CRC press release, 27 March 2017)[‡]

These and related CCS activities will continue at the Otway site until 2019/2020, and potentially beyond.

5.3. Future subsurface research opportunities

In Australia and around the world, the top 4–5 km of sedimentary basins constitute the zone that is most intensively explored and capitalized, whether for the extraction of oil, gas, coal, and other resources, or for the disposal of CO_2 and brines from energy production. Sedimentary basins are critical to energy futures in a carbon-constrained world (Fig. 3).

The previously described series of CO_2 storage projects at the CO2CRC Otway site have been highly successful in many ways: They are relevant to bringing down the cost of commercial CCS projects through improved monitoring; they have tested new subsurface technologies; and they have improved our understanding of subsurface processes, especially CO_2 migration and trapping. They have

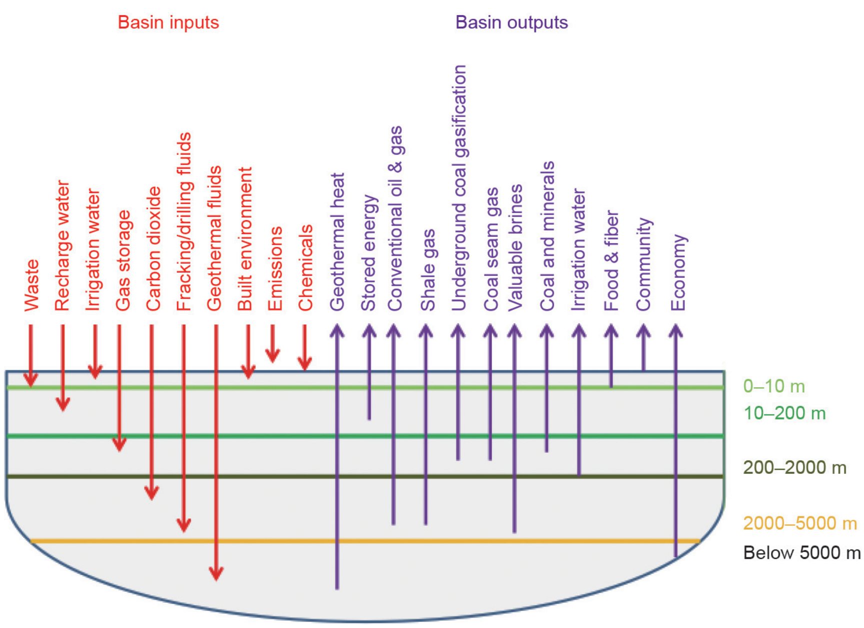

Fig. 3. Sedimentary basins are increasingly becoming the sites of multiple and sometimes conflicting uses, as resources are extracted (purple) and basins are used for a range of activities related to waste disposal or fluid injection (red), including CO_2 storage.

[†] http://www.co2crc.com.au/15000-tonnes-of-co-2-used-to-make-emissions-reduction-cheaper/
[‡] http://www.co2crc.com.au/41m-emissions-reduction-project-otway-victoria-begins/

also greatly enhanced the visibility and credibility of CCS as a mitigation option in Australia and around the world. Finally, they have served as a wonderful vehicle for encouraging national and international collaboration among hundreds of scientists and engineers from dozens of organizations in Australia and abroad.

Australia and the scientific world now has an extraordinarily valuable subsurface facility at the CO2CRC Otway site, not only for research relating to CCS, but also for potential investigations into energy opportunities and the more general use of the subsurface. The investment at the Otway site by CO2CRC—which totaled $140 million in subsurface and related surface facilities along with existing regulatory approvals and community, local, state, and federal government support for CCS activities—provides an exceptional starting point for developing the Deep Earth Energy and Environment Programme (AusDEEP).

AusDEEP can be compared to a telescope that looks downwards to a depth of 4–5 km. Its purpose is to expand our understanding of "inner space"—that part of the earth that hosts most of our energy resources. The strategy proposed for the program is to develop advanced instrumentation, monitoring, and three-dimensional (3D) and 4D multiphase modeling capabilities at Otway and possibly at other sites, in order to improve the effectiveness with which we can evaluate, utilize, and protect our resources. To do this, AusDEEP will develop an exceptionally comprehensive picture of a 100 km^3 "cube" of a sedimentary basin, at a scale and resolution not previously possible. This 100 km^3 near-field cube will be placed within the basinal context of a 500 km^3 far-field cube with a somewhat lower resolution. The facility will determine the geometry, dynamics, and composition of these cubes, monitor natural and anthropogenic processes within them, and determine the fluxes and pathways operating within them, over temporal scales ranging from diurnal to decadal.

AusDEEP carries the potential for industrial and commercial relevance in areas such as the following:

(1) Innovations arising from drilling, logging, and the instrumentation of wells or in-well completions and abandonments could decrease production costs and adverse impacts.

(2) Research into hydraulic fracturing or subsurface water disposal may prove to be very important, not only for improving recovery from tight formations, but also for informing the regulatory regime and concerns relating to social licensing.

(3) Much of the existing downhole technology will only operate up to temperatures of 150 °C; however, in some Australian basins, the operating temperatures are much higher. Instrumentation that is able to operate at high temperatures and pressures will be important for the future development of deeper resources.

(4) The presence of CO_2 greatly increases the complexity (and cost) of well abandonment; however, no facility or study center exists in the Asia-Pacific region to address this particular issue. Thus, AusDEEP can contribute to better abandonment procedures and technologies and can bring down costs for high-CO_2 wells.

(5) A recent workshop identified a number of important priority areas of energy research to which AusDEEP can make a contribution, such as pressure monitoring and management, passive seismic studies, storage optimization, and geochemical barrier generation. The scope of the CO2CRC Otway site, and perhaps of other related sites as well, can thus be progressively broadened to encompass a range of advanced energy research and technology activities that will serve to strengthen CCS-related research.

The current status of AusDEEP is that a proposal has been put forward to the government by CO2CRC Ltd. for future consideration and possible future funding. If funded, this program would represent a significant science and technology investment by Australia, and would enable us to better understand, manage, and preserve our energy resources. It would provide a platform for world-leading, collaborative, multidisciplinary, multi-institutional, and international earth science and technology that would greatly benefit Australia and other nations, by enabling us to better use resources such as conventional and unconventional gas, geothermal energy, subsurface energy storage, and CO_2 storage space in smarter, more economical, and more environmentally sustainable ways, including by decreasing our greenhouse gas emissions.

6. Conclusions

6.1. The national policy setting for CCS research

Because of its importance as one of the world's major exporters of fossil fuels, Australia has much to gain economically from the international deployment of CCS. Also, because of its geology and industrial base, Australia could potentially deploy CCS as a major domestic mitigation option for meeting its international greenhouse obligations. However, with the notable exception of the Gorgon LNG project, there is currently no other major Australian CCS project under development, although several projects are at an early (pre-feasibility) stage of consideration. Retrofitting CCS to some of Australia's current coal-fired power stations could be a cost-effective option for Australia to improve the security and stability of the existing electricity grid.

The recently released Finkel's report to the NEM and the recommendations arising from this report provide a basis for moving forward with CCS as a clean energy option within a technology-neutral setting. Coal or gas with CCS is seen as a potential part of the energy future, provided that expectations can be met regarding lowered emissions, grid stability, and cost effectiveness. This view is reinforced by one of the main conclusions in a recent study of the Australian grid that was undertaken for ANLEC R&D:

> *At high decarbonisation levels, dispatchable power like HELE+CCS will be required to deliver the required resilience for grid stability. It can also deliver the deepest decarbonisation ambitions at lowest cost.* (Boston et al. [23])

Along with the recommendations in Finkel's report, this message has the potential to reset current perspectives (and perhaps policies) relating to the use of fossil fuels and CCS in Australia's future energy mix.

In conclusion, if Australia's CCS research had been delayed until there were clear policy settings relating to CCS and energy, then little or no CCS research would have been undertaken and there would have been little or no CCS expertise available in Australia. In fact, extensive CCS research and demonstration has been undertaken over the past 20 years, in no small measure because the R&D community did not wait for policy to be clarified, but instead developed its own impetus. As a result, Australia now has the knowledge and the expertise to take CCS forward at scale, once the right policy settings are in place.

6.2. Learnings from Otway

The CO2CRC Otway Project has been and will continue to be Australia's premier CCS research activity. It is of direct relevance to commercial-scale operations and is providing a detailed picture of how CO_2 is trapped. It has also been of great importance in terms of learning. Some of the key activities from this project that resulted in significant learning are described below.

(1) This project involved the design of a very ambitious program; the development of a range of techniques; training, developing, and implementing activities to collect large amounts of data; demonstrations that regulatory requirements were being met; and the drawing together of large and disparate datasets. These activities were essential in providing a comprehensive picture of exactly what

was happening within the storage complex.

(2) Physical and legal access to the study area took time to establish and involved negotiating permissions with landowners, dealing with changing survey plans, coordinating access, and ensuring safety for site visits by the range of survey teams. All of this took more time and effort than anticipated. Physical changes at the site needed consideration; for example, changes resulted in a highly variable water table that affected the seismic surveys and the soil gas and soil flux measurements.

(3) Suitable analytical techniques were often unavailable. The development of reliable methods for the analysis of fluid samples was time-consuming and difficult. Tracers posed particular problems that were associated either with very low concentrations, or with contamination in measuring apparatus and associated contamination of samples.

(4) As in any experiment, establishing reliable error estimates for data posed a challenge, even when lab analytical techniques or other instrumental artefacts were well understood. For example, the groundwater data show wide seasonal variations that are probably related to environmental factors such as extraction by farmers.

(5) The monitoring program involves a wide range of skills and has been extended over a number of years. It was consequently necessary to establish robust procedures that can survive staff turnover.

(6) Large amounts of data have been gathered in the course of the monitoring programs, but they are very variable in type, volume, and associated meta-data. Curating these data is both very important and challenging.

In conclusion, the Otway Project has been of great value, not only to the scientific community but also to industry, governments, and environmental protection and water authorities and regulators. It has proved valuable in terms of the broader community, which had little or no knowledge of CCS and how it worked. The project has helped to improve instrumentation, data analysis, and field procedures, and will help to bring down storage and monitoring costs. Finally, it will accelerate the pace at which geological storage can be implemented, by decreasing risk and uncertainty and giving stakeholders greater confidence in the capacity of CCS technology to safely and effectively decrease carbon emissions to the atmosphere.

6.3. International collaboration

Through the Otway Project, Callide Oxyfuel Project, CCS Flagship, and many other Australian-based activities, Australia has gained experience in (and benefited from) international CCS collaboration, and is eager to enhance that collaboration in the future. Australia has also gained from its involvement in international activities, such as its early involvement in the Frio brine project. A foundation is already in place for strengthened CCS collaboration between Australia and China through existing programs such as the China Australia Geological Storage of CO_2 (CAGS) Project coordinated by Geoscience Australia, the low-emission program of the Federal Department of Industry, Innovation and Science, pilot-scale capture activities by CSIRO, and the recent international CCS initiatives with Peking University by BHP. Many universities and research organizations in Australia and China already have close ties with each other. The involvement of China, other countries, and other organizations in future research at the CO2CRC Otway site, in AusDEEP, or in some of the proposed large-scale CCS Flagship projects would be a welcome development.

In conclusion, it is necessary to collaborate more closely in order to tackle what is seen by many as the almost unmanageable problem of meeting increasing demands for energy and energy-intensive products, while simultaneously making deep cuts in our emissions. To a significant extent, this challenge will be met through international collaboration in research, development, and demonstration, and ultimately through the large-scale deployment of a range of emission-reduction technologies, with CCS as a key technology.

Acknowledgements

The author thanks his many colleagues at CO2CRC and the University of Melbourne for their insights, their friendship, and their contribution to CCS science. The contributions of Tania Constable and Barry Hooper to this paper are acknowledged with thanks. The support of industry and governments made it possible to undertake Otway and the other research activities summarized in this paper.

References

[1] International Energy Agency. 20 years of carbon capture and storage: Accelerating future deployment. Paris: International Energy Agency; 2016.
[2] Intergovernmental Panel on Climate Change. IPCC special report on carbon dioxide capture and storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change. Metz B, Davidson O, de Coninck HC, Loos M, Meyer LA, editors. New York: Cambridge University Press; 2005.
[3] Finkel A, Moses K, Munro C, Effeney T, O'Kane M. Independent review into the future security of the National Electricity Market: Blueprint for the future. Canberra: Commonwealth of Australia; 2017 Jun.
[4] Bongers G, Byrom S, Constable T. Retrofitting CCS to coal: Enhancing Australia's energy security. Melbourne: CO2CRC Ltd.; 2017.
[5] Hooper B. Submissions to the independent review into the future security of the National Electricity Market. 2017. Available from: http://www.environment.gov.au/energy/national-electricity-market-review/submissions.
[6] Electric Power Research Institute, Inc. Australian power generation technology report. Melbourne: CO2CRC Limited; 2016.
[7] Chambers M. Gas carbon capture "cheaper" than wind and solar, experts say [Internet]. Sydney: The Australian; 2017 Feb 20. Available from: http://www.theaustralian.com.au/business/mining-energy/gas-carbon-capture-cheaper-than-wind-and-solar-experts-say/news-story/0d1a7971f3dc872192ab28baccacb1f6.
[8] Cook PJ, Rigg A, Bradshaw J. Putting it back where it came from: Is geological disposal of carbon dioxide an option for Australia? APPEA J 2000;40(1):654–66.
[9] Mac Dowell N, Fennell PS, Shah N, Maitland GC. The role of CO_2 capture and utilization in mitigating climate change. Nat Clim Change 2017;7(4):243–9.
[10] Pour N, Webley PA, Cook PJ. A sustainability framework for bioenergy with carbon capture and storage (BECCS) technologies. Energy Procedia 2017. In press.
[11] Cook PJ, Causebrook R, Gale J, Michel K, Watson M. What have we learned from small-scale injection projects? Energy Procedia 2014;63:6129–40.
[12] Jenkins CR, Cook PJ, Ennis-King J, Undershultz J, Boreham C, Dance T, et al. Safe storage and effective monitoring of CO_2 in depleted gas fields. Proc Natl Acad Sci USA 2012;109(2):E35–41.
[13] Stalker L, Boreham C, Underschultz J, Freifeld B, Perkins E, Schacht U, et al. Geochemical monitoring at the CO2CRC Otway Project: Tracer injection and reservoir fluid acquisition. Energy Procedia 2009;1(1):2119–25.
[14] Underschultz J, Boreham C, Dance T, Stalker L, Freifeld B, Kirste D, et al. CO_2 storage in a depleted gas field: An overview of the CO2CRC Otway Project and initial results. Int J Greenh Gas Con 2011;5(4):922–32.
[15] Cook PJ, editor. Geologically storing carbon: Learning from the Otway Project experience. Melbourne: CSIRO Publishing; 2014.
[16] Bunch M, Daniel R, Lawrence M, Browne G, Menacherry S, Dance T, et al. Multi-scale characterisation of the Paaratte Formation, Otway Basin, for CO_2 injection and storage. APPEA J 2012;52(2):664.
[17] Haese RR, LaForce T, Boreham C, Ennis-King J, Freifeld BM, Paterson L, et al. Determining residual CO_2 saturation through a dissolution test—Results from the CO2CRC Otway Project. Energy Procedia 2013;37:5379–86.
[18] Paterson L, Boreham C, Bunch M, Dance T, Ennis-King J, Freifeld B, et al. Overview of the CO2CRC Otway residual saturation and dissolution test. Energy Procedia 2013;37:6140–8.
[19] Paterson L, Boreham C, Bunch M, Dance T, Ennis-King J, Freifeld B, et al. CO2CRC Otway Stage 2B residual saturation and dissolution test. In: Cook PJ, editor Geologically storing carbon: Learning from the Otway Project experience. Melbourne: CSIRO Publishing; 2014. p. 329–60.
[20] Pevzner R, Urosevic M, Caspari E, Galvin RJ, Madadi M, Dance T, et al. Feasibility of time-lapse seismic methodology for monitoring the injection of small quantities of CO_2 into a saline formation, CO2CRC Otway Project. Energy Procedia 2013;37:4336–43.
[21] Pevzner R, Caspari E, Gurevich B, Dance T, Cinar Y. Feasibility of CO_2 plume detection using 4D seismic: CO2CRC Otway Project case study—Part 2: Detectability analysis. Geophysics 2015;80(4):B105–14.
[22] Shulakova V, Pevzner R, Dupuis JC, Urosevic M, Tertyshnikov K, Lumley DE, et al. Burying receivers for improved time-lapse seismic repeatability: CO2CRC Otway field experiment. Geophys Prospect 2015;63(1):55–69.
[23] Boston A, Bongers G, Byrom S. Balancing flexibility whilst decarbonising electricity on the NEM. Canberra: Australian National Low Emissions Coal Research & Development; 2017.