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The University of Queensland Surat Deep Aquifer Appraisal Project (UQ-SDAAP)

Scoping study for material carbon abatement via carbon capture and storage

Extended socio-economic technical summary

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1. Executive summary

The main aim of The University of Queensland Surat Deep Aquifer Appraisal Project (UQ-SDAAP) is to inform policy and decision makers as to whether or not material carbon abatement is feasible through implementing industrial-scale carbon capture and storage (CCS) in southern Queensland. "Material" in this sense is taken as safely and securely injecting at least 5 million tonnes per annum for at least 20 years – roughly equivalent to the emissions from one of the large, modern supercritical power plants in the area. In this study, a scheme with around 13 million tonnes per annum (Mtpa) has been matured, with potentially longer durations, under very conservative assumptions.

"Feasible" was taken to mean (i) demonstrably lowest risk storage locations; (ii) high levels of technical confidence; (iii) a robust, conservative capture scenario minimising disruption to power supplies; (iv) no obvious showstoppers for pipeline routes; and, (v) reasonable cost estimates, in line with published estimates. A scale of around 12.7 Mtpa for over 20 years appears to be technically feasible with technical uncertainties that can be addressed through new data gathering. The main risks and uncertainties are non-technical.

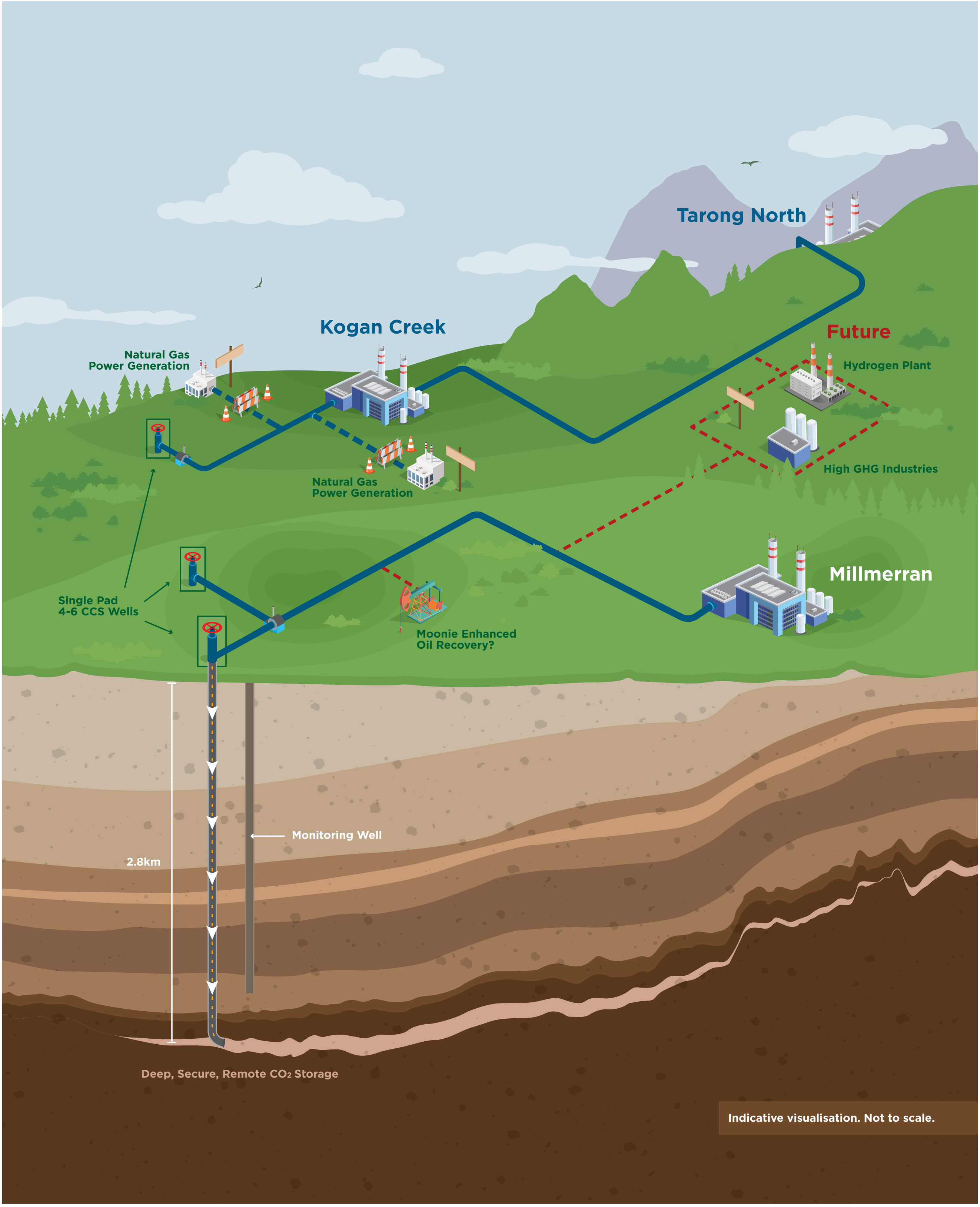
This research shows that deep emission cuts could be achieved by the establishment of a large-scale CCS "hub" scheme conceptually built around retrofitting existing modern power plants. This does not discount the opportunity for new-build plants or other emissions sources. The research demonstrates that a material abatement opportunity is likely to be a feasible option in the Surat Basin, though not yet quite 'confirmed'.

There is a limited window to take advantage of the main opportunity studied in this scenario, which is tied to significantly reducing the emissions of existing supercritical power stations. These plants have a finite technical lifespan in the order of 35 years. The sooner this abatement option is set up in the lifespan of these power stations, the greater the impact of the initiative. It is estimated that each year such a project is delayed would result in up to 13 million tonnes pa of CO_2 less being captured, which is the equivalent of taking around 2.8 million cars off the road each year. The establishment of secure, sustained high-rate CO_2 storage may also create opportunities for additional high emissions industries (such as hydrogen production or more power generation). Recent work done in parallel with this study indicates that pressure on power prices can be minimised by reducing total system cost, and that to do this, even more carbon abatement would be required via CCS as the national electricity market evolves into a low-emissions network.

The study considered techno-economic, social and regulatory aspects. The main new contributions of this study are a more profound understanding of the dynamic limits to safe, secure, high-rate storage, and a promising new approach to public engagement on energy futures.

The research found that material abatement of southern Queensland emissions appears technically feasible with CCS as part of the future energy mix. However, in addition to the need for specific new data, the research highlighted a number of non-technical challenges that need to be addressed to establish CCS in southern Queensland. These include acceptance of the need for trade-offs between carbon abatement aims, regional jobs, aquifer recharge and groundwater use as well as regulatory changes that may be needed.

Figure 1 Visualisation of a potential CCS initiative.



2. Societal

As carbon-intensive fossil fuels continue to dominate much of the world's energy generation and industrial activities, CCS (or CCUS [carbon capture, utilisation, and storage] as it is now more often referred to globally) is one technology that has been proposed to play a major role in mitigating greenhouse gas emissions (e.g. IEA 2013). In addition to developed countries reliant on fossil fuels, CCS is also relevant to a number of fast-developing and developing countries whose future CO_2 emissions are expected to continue to rise (Dütschke et al. 2016). In light of the recent IPCC Report 2018 examining the impacts of global warming at 1.5°C, CCS and other carbon dioxide removal (CDR) technologies have been identified as critical technologies for managing the transition to a more sustainable energy future (Boot-Handford et al. 2014).

However, early discussions about CCS have not been without controversy. Opponents argue that it promotes "dirty energy" and, if deployed, its impact may lead to a technology lock-in that hinders the development of more renewable energy options (Marshall 2016). Similarly, as some CCS projects have been put on hold or cancelled due to public opposition and failing to gain or sustain support from political actors (Wallquist et al. 2012; Hammond & Shackley 2010), it has been recognised that the public's perception and evaluation of CCS technology is critical for its commercial deployment (L'Orange Seigo et al. 2014).

Reviews examining the psychological, social and cultural factors that underlie the support (or lack of it) for CCS projects (e.g. Ashworth et al. 2013; de Coninck & Benson 2014; L'Orange Seigo et al. 2014) show that public understanding and awareness of the technology have been the most frequently analysed topic. The research consistently shows a lack of knowledge and familiarity with CO_2 and the process of CCS (e.g. Wallquist et al. 2012; Jeanneret, Muriuki & Ashworth 2014; Hobman & Ashworth 2013). However, this poor knowledge does not hinder individuals from forming an opinion about CCS, and often fosters misconceptions about the technology (e.g. Itaoka et al. 2013).

Risk perceptions and attitudes towards CCS are the next most investigated factors. The early research identified that perceptions of risk about CCS tend to be high – with a variety of stakeholders expressing concerns about the possible negative human and environmental impacts of the technology (e.g. Howell et al. 2012). The risk research also showed that risk perceptions can be modulated by local contexts and personal experiences with how different companies have operated in certain countries (e.g. Bradbury et al. 2011). Perceptions of risk have also been shown to be closely related to trust in information sources, which has also been examined in social CCS research (e.g. Ashworth 2010, Terwel et al. 2009).

Given the slow progress of CCS projects and the relative importance of understanding and gaining public support for CCS, socio-economic studies were deemed an essential component of the UQ-SDAAP project. The core objectives for this component included:

1. Undertaking an up-to-date assessment of current knowledge of and support for CCS across Australia
2. Identifying the factors and message frames that may enhance support for CCS
3. Understanding how CCS is being portrayed in the media
4. Undertaking knowledge sharing and comparative research with China.

It was always envisaged that as the UQ-SDAAP project progressed, the socioeconomic research would converge with the technical program of research. This eventuated through the more recent investigation into the public's response to enhanced water recovery (EWR) for the Great Artesian Basin (GAB) using managed aquifer recharge (MAR) processes with CCS, as opposed to the reinjection of water currently being trialled by the coal seam gas (CSG) industry.

Table 1 Project stages

Study	Timeframe	No. of participants
Analysis of global and Australian media coverage of CCS technologies 2003-2018	June 2017 – October 2018	N/A
Nationally representative survey of Australian public • Main sample • Communities of interest • Experimental conditions	June – August 2017	3402 • 2383 • 550 • 469
Focus groups investigating public and policy responses to MAR	October – November 2018	57
Message testing experimental workshops	December 2018	26
International survey in five countries (Australia, USA, UK, China and India)	February – March 2019	1000

The studies in the social program began with an analysis of global and Australian media coverage of CCS technologies from January 2003 to 30 September 2018 using Factiva as our database for articles. The main aim of the analysis was to examine how the volume and content of global and Australian media coverage of CCS had changed over time and in response to events such as project and policy announcements. The media, in all of its forms, has been shown to be a critical influencer on stakeholder attitudes. Whether it is those in positions of power or general public, the information being portrayed in the media can have a huge impact, both positive and negative, on attitudes towards a technology such as CCS. Therefore, examining how CCS is being portrayed in the media, the issues that are being discussed and by whom, are important factors when considering further communication and engagement activities.

The data analysed was a collection of 4668 media articles from 621 different sources. Globally, the volume of coverage of CCS started to grow in 2004 and reached its highest levels in 2007 and 2008. The volume of coverage dropped sharply in 2010, and has remained at relatively low levels ever since. Although relative to peak levels, the volume of coverage in Europe has not fallen as dramatically as it has in Australia and North America. The trends in volume and content of coverage over time within the Australian media were broadly similar. However, relative to the peak level, the volume of Australian coverage dropped to even lower levels than occurred elsewhere.

Spikes in coverage have in most cases been driven by announcements about policies and funding arrangements relating to CCS projects. The data also shows that globally relevant events, such as climate conferences, have generally not had much of an impact on the level of coverage of CCS. In Australia, the highest spike in coverage occurred in June 2008, when the federal Resources Minister, Martin Ferguson, unveiled a world-first legislative framework for CO_2 geosequestration – a move that came on the heels of BP and Rio Tinto abandoning a geosequestration trial project in deep offshore formations near Perth. The last significant spike in Australian media coverage of CCS occurred in September 2009, after the then federal Environment Minister, Peter Garrett, granted approval to the Gorgon LNG project.

The proportion of content relating specifically to geosequestration has declined since 2014. Meanwhile, the amount of content dedicated to other aspects of CCS, including carbon capture technologies and their integration with other industrial processes, such as cement and biofuels production, has been steadily increasing since at least 2004. Also becoming more prominent in the coverage is content about alternative carbon sequestration methods, such as direct-air capture and soil sequestration.

The most frequently discussed topics in the global media coverage can be classified under two broad themes: *energy governance* (including the regulation of emissions and fossil fuels, and the funding and subsidisation of CCS and other power generation projects) and CCS *projects*. Together, these two themes account for about half of the content in the dataset. The proportion of coverage devoted to energy governance has declined gradually over time, perhaps reflecting a lessening of involvement from governments in supporting, financing and regulating CCS projects. Another prominent theme in the coverage (accounting for 16% of all content) is climate and energy politics. The prominence of this theme declined between 2006 and 2013, but since then has been rising, and accounted for more than 20% of all content in 2018.

In the context of recent publications from organisations such as the Intergovernmental Panel on Climate Change (IPCC) and International Energy Agency (IEA), the findings of the study suggest that there is a disparity between public and expert views towards CCS. At the same time as prominent experts in climate and energy policy are calling for renewed investment in CCS in order to avert dangerous climate change, most media outlets appear to have largely lost interest in the technology, or view it with increasing scepticism. The extent to which the media coverage examined here is reflective of public sentiment towards CCS cannot be determined from this analysis alone. However, these findings highlight the possibility that any moves in the short term by governments to invest heavily in CCS could be met with opposition from a sceptical and uninformed public.

This disparity between public and expert views was reflected in the results of our national survey. To undertake an up-to-date assessment of the Australian public's current views towards CCS in the context of other energy technology choices, we ran, between June and August 2017, a nationally representative survey of individuals aged 18 years of age and older (n=3402). The survey questionnaire included a broad variety of questions to provide a solid contextualisation of the factors that are associated with public understanding and support for different energy sources and technologies. Key themes included: (i) knowledge about and support for different energy technologies; (ii) perceived risks and benefits of CCS compared to other renewable energy technologies; and (iii) perceptions about global climate change.

Our analysis of the results suggests that despite the increased media attention on issues surrounding affordability, energy security and supply, the Australian public's self-rated knowledge of the range of energy technologies has decreased since 2011, as has support for most energy technologies. The findings confirmed that support of an energy technology is influenced by exposure and familiarity, as well as local concerns and impacts, as demonstrated in attitudes that appeared to be regionally specific.

Overall, our results convey low levels of knowledge and support for CCS, combined with some concerns for risks of accidents in storing and transporting CO_2. While the key benefit of CCS was perceived to be reducing CO_2 emissions, the results demonstrated that less than half of the participants considered that the advantages of CCS as a carbon reduction option outweigh the risks it may pose. About one-third of participants either don't know whether the advantages of CCS outweigh the risks, or believe there are neither net benefits nor net risks to CCS. This suggests that more effort around increasing awareness and understanding will be needed if CCS is to be accepted as a beneficial technology for mitigating climate change as recommended by the IEA. Lack of understanding in the Australian general public may increase public opposition towards some new energy projects if there is no recognition of the benefits such projects might bring.

The survey also provided an opportunity to examine the relative effectiveness of alternative message frames in promoting better understanding and informed decision-making about CCS. A growing body of research has explored framing effects and prompts/cues on perceptions of climate change and support for climate policy, and is well established in the social sciences (Bernauer & McGrath 2016; Bolsen & Druckman 2018). However, there are fewer published studies in the area of energy sources and technologies (see Bolsen, Druckman & Cook 2014; Bruine de Bruin & Wong-Parodi 2014).

The specific objective of this study was to explore the impact of increasing the salience of frames that prompt a variety of motives or criteria upon which people based their support for energy technologies, with a particular interest in CCS. We did this by varying the first group of questions participants were presented with in the survey, thus altering the message frame. Our control group was given no information preceding the support questions. The four experimental frames were: Knowledge (objective and perceived); Cost and Reliability (economic trade-offs and reliability concerns); Climate Change (beliefs about the occurrence and causes of global warming); and Energy Behaviours (personal and household pro-environmental and energy efficiency actions).

When we examined the differences between levels of support for individual energy technologies according to the experimental condition, an interesting difference between the technologies arose. Compared to the control group, participants in the Knowledge frame reported a strong bias towards alternatives that perpetuate the status quo, demonstrating higher levels of support for conventional energy technologies that have been around for longer and with which the general population are most familiar, as well as those that are seen as reliable and more affordable. Surprisingly, similar results were seen in the Climate Change frame, regardless of whether participants did or did not believe that global warming is happening and is caused mostly by human activity.

Of all the experimental conditions, the Cost and Reliability condition demonstrated the least effect, and there were no significant differences in the support reported for different energy technologies compared to the "No Information" group. This suggests that economic issues, energy costs, and reliability are baseline factors people use when considering trade-offs and support for energy technologies. Most surprising was that the Energy Behaviours frame increased reported levels of support for nearly all energy technologies, notably for fossil fuel-related technologies, including CCS, nuclear and biomass – a group of technologies that typically receive the lowest support in other surveys. It was the only frame that significantly increased overall levels of support for CCS. However, support for renewable energies remained relatively constant.

One possible explanation is that when individuals realise the insignificance of their own personal contribution to reducing greenhouse gas emissions, there is a recognition for a suite of options to be used, including CCS. However, the reasons underlying this pattern of results is unclear, and points to the need for further research about the relationship between individual behaviours and levels of support for more radical structural changes, and the thought processes that influence that support.

Based on the significantly different results that arose from the Energy Behaviours frame, in December 2018 we ran some face-to-face experiments in UQ computer labs with three different groups of 8-9 participants (26 total). The aim was to further test the impact on expressed support for CCS and other energy technologies when leading with the Energy Behaviours frame, as well as including some information provision. A key consideration for this activity was to locate respected and trusted information sources (i.e. NGOs, experts, research) that were freely available in different formats (i.e. videos, internet fact sheets, and numerical tables and graphs). We tested levels of support for five energy technologies (coal, CCS, nuclear, solar PV, and wind) both before and after the presentation of varying combinations of information sources.

While the group sizes are too small to make any generalisations, our preliminary results from each of the experimental groups demonstrate that support for CCS increased in all groups, and appeared to be related to the types of information provided. We have used these early findings to develop an international survey of the general public, with 200 participants in each of five countries (Australia, USA, UK, China and India). The aim of this study is to further test the effect of both prompting participants with Energy Behaviour questions and varying the information sources to see if these preliminary results can be replicated on a larger scale.

Alongside our survey and media analysis studies, the social program's other area of focus was investigating public responses to managed aquifer recharge (MAR) and CCS in the GAB. A core component of the technical program has been assessing the potential of the Surat Basin for storing CO_2, especially because of its proximity to some coal and gas-fired power plants with an expected lifetime use out to the 2040s and '50s. To further test the concept of re-pressurising water in the GAB, the technical team have also undertaken modelling to see whether injecting CO_2 into the aquifer would bring about a similar result for enhanced water recovery (EWR). The early modelling results have been promising.

The social science literature indicates there is benefit in taking into account the social characteristics of a potential host site, and developing effective and appropriate stakeholder communication (Ashworth et al. 2015; Bruine de Bruin 2015). This study was also motivated by the understanding that a key issue for any technology is the trade-offs involved in the decision making to enable its deployment, including trade-offs between risks and benefits at the economic, social and environmental levels (e.g. Huijts et al. 2014). Therefore, it was timely to test the concept of using the injection of CO_2 for EWR on a range of stakeholders. The identified stakeholders included farmers, landholders and townspeople with an interest in the GAB, (being located in the Surat Basin area); as well as the general public living in Brisbane and therefore less impacted by the process; and Queensland policymakers.

We conducted seven focus groups in October and November 2018. Six of the focus groups were conducted in rural, regional and metro locations, and group size ranged from 4 to 12 participants; in total 47 members of the general public participated in the research. Another 10 people attended a focus group in Brisbane that was run specifically for policymakers.

The results of the focus groups demonstrate a mixed response to using CCS as part of an EWR process in the Surat Basin. Participants had generally low levels of knowledge about CCS, and their perceptions of CCS largely aligned with the survey results from our previous studies. While some participants were encouraged by the prospects of the process and indicated they believed the advantages of CCS outweighed the risks, it was clear across all groups that there were a number of concerns that would need to be addressed if public confidence was to be gained and the process endorsed. It seems that policymakers and the general public agreed on most of these concerns, which centred on safety, storage, maintenance of water quality, risks, costs, and governance issues (i.e. regulation, monitoring).

It was apparent from views expressed across the general public groups, and reiterated by policymakers, that there was a lack of trust in government and industry, compounded by legacy issues resulting from underground coal gasification in the Surat Basin. In addition, trust in science was mixed in the groups, with particular concerns about the ability of scientists to accurately assess the potential risks and the long-term consequences of new technologies, again due to legacy issues of technologies or innovations that were thought to be safe but proved not to be so (e.g. thalidomide and DDT).

2.1 Implications

As concerns increase about the world's slow progress towards the Paris COP21 target of keeping global warming to less than 2°C, it may be that CCS becomes more widely accepted. However, while prominent experts in climate and energy policy are calling for renewed investment in CCS to avert dangerous climate change, the collective results of our studies suggest that CCS remains largely unknown and poorly understood by the Australian public. It will require far greater communication efforts and investment if support for, and acceptance of, CCS is to become a reality. This is particularly so in terms of educating the public about the fundamental value of CCS in enabling grid stability and reliability through supporting synchronous generation from traditional fossil fuels. Communication about any of these topics will be paramount, and opportunities to raise awareness of such processes should be implemented in schools, at the community level and across larger society. If there was interest in raising awareness of the technology, it may be wise to proactively engage journalists and associated media outlets to encourage more sharing of information and discussion.

A major challenge is that the political and media debate in Australia has been polarised and polarising when it comes to climate change, energy policy, and associated long-term strategic and infrastructure planning. Our media analysis suggests that most media outlets appear to have largely lost interest in CCS, or view it with increasing scepticism. Our survey and focus group findings echo those of other recent studies that demonstrate low levels of public trust in the media and in the government (e.g. see Stoker, Evans & Halupka 2018). Public trust in institutions regarded as independent or neutral, such as universities and scientific organisations, is higher. However, when public discourse is fragmented, and scientists are perceived to be presenting opposing expert views on complex issues such as climate change, and which energy technologies should be prioritised for development and investment, people without high levels of energy literacy can struggle to know who to believe. These combined factors can contribute to public confusion, cynicism and disengagement from critical issues such as climate change mitigation.

Being aware of this broader social and political context is critical for informing effective communication strategies, as is understanding how the public accesses and processes information about energy technologies. Both the medium and the message may influence levels of support for, and acceptance of, energy technologies, and perceptions of the associated risks and benefits. Our findings demonstrate that using different message frames affects the reported levels of support for energy technologies in sometimes surprising ways. These effects remain largely ignored if no assessment or evaluation is performed of the messages and communications that industry, companies, universities and other stakeholders disseminate to the public.

As highlighted above, our results suggest that reliability, energy costs and economic issues are baseline factors used by people when considering trade-offs and support for energy technologies. Therefore, one recommendation might be to base messages on economic cost and affordability to reduce activating potential bias, and in a second order of priority, mention the collateral environmental benefits that the technology may bring. This may be a useful strategy for lesser known technologies, such as CCS, highlighting its potential economic benefits, and downplaying links to arguments of climate change mitigation and adaptation that may be more polarising. However, the success of this type of message reframing using alternative justifications that highlight technological, economic and personal benefits rather than reducing climate change risks is unclear (e.g. see Bernauer & McGrath 2016). It is important to take into account that people often have strong opinions on topics that they know little about, and once they have formed opinions, they process facts in a biased manner, consistent with these prior opinions (Druckman & Bolsen 2011 pp 681). Messages should thus be tailored to take into account individual beliefs about climate change and its causes, and individual values and norms.

These results will help to inform future research in this area, as well as policy recommendations and community engagement activities.

2.2 Suggested ongoing actions

There are a number of activities that will be required to overcome the low levels of knowledge about CCS that exist in society, particularly in regional areas across the Surat Basin, if the CCS hub project was to go ahead. We outline some of these activities below in no priority order.

2.2.1 Engaging with local communities

1. Clearly, there is a need to continue the **engagement in local communities** and explore in more detail individual concerns that arise from discussions around injecting CO_2 into the Great Artesian Basin. We recommend using the large-group process (designed by Professor Ashworth) because it has already successfully trialled across Australia, and subsequently in Canada, Scotland and the Netherlands. The process provides a way to maximise time and engage a larger group of individuals together, to allow the opportunity for everyone to hear a variety of views.
2. **Influential stakeholders across the region,** local council representatives, small business owners, and other community groups should be engaged in a more targeted fashion. Depending on the final proposed injection site locations, this could be through establishing community interest and advisory groups that serve as a reference point into communities.
3. **Local employees of power plants and associated mines** – there is no doubt this is an important stakeholder group that needs to understand the risks to them of power plant shut downs, and the opportunities that could arise from investment in a CCS hub. This engagement could be a mix of face-to-face and print material that is openly shared across the region.
4. **Schools** also form a good vehicle to raise awareness about CCS and where it fits in the portfolio of mitigation options. Different materials have already been developed that could be easily adapted and implemented over the school year.

2.2.2 Awareness-raising at the national level

1. While **media coverage** has dropped considerably to be almost non-existent, there is an opportunity to provide **more active blogs about CCS** in the portfolio of responses to climate mitigation. However, the focus of the blogs should centre on the need for baseload power, the jobs and services that would be sustained in the region, and economics over time. Ideally, moving the discussion away from us versus them would be helpful.
2. It will be important to **engage influential stakeholders,** politicians, journalists and financiers on the opportunities presented by following on the UQ-SDAAP project and just what it entails. Similarly, this would take consistent and repeated engagement but should not be overlooked.
3. **Policymakers, both state and federal,** will need to be included in the discussions about latest requirements and changes around regulatory requirements and how this can be managed.

2.2.3 Monitoring of attitudes

1. The national survey with an overemphasis on regional Australia provides good insights into ongoing knowledge and awareness of CCS. This should continue with a replication of the previous survey in 2019 to allow comparisons over time. It can also allow testing of whether any of the targeted community engagement is increasing knowledge and awareness over time.

A clear regulatory pathway needs to be progressed beyond the appraisal stage. UQ-SDAAP suggests a taskforce approach working with the Queensland Government.

3. Regulatory

The large-scale implementation of CCS requires the development, adaptation or modification of Queensland's existing greenhouse gas (GHG) and environmental and water regulations. A regulatory roadmap needs to be constructed with the Queensland Government. Furthermore, interaction (if any) with the federal *Environment Protection and Biodiversity Conservation Act 1999* needs to be defined.

The UQ-SDAAP study found that it would be important to conduct early engagement with the regulator in five key areas:

1. Whether a waste stream of CO_2 would be classified as an "end-of-waste" product or not
2. Whether deep aquifer storage of CO_2 could be considered a public amenity. It is important to note that managed aquifer recharge (MAR), as practiced by coal seam gas operator APLNG, is considered "beneficial use"
3. Whether remote pressure inflation or water level increases off-tenement would be recognised as a benefit, and could be allowed through some appropriate instrument
4. Whether this benefit and/or GHG emissions mitigation could be argued to trade off against what might be classed as environmental "harm" or changes to localised groundwater quality
5. It may be that water licences held by or offered in future to resource companies and, to a lesser extent, stock and domestic users (and Aboriginal and Torres Strait Islander people) may need to be restricted from the injection reservoir in the local injection area to prevent interference with an emplaced CO_2 plume

A clear regulatory pathway needs to be progressed beyond the appraisal stage. UQ-SDAAP suggests a taskforce approach working with the Queensland Government.

4. Economy

The future of electricity supply in the NEM is evolving, plans are afoot to implement significant new capacity of intermittent renewables. Low emission solutions for large-scale, *baseload* capacity are not available, concerns are growing for both power prices and emissions targets. The UQ-SDAAP research outlines the possibility for both low emissions baseload and material annual emissions reductions.

Retrofit options have been investigated for the three modern supercritical coal-fired power plants in the UQ-SDAAP region. Deployment has been modelled in which the plants are partially retrofitted in sequence. This minimises disruption to baseload power generation, shares the disruptive load across plants/owners, allows for maximum learning between retrofits, and also allows for a large investment to be broken down into several smaller incremental decisions, each of which could enable either full deployment, a pause in developments, or a complete halt. A series of plausible scenarios exist, with significant opportunity to accelerate deployment if required

Material abatement. Given injection rate constraints, a conservative, lowest risk, minimum-footprint storage development could safely accept about 12.7 million tonnes pa (reference case reservoir). Notwithstanding social and regulatory challenges, it may be technical feasible to capture and safely store the majority of the CO_2 emissions from these plants, starting from around 2032 up to (and beyond) their estimated technical lifetime (2052-57). Uncertainty on deployment scheduling and pace is mainly related to the challenges in accessing financing, lack of a clear regulatory pathway and the need for a first-of-a-kind environmental impact statement (EIS) for CO_2 storage in the deep Precipice aquifer. Nevertheless, there is a technical possibility of significant additional injection potential remaining for 20–30 years beyond 2060, allowing for either extensions, or for new builds, or for capture from CCGT gas plants in the area, pending the observed injection reservoir performance during initial stages.

Regional jobs development. A CCS hub development project, as described in this study, represents a major industrial enterprise. In addition to generating jobs during the design phase, a significant number of regional jobs would be created through the lengthy, sequential, retrofit construction phase. In addition, the emplacement of CCS infrastructure and a reduction in emissions intensity may safeguard existing jobs related to generating power or providing fuel for the three power plants (and the many "multiplier" jobs in the regional communities). This could create about 250 new regional jobs in the retrofit and construction phase, as well as either safeguarding, or even extending the need for, about 500 existing regional jobs in the power plants and adjacent mines (Gamma Energy Technology 2019). Indirect employment multipliers in the local economy have not been assessed in this study, however previous work has suggested this would be statistically significant (Fleming & Measham 2014), and in the range of 1 to 6 (Knights & Hoods 2009; Rolfe, Lawrence & Rynne 2011).

Enabling higher GHG industries (e.g. Hydrogen). CCS is seen as an enabler for other high emitting industries. This could include cement or urea manufacturers (e.g. from natural gas). However, it is also likely to be critical for a future hydrogen economy. There are generally four methods for producing hydrogen (i) coal gasification; (ii) steam methane reforming to produce hydrogen directly; (iii) steam methane reforming to produce ammonia as a hydrogen carrier fluid; and (iv) electrolysis (possibly using renewables). Queensland is well situated for each of these methods. However, the first three require a CCS solution to generate "green" hydrogen.

Low emissions baseload power. An additional benefit to a large-scale CCS scheme as outlined by this research, is the creation of low carbon emissions intensity (ca.135 kg CO_2 per MWh), baseload power generation. The value of this, in a grid in which intermittent renewables form an increasing proportion of generating capacity, is like to be substantial. This value is in terms of both ensuring security of supply as well as keeping a downward pressure on power prices. The NEM currently has approximately 27 GW of installed fossil fuel baseload power. Without any new builds, by 2035, this may be reduced to 12.4 GW through a normal retirement process. The three Queensland super-critical, coal-fired plants in this study have a combined capacity of around 2.05 GW. They currently emit about 16 million tonnes of CO_2 pa. This currently represents about 8% of current baseload capacity, however, this baseload-share is projected to rise to 17% by 2035 (40% by 2050), other things all equal. By 2035, the plants would represent around 37% of Queensland's NEM emissions if they remain unabated.

A recent paper, *Net Zero Emissions Electricity. A total system cost approach for Queensland* (Boston, Bongers, Byrom & Garnett 2019) investigated total system costs (TCS) for the NEM in the future. The approach was to seek a minimum TCS pathway to a goal of deep decarbonisation as old fossil fuel plants are replaced. It was constrained to ensure stability i.e. that "*the lights stayed on*".

The lowest cost path in that study indicated that relying solely on intermittent renewables beyond around 40% emissions reduction, leads to major power price increases because other measures (typically gas-fired power) need to be built to compensate for intermittency. It showed that beyond 40% decarbonisation, there may be an important role for gas. However, it also demonstrated that CCS will be essential to enable **deep decarbonisation** of the NEM beyond about 70%. The authors concluded that CCS development must commence early to enable adequate deployment, with the aim to commence in the late 2020s.

Stage gated investments. Moving forward, an investment of $30 to $100 million[1] is now required, spread over the next 3-4 years to progress all the recommended action themes (section 7). These are conservative (high) estimates, the lower bound relates to the situation where un-expectedly low quality reservoir is encountered on drilling a new data gathering well (or there is no progress on regulations). It is expected that the action themes will then enable a major project to be defined. A further some $100 million might then be required, spread over 4-6 years to progress to a final investment decision (FID). Again this is a very conservative estimate. As well as the necessary environmental, engineering and sub-surface study costs, it includes a significant allowance for drilling deep aquifer monitoring wells which might be needed for baseline easements as part of the EIS process. The first FID (late 2020s) would be for approximately $1 billion, spread over a 3 year period, to construct a 50% retrofit of one of the main super-critical, coal-fired power plants. Subsequent, incremental retrofit decisions are of similar order.

Assuming appraisal and regulatory development are successful, the subsequent work can be considered to be part of the deployment project proper. For such a project, the unit technical costs of CO_2 injection (abatement) are in the range $57 to $75/tonne, though considerably more engineering work is required to validate these estimates. Storage and transport costs combined are in the range of $10 to $20/tonne, limited by the lifetime of the retrofit assets rather than the ability to continue to accept high-rate injection. Extending the injection period at similar rates for 30 years could reduce these costs by around $2 to $3/tonne.

Levelised costs of electricity (LCOE) for fully retrofit plants are around $70/MWh. Importantly, engineering factors which require capture plants to be run at as much possible at steady rate; along with the intent to minimise emissions, suggest that **a new market position and dispatch rules will likely be needed for retrofitted CCS plants** (this in agreement with extensive work previously done on an IGCC plant with CCS in Queensland, Garnett et al. 2012 and as further discussed in Greig et al. 2016b).

Major hub development will rely on public financing to a large degree. This is in itself a major risk factor. We agree largely with Kapetaki & Scowcroft (2017), who concluded in their review of business models, risk and enablers that "...successful CCS project development depends on multiple factors, such as (i) clarity of regulatory frameworks, (ii) efficiency of permitting processes, and (iii) early and sustained stakeholder engagement for public acceptance. However, project finance remains the most challenging piece" (*ibid*, p6623).

A suitably qualified special project entity would be required to progress this, possibly along the lines of the structure used for the ZeroGen project which remains the structure which has achieved most project maturation activity in the minimal amount of time.

1 All figures are real terms 2018 dollars unless otherwise stated.

5. Techno-economic

The techno-economic assessment is based on a fundamental revision of the Precipice Sandstone and Evergreen Formation geological characterisation in the deepest and oldest parts of the Surat Basin. The concept of a sub-surface "container", where CO_2 may notionally be injected at high rate for a limited period of time to be securely and indefinitely stored, is termed the Storage Complex. While CO_2 is not currently sequestered in the Surat Basin, there is substantial evidence from many different and independent sources that support the case for secure long-term storage in the Precipice Sandstone Formation. For CCS to be a valid climate change mitigation approach, there not only needs to be high confidence in containment, but also it must involve material rates of CO_2 injection. Again, there is substantial and diverse evidence that suggest relatively high rates can be achieved and sustained.

The UQ-SDAAP geological, geophysical and petrophysical investigation used all relevant available data – core, wireline log, well test, and seismic – to assess the Carbon Storage "Play" in the Precipice Sandstone and Evergreen Formation of the Surat Basin. The following key findings were made:

- Nine wells with significant sections of core from the Precipice Sandstone and Evergreen Formation were used to identify 19 sedimentary facies grouped into five main facies associations corresponding to: (1) braided channel complex; (2) lower delta plain; (3) subaqueous delta; (4) tidal flats; and (5) shoreface. These defined the paleoenvironmental interpretations used to aid sequence stratigraphic correlations across the basin. The facies and facies associations were used to construct the sequence stratigraphic framework by identifying depositional hiatuses
- The facies interpretation of core data was compared to wireline logs to define equivalent electrofacies that could then be identified in wells with petrophysical logs but no core. These together constrained the interpretation of depositional environments consistent with the observed facies within an overall sequence stratigraphic framework that includes the following points:
  - The Blocky Sandstone Reservoir covered a large central part of the Basin, and was dominated by sediments deposited within a braided plain system
  - The Transition Zone strata recorded a rapid base level rise where meandering river, delta plain, and subaqueous delta (delta front and prodelta) deposition became dominant. Basinal facies were limited to a narrow belt in the central basin. Many large-scale deltas were building at this time towards the central basin. Overall, the stratal stacking patterns are indicative of progressive backstepping of depositional environments up-section and towards the basin margins
  - The Ultimate Seal strata represent a period when the entire basin became heavily influenced by marine processes, and marine water flooded the central and the north-eastern parts of basin. Through time, the eastern provenance was flooded and became the epicentre of oolitic shoals. Shorefaces mainly develop in the northeast, facing the open sea, whereas the tidal environments were restricted mainly to a narrow strip in the south
- The core and wireline facies were mapped to synthetic seismograms at each well, and calibrated with the actual seismic to define the correlatable horizons. The seismic interpretation provides critical data control away from wells that serves to constrain the uncertainty of the static geological model. It has also identified some geometric features of the various sequence stratigraphic intervals that have important implications to the anticipated flow behaviour of the defined container. These include the following:
  - The Blocky Sandstone Reservoir has limited geographic extent, and pinches out against the sub-Surat Unconformity to the western edge of the Surat Basin and to the south into New South Wales. The eastern edge becomes thin, filling in the topography of the sub-Surat Unconformity surface but also extending to the east (south of the town of Roma), apparently into the Clarence-Moreton Basin. This geometry restricts the reservoir volume and, thus, will affect the anticipated pressure response to material CO_2 injection
  - The seismic reflectors within the Transition Zone interval are discontinuous. This corroborates the facies interpretation that suggests the geobodies of these depositional environments are of limited lateral extent. The anticipated fluid response would be for limited vertical migration of CO_2 and limited transmission of pressure through a geological system of discontinuous baffles
  - The Ultimate Seal strata marks a return to regionally correlatable seismic reflectors that are more geographically widespread than the underlying extent of the Blocky Sandstone Reservoir. This suggests that the Ultimate Seal is likely to have regionally continuous geobodies, unlike the Transition Zone below. In addition, its sealing characteristics are more widespread than the distribution of either the Transition Zone or Blocky Sandstone Reservoir below

- The palynology data provides increased confidence in the sequence stratigraphic correlations, and confirm that the combination of matching sequence boundaries in core and on log analysis linked with regionally correlatable seismic reflectors produced time-correlative sequence stratigraphic interpretations consistent with depositional processes that then have higher predictability away from well control. The data is also consistent with the depositional environment interpretations from core and wireline facies
- The occurrence of faults near a commercial-scale carbon storage project are important because they present both a risk of up-fault or across-fault leakage of CO_2, or if the fault is of low permeability, the fault could present a pressure transmission barrier that limits the reservoir volume and allows the injection reservoir pressure to increase sooner than anticipated. Both could negatively impact on the CO_2 storage project. The structural analysis in the UQ-SDAAP project includes both juxtaposition and fault reactivation analysis. The main findings include the following:
  - The region around the notional injection sites are relatively unstructured, however the potential for small-throw, strike-slip, high-angle faults has been identified
  - Small-throw basin-centred faults generally do not pose a juxtaposition across fault leakage risk
  - Previously mapped large-scale fault trends in the Bowen Basin are reactivated to various degrees in the Surat Basin, often with only a loose mechanical linkage
  - The Moonie field provides a good case study due to the availability of 3D seismic coupled with the hydrocarbon migration history
- The petrophysical analysis provides the UQ-SDAAP analysis with an important methodology for populating the static geological model cells with geologically realistic porosity and permeability values that are constrained by well control and facies analysis, and have been calibrated with core plug analysis and well test data, such as drill stem tests (DSTs). Importantly, the petrophysical analysis also provides an uncertainty quantification that allows for a low, medium, and high scenario to be applied that feeds uncertainty analysis of the dynamic simulation
- Importantly, 10x10 sector models were developed to provide UQ-SDAAP with a range of three realistic geological conceptualisations for the notional injection located, defining the range of uncertainty in the facies models and paleo depositional environments. For each of the three realisations, there was also a low, medium, and high rock property scenario based on the uncertainty defined in the petrophysical analysis. Together, this provides nine combinations of geological scenarios and rock property parameterisation with which to run dynamic simulations of notional CO_2 injection
- Finally, although a large-scale CO_2 injection and storage operation may have a small physical sub-surface footprint (<10 km) where the CO_2 can move to, the induced increase of pressure, is transmitted much further. The direction and magnitude of pressure inflation needs to be assessed across areas far greater than those typically modelled in reservoir simulators. For this, regional structural and stratigraphic variability need to be defined over hundreds of kilometres in a regional geological model

All the technical geological evidence and analysis described above informs an identification of the best (lowest containment risk) notional injection sites. While detailed pipeline studies are beyond the scope of this study, as a sense check, sensitivities and notional pipeline routes have been investigated from the three main power plants (Millmerran, Kogan Creek and Tarong North) to the lowest risk storage sites.

The safe development of any natural resource is dependent on a combination of the given geological parameters and of engineering choices made, such as well location, well trajectory, well count, site facilities operations, and flow assurance. Storage sites will need to be operated within carefully defined pressure constraints, and these, together with the development plan, will dictate the final estimates of sustainable injection rates, duration of operations, and the basis of design for capture plants. Notional injection development scenarios are devised, which assume a ramp-up period as power plants are sequentially retrofitted, followed by continued injection for a sustained period of 30 to 40 years. Most importantly, iteratively and in conjunction with the development of notional injection plans, the groundwater impact of such a development both in the near-field and the far-field has been investigated. Sensitivity analyses to remaining parameter uncertainty is then described.

The conclusions are that large-scale injection of around 13 Mtpa for around 30+ years can likely be securely stored by injecting into the deepest, lower-most aquifer of the Surat Basin, by transporting captured CO_2 by pipeline to just two or three remote well pads. However, more site-specific data is required from these notional injection sites to increase technical confidence before development decisions can be made. Retrofit and deployment scenarios have been investigated and costed, and the staging and size of the main investment decisions have been estimated.

5.1 The storage complex

For climate change mitigation to be accomplished through CCS, the large majority of CO_2 injected into the sub-surface must be securely contained indefinitely. To demonstrate containment requires the definition of a "container". To analyse leakage, risk must be within the context of this defined container. A container comprises the intended injection and storage reservoir and an overlying seal or seal complex that defines a vertical extent. The container also requires defined, lateral boundaries. If CO_2 migrates above the seal complex and/or beyond the lateral boundaries, it can be considered to have "leaked". For clarity, this is not the same as causing "damage", either in terms of the local environment or in terms of increased emissions to the atmosphere. Even in these cases, there are many mechanisms that will cause the CO_2 to become trapped or fixed (e.g. residual or mineral trapping). Furthermore, to define "damage" requires an assessment of the amount leaked and the sensitivity of the receiving environment. In any case, a container should be selected and defined as having very low risk of any leakage (and thus significantly lower risk of "damage").

The Storage Complex proposed for notional commercially significant CO_2 storage in the Surat Basin comprises the Blocky Sandstone Reservoir (roughly equivalent to the Precipice Sandstone) of the lower-most Jurassic as the injection/storage reservoir. Notional injection sites are located in the deepest part of the basin where the strata are relatively flat lying. The injection reservoir is overlain by a seal complex that comprises a thick Transition Zone (acts as a baffle or buffer) and an Ultimate Seal (roughly equivalent to the Evergreen Formation). The lateral extent of the Storage Complex will be defined as the furthest modelled extent of an emplaced plume plus a margin. This is expected to be a distance of about a 10 km radius from an injection well site.

In addition to the geological storage complex within which the injected CO_2 will be contained, a CO_2 injection project must also consider the impacts of CO_2 injection and storage beyond its boundaries (i.e. beyond the CO_2 plume itself). This sub-surface physical boundary is referred to as the "area of review" in the Canadian Standards on geological storage of carbon dioxide (CSA Z741 2012).

5.2 Evidence of containment

UQ-SDAAP examined a number of lines of evidence regarding the likely seal performance of the Transition Zone and Ultimate Seal, including the following:

- The facies analysis, stratigraphic correlations and depositional environment interpretations based on core, wireline petrophysical analysis and seismic interpretation suggest that the Transition Zone becomes less sandy (more mud prone) towards the centre of the basin, and stratigraphically younger as part of an overall transgression and onset of marine conditions. This is corroborated with the petrophysical analysis calibrated with core analysis and DST well test interpretations of permeability. While the lateral continuity of the geobodies (both the sandy and muddy ones) in the Transition Zone are limited, the reverse is true for the Ultimate Seal, where a marine transgression resulted in widespread deposition of the very low permeability Westgrove Ironstone Member and subsequent mud units
- The hydrocarbon systems analysis demonstrates commercial hydrocarbon accumulations on the eastern and western basin margins below the Ultimate Seal. These include the Moonie field as well as the hydrocarbon accumulations on the Roma Shelf. The accumulations that occur within various sandy units of the Transition Zone are generally isolated both vertically (i.e. not vertically continuous between stacked sands) and also laterally. This corroborates the facies analysis, stratigraphic correlations and depositional environment interpretation for the Transition Zone strata as having generally low permeability with both sandy/silty geobodies, as well as low permeability muddy geobodies forming baffles and barriers, none of which are laterally continuous. The hydrocarbon migration indicators in the Hutton Sandstone generally are coincident with major fault zones, suggesting that some fault segments may have transmitted hydrocarbons vertically across the Evergreen Formation over geological time
- The regional hydrogeological analysis identified that the Blocky Sandstone Reservoir and the Hutton Sandstone aquifers discharge to the Dawson River low topography boundary condition where the surface elevation is less than 200 m above sea level (ASL). The Blocky Sandstone Reservoir may also discharge eastward into the Clarence-Moreton Basin to outcrop in the Lockyer Valley at surface elevations of less than 250 m ASL. This is supported by surface water and spring hydrochemistry and isotope chemistry. Finally, the Blocky Sandstone Reservoir may discharge to surface via up-fault hydraulic communication along certain segments of the Moonie-Goondiwindi Fault system to surface topography less than 250 m ASL. There is, however, no hydrochemical indicators found in the current surface water (river drainage). Regionally, there is generally a difference in hydraulic head between the Blocky Sandstone Reservoir and the Hutton Aquifer System of more than 5 m (see OGIA 2016 and this report) suggesting that the intervening Transition Zone and Ultimate Seal act regionally as a seal

- Fault seal analysis suggests that the faults in the Surat Basin are generally not critically stressed, with fault reactivation pressure threshold well above the formation breakdown pressures. Juxtaposition analysis of potential basin-centred low-offset strike-slip faults do not provide across-fault leakage potential, however similar analysis of the Moonie fault segments suggests the potential for juxtaposition of Blocky Sandstone Reservoir against the Boxvale Sandstone Member (within the UQ-SDAAP Transition Zone)
- Although historical oil and gas exploration wells and groundwater extraction bores provide a vertical leakage risk for carbon storage, the well density dramatically decreases towards the basin centre where notional injection sites have been identified. The site locations were selected using a philosophy of risk avoidance (i.e. staying a minimum lateral distance away from historical well locations and known faults)
- The reactive geochemistry analysis applied to predicting any changes to permeability suggest that the Transition Zone and Ultimate Seal would, if anything, promote precipitation of carbonate minerals that would further reduce permeability
- Fracture analysis of core and image logs suggests that natural fractures occur in higher density near major faults such as the Moonie-Goondiwindi fault system. These also show evidence of paleo fluid-flow events in the diagenetic history observed in thin section microscopy. This corroborates the hydrocarbon systems data of up-fault fluid migration potential over geological history
- Mercury Injection Capillary Pressure measurements on core samples from the Transition Zone indicate high capillary entry pressures well in excess of any anticipated CO_2 column height that might be generated by notional CO_2 injection. In the case of the Moonie oil field, the calculated seal capacity is well in excess of the observed oil column height, suggesting that the Moonie oil field free-water level is controlled by fault seal rather than top seal limitations

Collectively, the evidence would suggest that the Transition Zone is of generally low permeability, but with geobodies of limited lateral continuity that will likely allow a small portion of vertical migration of injected CO_2 and pressure transmission. The overlying Ultimate Seal provides an ultra-low permeability regional sealing unit with lateral continuity. The locations where the Transition Zone and Ultimate Seal may have vertical seal capacity compromised is at historical well locations and along certain fault segments.

The overlying Ultimate Seal provides an ultra-low permeability regional sealing unit with lateral continuity.

5.3 Evidence of injectivity

UQ-SDAAP examined a number of lines of evidence regarding the likely Blocky Sandstone Reservoir injection performance, including the following:

- The facies analysis, stratigraphic correlations and depositional environment interpretations based on core, wireline petrophysical analysis and seismic interpretation suggest that the Blocky Sandstone Reservoir represents a widespread clean sandstone deposited in a large high-energy braided plain depositional environment. This occurred in a northern and southern depositional centre each with different provenance. The northern depositional system is characterised by a “cleaner sandstone”, with less clay content and higher matrix permeability. Conversely, the southern depositional system has more clay and relatively lower permeability
- The managed aquifer recharge groundwater inversion focused on the northern depositional centre confirms not only the high matrix permeability of the Blocky Sandstone Reservoir but also a secondary fracture permeability resulting an extremely high bulk permeability (100s of Darcy equivalent)
- Fractures in core have been observed in the vicinity of major fault systems of the southern depositional system. The Moonie oil field production history match requires a higher bulk permeability assumption than is justified from the petrophysical analysis. It is speculated that the difference is due to fracture permeability associated with a damage zone near the Moonie Fault. This is corroborated by the strong aquifer support and the relatively low formation pressure drawdown that has occurred with ~30 years of Moonie oil field production
- The well test (DST) analysis, core and petrophysical analysis define a range of bulk permeability for the Blocky Sandstone Reservoir in the southern depositional centre that corroborates the facies analysis, stratigraphic correlations and depositional environment interpretations
- Thermal and geomechanical modelling of the notional injection locations in the Blocky Sandstone Reservoir of the southern depositional centre define the formation breakdown pressure, taking into account thermal cooling of relatively cool CO_2 being injected into relatively warm reservoir rocks. The modelling defines bottomhole pressure constraints and drive a well design that favours well pads with 3-4 km radial horizontal wells to maximise the injectivity and to reduce the surface footprint.

The combination of evidence on injectivity would suggest that large-scale injection of around 13 Mtpa for about 30 to 40 years can likely be securely stored by injecting into the Blocky Sandstone Reservoir (the deepest, lower-most aquifer of the Surat Basin) at two or three remote well pads via up to six 3-4 km horizontal wells per pad.

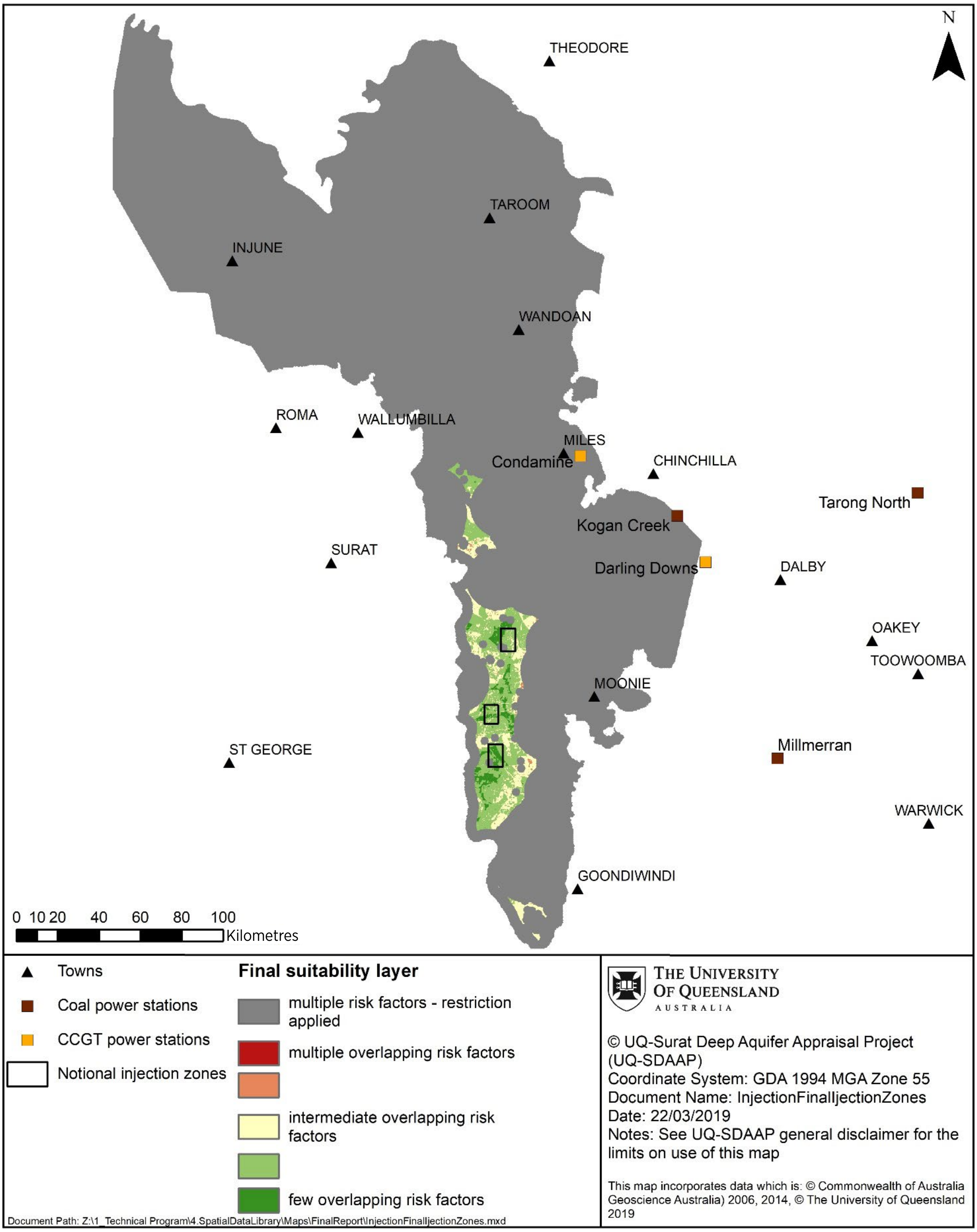
5.4 Notional injection site identification

UQ-SDAAP has adopted an approach to notional site selection based on minimal containment risk, and not on optimal economic grounds. The main approach has been to maximise the distance between possible injection sites and potential risk features and the potential users of other resources; and to maximise depth. For clarity, sites discussed in this section are *not* yet proposed for full-scale injection; rather, they are the key sites where further data is required *before* suitability can be *confirmed,* and any final selection decision can be made. Extensive but fairly conventional data gathering is required at the next stage, similar to oil and gas exploration and appraisal phases. This data gathering will include seismic, drilling, logging and testing; but it will not require the injection of any CO_2 into the aquifer (and not any hydraulic stimulation).

We chose three locations within the bottom part of the Blocky Sandstone Reservoir as notional injection locations for use in the UQ-SDAAP project analysis. The choice was based on the suitability of the area and the proximity to power stations, so that the length of the pipeline between the injection site and the power station could be deduced (Figure 2). All green areas within the bottom green-to-red zone represent a location that, given current data, has *demonstrably the lowest, practicable risk* for CO_2 injection. Any appraisal program for this area should therefore cover the bottom green-to-red zone to reduce uncertainty in the data used to perform this analysis and narrow down the most suitable areas.

Detailed pipeline network design and planning was outside the scope of this project. However, the feasibility of material carbon abatement through CCS relies on the ability to license suitable transport routes from sources to sinks. This required at least a scoping study and sensitivity analysis of several pipeline routes to investigate the main likely variables and options. Depending on environmental values, which would ultimately be agreed upon after public consultation and with the Queensland regulator, there are reasonable options for pipeline routing that can minimise disturbance of higher value land and make maximum use of existing easements. There are no obvious showstoppers.

Figure 2 Final suitability (low-risk) map with notional injection locations and key power stations.



5.5 Notional injection site modelling and field development plan: reference case

One of the main challenges affecting UQ-SDAAP was the lack of sub-surface data available from the areas identified as notional sweet-spots for injection. This was overcome by using properties of the Blocky Sandstone Reservoir, Transition Zone and Ultimate Seal in the areas where data was available. Adjustment of properties was based on geological trends in depth and sandiness to represent the expected properties in the notional injection areas. The resulting estimates of these properties were then used to populate dynamic simulation models. The estimated properties could not be validated (and will not be validated without further data acquisition), and for this reason, significant uncertainty remains about the properties of the reservoir in the notional injection areas.

UQ-SDAAP used two approaches for addressing these uncertainties. The first involved creating a range of static reservoir models with properties that envelop the expected variation in porosity and permeability. These were, in turn, used in dynamic simulations, and allowed UQ-SDAAP to identify notional development plans that appear to be technically feasible in the circumstances represented by each of the models (Ribeiro et al. 2019b).

A second approach described here involves simulating the notional injection using the base case reservoir properties used in notional field development plans, but modifying key parameters one at a time for each simulation. This task was performed using CMG's CMOST software (CMG 2018a). Simulation results were analysed to assess the impacts of changes in reservoir properties on two key sub-surface criteria for such a project:

1. Injectivity – If different reservoir properties were encountered, injection rates and, thus, the number of wells required to achieve the desired injection volume would change, which would therefore affect the cost of the notional CCS project. As some of the cases were unable to achieve the desired injection, the results are presented in terms of tonnes of CO_2 injected per well, where higher values would typically be associated with lower cost per tonne.
2. Containment – One concern that often surrounds CO_2 injection projects is migration of the CO_2 plume after injection. The supercritical CO_2 plume area (km^2) is presented for each simulation to indicate the parameters that most significantly affect CO_2 movement within the Blocky Sandstone Reservoir (i.e. lateral containment). In addition, the percentage of the injected CO_2 that migrates vertically from the Blocky Sandstone Reservoir into the Transition Zone is used as a measure of the impact of each parameter on vertical containment.

Comparisons of these results for the various simulations are intended to help identify the parameters that would be expected to have the most significant impacts on likely success of a CCS project in the Surat Basin, and thus inform a data appraisal program.

Two different injection scenarios were used as reference cases for the subsequent sensitivity study. Both used the base case UQ-SDAAP notional injection sector model (Gonzalez et al. 2019b), but with different CO_2 delivery schedules. Details of the notional injection sector reference case can be found in Roger et al. 2019f.

5.5.1 Injection scenario 1

The first schedule was based on injection of CO_2 from two power stations: CO_2 from Millmerran (M) into the two notional injection sites in the south; and CO_2 from Kogan Creek (K) into the notional injection site in the north. The estimation of CO_2 mass rates from these power stations was based on current emissions, and CO_2 delivery to the notional injection sites was staged to represent retrofitting of the power stations as the notional injection project progressed.

Injection started first in the south, then alternated between north and south, with rate increases in years 3, 6, and 9 as the notional retrofit sequence progressed (Table 2). Each injection "stage" lasted 30 years before the injection rates were stepped down, eventually stopping completely in year 39. This resulted in a total peak injection rate of 9.2 Mtpa for 21 years.

Table 2 Mass rates for MKMK schedule

Year	0	3	6	9	...	30	33	36	39
North Injection Rate (Mtpa)	0	2.2	2.2	4.4	...	4.4	2.2	2.2	0
South Injection Rate (Mtpa)	2.4	2.4	4.8	4.8	...	2.4	2.4	0	0

For the MKMK schedule, a wellhead pressure constraint of 15,000 kPa (150 bar) for all wells was used as the reference case. Based on this constraint and the base case reservoir model, a notional development plan was created after testing various configurations of well count, length, and layout (Ribeiro et al 2019b). The notional development plan for this scenario required three horizontal wells at the north notional injection site, and two horizontal wells at each of the south notional injection sites.

UQ-SDAAP have assumed an N+1 redundancy philosophy, where one additional well would be drilled at the north notional injection site, and one additional well at one of the south notional injection sites, which would mean two additional wells on top of these would be required to reach the injection targets. These additional wells would provide more injection capacity such that injection could continue if any well became unavailable, whether this was planned or unplanned. This is defined in the sensitivity study. This meant nine wells were defined for all MKMK simulations (Table 2), although not all wells were opened in every simulation.

Figure 3 Well layouts for the MKMK schedule. Refined cells are visible around each well. The apparent "wobbling" of some of the north wells is due to these refined cells, but is not expected to affect the results of this particular study.

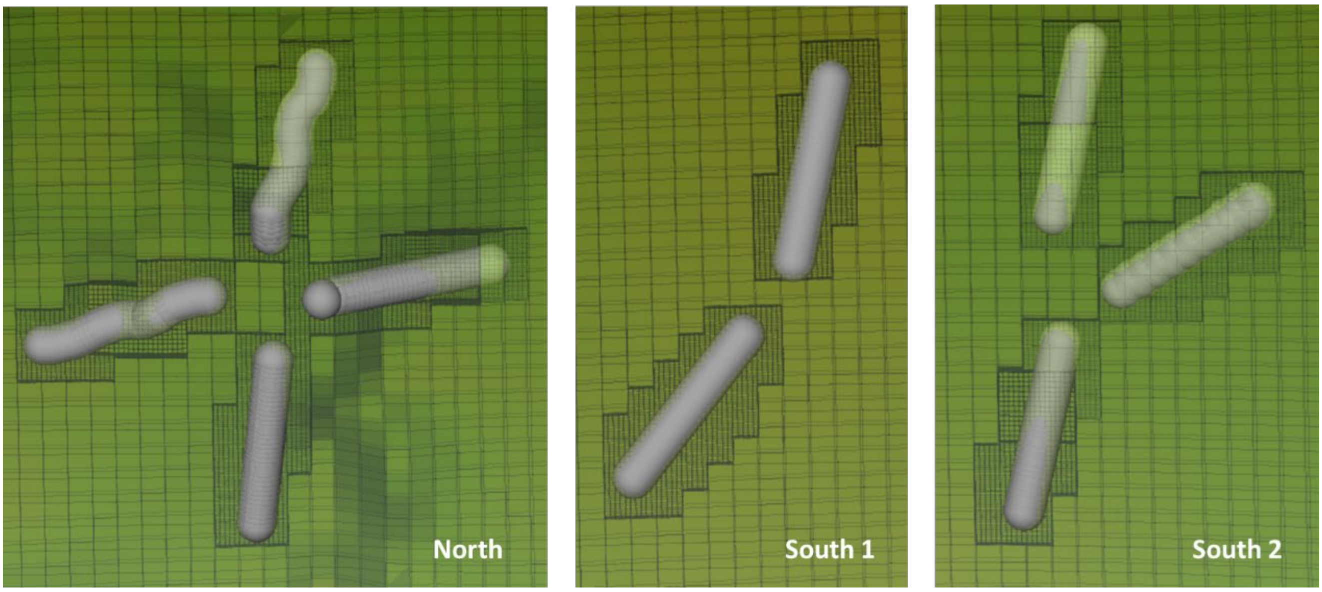
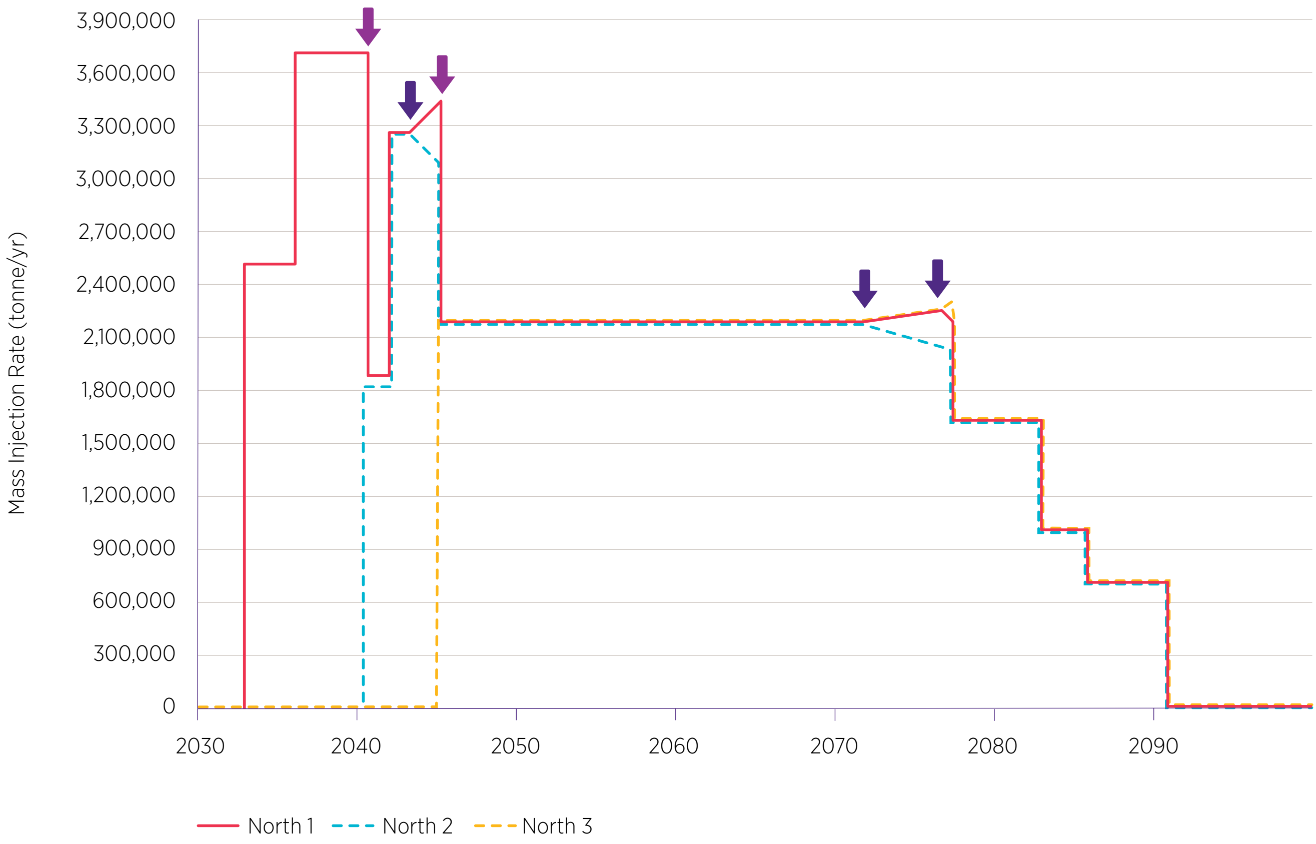


Figure 4 shows the mass injection rates for the north notional injection site and MKTMK extended delivery schedule. The arrows indicate points where wells become limited by a pressure constraint, in this case, wellhead pressure. If another well is already injecting when this happens, the injection rate per well is redistributed to sustain the overall mass rate (blue arrows). If all currently injecting/open wells are limited by a pressure constraint, the next well in the queue will open and start injecting (red arrows).

Figure 4 An example of CMG GEMs AUTODRILL control for wells at the north notional injection site and MKTMK extended delivery schedule. Most of the time, all wells inject at the same rate. Arrows indicate points where wells become limited by wellhead pressure, and either: (A) Injection is redistributed to other wells (blue arrows); or (B) All currently open wells are pressure limited, so the next well in the queue is opened and starts injection (red arrows).

Northern Site Mass Injection Rates



5.5.2 Injection scenario 2

The second scenario, MKTKM extended, represents a larger CCS project than Case 1, involving capture and injection of CO_2 from all three power stations: CO_2 from Millmerran (M) into the two notional injection sites in the south; and CO_2 from Kogan Creek (K) and Tarong North (T) into the notional injection site in the north. This scenario also featured a longer injection period (50 years for each stage, and 62 years in total), as well as higher estimates for the CO_2 capture rates from the individual power stations (Table 3).

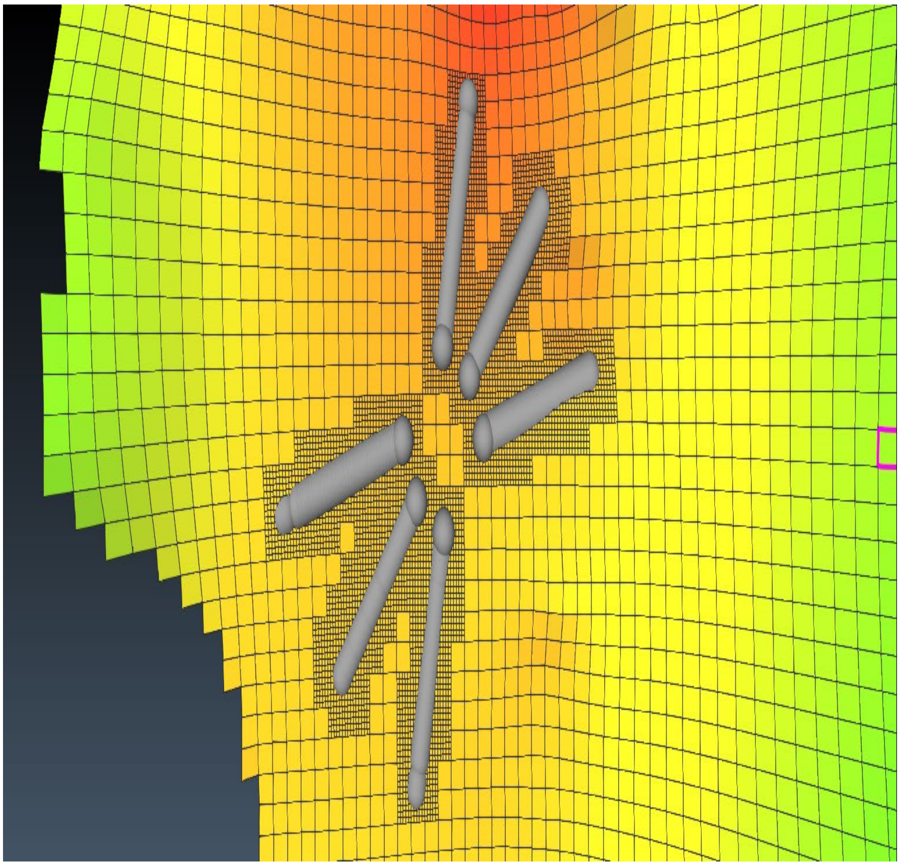
Table 3 Mass rates for MKTMK schedule.

Year	0	3	6	9	12	...	50	53	56	59	62
North Injection Rate (Mtpa)	0	2.5	3.69	3.69	6.5	...	6.5	4.0	2.81	2.81	0
South Injection Rate (Mtpa)	2.54	2.54	2.54	6.18	6.18	...	3.64	3.64	3.64	0	0

As in the MKMK scenario, injection from Millmerran started in the south in the modelled year, 2030, three years before injection from Kogan Creek. Three years further on, the rate at the north notional injection site was increased to represent injection of CO_2 captured at Tarong North. The schedule then progressed, with the rates at each site increasing as the second stages of CO_2 capture at Millmerran and Kogan Creek are added in years 9 and 12, respectively. Each "stage" lasted 50 years, before the injection rates were stepped down, eventually stopping completely in year 62. This resulted in a total peak injection rate of 12.68 Mtpa for 38 years.

A different approach was used to assess the injectivity and CO_2 plume spread when considering the MKTMK scenario. Rather than defining only wells that had been required for the base case, a total of 18 wells spread between three notional injection sites (North, South 1, and South 2) were defined for all cases, although not all wells would become active in every case. The notional injection sites were each set up with six 3.75 km-long horizontal wells extending approximately radially from a notional well pad, but avoiding running in a NW-SE direction to avoid limitations from in situ stress (Figure 4). As in the MKMK scenario, CMG's AUTODRILL feature (CMG 2018) was used to bring wells online as required to achieve the pre-defined injection rates without breaching any other constraints. An N+1 redundancy scheme was assumed and, thus, two wells (one north, one south) would need to be added to the totals required in each simulation. The results are presented in terms of the wells *required* for injection, not including the redundant wells.

Figure 5 Well layout at South 1 notional injection site for all MKTMK simulations. The same layout was used at the other two notional injection sites. This figure shows one layer of cells only, which can be seen to "pinch out" at the bottom left of the figure. Also note the refined cells around the wells. For reference, large grid blocks are approximately 500m x 500m, and well completions are approximately 3.75 km long.



For the MKTMK case, a wellhead pressure constraint of 20,000 kPa (200 bar) for all wells was used as the reference case for simulations, which had been determined to be a suitable method of achieving the required injection rate in previous simulations (Ribeiro et al. 2019b). The effect of the lower wellhead pressure limit of 15,000 kPa on the number of wells required for this schedule will be tested as part of this sensitivity study. The higher wellhead pressure meant several wells became constrained by bottomhole pressure limits, which had been calculated as 90% of the estimated thermally reduced fracture pressure (Rodger et al. 2019a).

5.6 Notional injection site modelling summary

The UQ-SDAAP combined the supporting geological, petrophysical, geophysical, hydrogeological, hydrochemical, and geomechanical information with techno-economic data regarding the CO_2 source, volume and timing to develop a rate-based field development plan with matched dynamic simulation and sensitivity analysis. The following are the key findings:

- Large-scale injection of around 13 Mtpa for about 30+ years can likely be securely stored by injecting into the Blocky Sandstone Reservoir (the deepest, lower-most aquifer of the Surat Basin) at just two or three remote well pads via up to six 3 to 4 km horizontal wells per pad within the wellhead and bottomhole pressure constraints anticipated
- Regardless of the permeability or CO_2 wettability scenario tested in a sensitivity analysis for the range of geologically plausible uncertainty, CO_2 generally migrates up to 10 m vertically into the Transition Zone by the end of the 100-year simulation. In the worst-case scenario, with relatively high permeability and zero capillary pressure (assuming CO_2 wetting), the CO_2 migrated 28 m vertically into the Transition Zone. This is still 80 m below the base of the Ultimate Seal, which means that no CO_2 migrates as far as the base of the Ultimate Seal, even in the worst-case scenario
- Only 3.1% of the total injected CO_2 migrated into the Transition Zone 100 years after injection stopped, even in the worst case (zero capillary pressure) simulated, and that the CO_2 did not manage to migrate beyond the lowest 25 m of the Transition Zone in any of the simulations
- Because of the low dip, the lateral extent of the CO_2 migration using a 10% saturation cut off is ~10 km radius from the wellhead location
- The distance between the dissolved CO_2 front in advance of the CO_2 plume is up to 2 km after 100 years
- The simulations indicate the horizontal permeability in the Blocky Sandstone Reservoir is the most important factor influencing injectivity. Halving the permeability meant that even using twice as many wells, it was not possible to sustain the required injection rates throughout the injection period
- Porosity had the most significant effect on the plume spread, both of supercritical CO_2 and water containing elevated levels of dissolved CO_2

The supercritical CO_2 plume likely remains within ~10 m radius of the injection sites after 100 years within the Blocky Sandstone Reservoir.

6. Groundwater

Groundwater modelling of the notional field development plan reference case shows that significant groundwater pressure increases due to CO_2 injection will occur in the strata between the Blocky Sandstone Reservoir and Hutton Sandstone aquifer in the deep southern depositional centre of the Surat Basin. At existing wells (drilled for oil and gas exploration) near the notional injection sites, pressure increases are predicted to exceed 250 m of groundwater head. However, available records show that the Precipice Sandstone in these wells has been isolated and plugged and abandoned. During injection, the increased pressure will continue to propagate horizontally in the Blocky Sandstone Reservoir and, to a lesser extent, vertically through the Transition Zone and Ultimate Seal into the overlying Hutton Sandstone. This propagation and spreading of pressure increases continues post-injection away from the injection sites, while pressures diminish somewhat at the notional injection sites themselves.

At some locations in the future, remedial well-headworks or downhole works may be required to manage pressure increases. Due to the depth and relative isolation of the Blocky Sandstone Reservoir in the deepest part of the Surat Basin, the number of potentially significantly affected wells is small. A larger number of wells in the Precipice and Hutton sandstone aquifers are predicted to experience smaller pressure (water level) increases of 10 to 30 m. The predicted pressure increases over a large portion of the Surat Basin can be considered a positive impact, helping re-pressurise otherwise declining Great Artesian Basin aquifers and lowering pumping costs. This pressure benefit to both the Precipice Sandstone and the Hutton Sandstone aquifers is projected to occur across some 25,000 km^2, while the CO_2 plume itself remains within less than ~10 km of the injection locations in the Blocky Sandstone Reservoir.

Some deep wells are known or suspected to be completed across both the Hutton and Precipice Sandstones. However these wells are many tens of kilometres outside the predicted footprint of the CO_2 plume. Therefore, they represent a potential pathway through which pressure (not CO_2) can more rapidly propagate and flow, and could therefore be induced to occur between formations of differing water quality. Remedial well works may be necessary to eliminate this potential pathway.

With increased pressure induced in the Blocky Sandstone Reservoir, the new vertical pressure gradient will induce some increase in the flux of formation water upwards out to the Ultimate Seal (Upper Evergreen Formation) and into the overlying Hutton Sandstone aquifer. If the water quality of the Upper Evergreen Formation in the southern depositional centre of the Surat Basin is poor (this is currently unknown), for example, with high total dissolved solids (TDS), there is a risk that inter-formation vertical flow could cause water quality degradation in the Hutton Sandstone aquifer. Current modelling shows this risk to be small because the increase in flux is small, given low bulk permeability of the Ultimate Seal, and the reservoir volume of the Hutton Sandstone aquifer is relatively large. As more information about formation water quality and vertical permeability becomes available, further assessment of this risk is required.

The groundwater model sensitivity analysis shows that the low and high permeability cases mainly change the timing of impacts propagating to known well locations, without substantially altering the maximum pressure changes predicted. The overall assessment of groundwater impact modelling, including the sensitivity analysis, suggests the following conclusions and observations:

- The supercritical CO_2 plume likely remains within ~10 km radius of the injection sites after 100 years within the Blocky Sandstone Reservoir
- The supercritical CO_2 plume could migrate up to ~10 m vertically into the Transition Zone (even in a worst case scenario), but remains ~80 m below the base of the Ultimate Seal after 100 years
- The pressure footprint defined by the area of 10 m or more groundwater head increase is approximately 90 km from the injection sites for both the Blocky Sandstone Aquifer and the Hutton Aquifer (an area of ~25,000 km^2) after 100 years
- The pressure increase near the notional injection sites in the Blocky Sandstone Aquifer dissipates post-injection and, at 100 years, the maximum pressure increase remains at ~100 m groundwater head in the Blocky Sandstone Reservoir, and ~40 m groundwater head in the overlying Hutton Sandstone aquifer
- The pressure increase continues to build, and lasts longer further away from the injection sites in the Blocky Sandstone Reservoir and in the overlying Hutton Sandstone aquifer

- The pressure benefits to groundwater resources occur over a considerable geographic area (~25,000 km^2), and may last over a period of time which is more than 100 years in both the Precipice Sandstone and Hutton Sandstone aquifers
- The maximum pressure increase in the vicinity of the Moonie Fault is ~200 m of groundwater head (~2000 kPa), and the fault reactivation analysis suggested reactivation at ~30,000 kPa pressure increase. The fault reactivation risk is therefore low
- The estimated change in flux across the Ultimate Seal is low, and presents an equivalently low risk of low water-quality leakage from the Ultimate Seal into the overlying Hutton Sandstone aquifer
- Future work should examine the location of Precipice Sandstone and Hutton Sandstone aquifer-related groundwater-dependent ecosystems (GDEs), and evaluate them in relation to the modelled pressure increase at 100 years, and the associated increased discharge
- The risk of lateral changes of water quality within the Precipice Sandstone aquifer remains untested due to a lack of high-confidence water quality data. A current project by ANLEC R&D is gathering this data over the next two years and, once achieved, this risk could be evaluated in the future
- The previous work on inverse modelling of MAR would indicate a roughly 1 m groundwater head increase at the northern boundary of the southern depositional centre. The risk of significant pressure interference between MAR in the northern depositional centre and carbon storage in the southern depositional centre is considered low
- A future work package could take the groundwater model outcomes for the pressure distribution in the Precipice Sandstone and Hutton Sandstone aquifers at 100 years, and evaluate the degree of ground heave expected. This could prove to be a useful monitoring tool of CO_2 plume distribution using InSAR

The pressure benefits to groundwater resources occur over a considerable geographic area (~25,000 km^2), and may last over a period of time which is more than 100 years in both the Precipice Sandstone and Hutton Sandstone aquifers.

7. Next steps

Theme 1. Clarify regulatory pathways.

Theme 2. Continue and deepen community and stakeholder engagement.

Theme 3. Acquire site-specific sub-surface data.

Theme 4. Set up and grow a suitable venture company or entity.

The societal part of this report (section 2) summarises an updated understanding of public perceptions and options on future energy choices (with CCS as one of a mix of options). It also summarises current ambiguities in Queensland regulations that need to be addressed. Two action themes arising from this are:

Theme 1. Clarify regulatory pathways.

Theme 2. Continue and deepen community and stakeholder engagement.

The techno-economic part of the report (section 5) investigates the potential for carbon abatement, through CCS in particular, to establish the rate potential and for how long CO_2 can be safely injected. For this, a complete revision of the lower-most basin geology was required. Additionally, the project accessed a significant amount of large-scale, dynamic calibration data courtesy of the oil and gas industry. A lowest risk (not lowest cost) philosophy to site screening and CO_2 storage development was created. This resulted in the demarcation of an area of the deepest parts of the Surat Basin (>2.3 km) where a high rate of CO_2 can be injected, with few containment risk features and minimal lateral migration of the emplaced plume. It is likely that 12.7 Mtpa of CO_2 can be injected for more than 20 years. There is also a reasonable chance of this extending out to 40 years. It is further possible, but not *knowable* on existing data, that this could extend out to 60 years without major injection rate decline. This magnitude could accommodate the majority of emissions from the three existing, modern, supercritical power plants for their remaining lifespan. There are also plausible sub-surface scenarios that would allow an extension well beyond. However, another crucial action theme arises in order to reduce the remaining uncertainty:

Theme 3. Acquire site-specific sub-surface data.

The basic geotechnical activities required next include the following:

- The collection of new 2D seismic surveys (location optimisation)
- The drilling of one deep appraisal well and one shallower aquifer monitoring well per notional injection site. Since the northern and southern sites are independent, completion of data gathering on one could lead to further work on the intended capture sites and pipelines, i.e. there is no need to complete data gathering at all notional injection sites before progressing with plant-specific engineering studies
- Conventional well-data acquisition (coring, logging, testing) for each site, including additional routine and special lab data analysis
- Extended well production and/or injection tests would be required over a few months, using water (no CO_2 is required in the field at this stage)

Data and analyses from these activities should confirm (or otherwise) the suitability of each site for four to six injection wells to be drilled at a later date, as well as better define maximum injection rate and constrain operational pressure envelops.

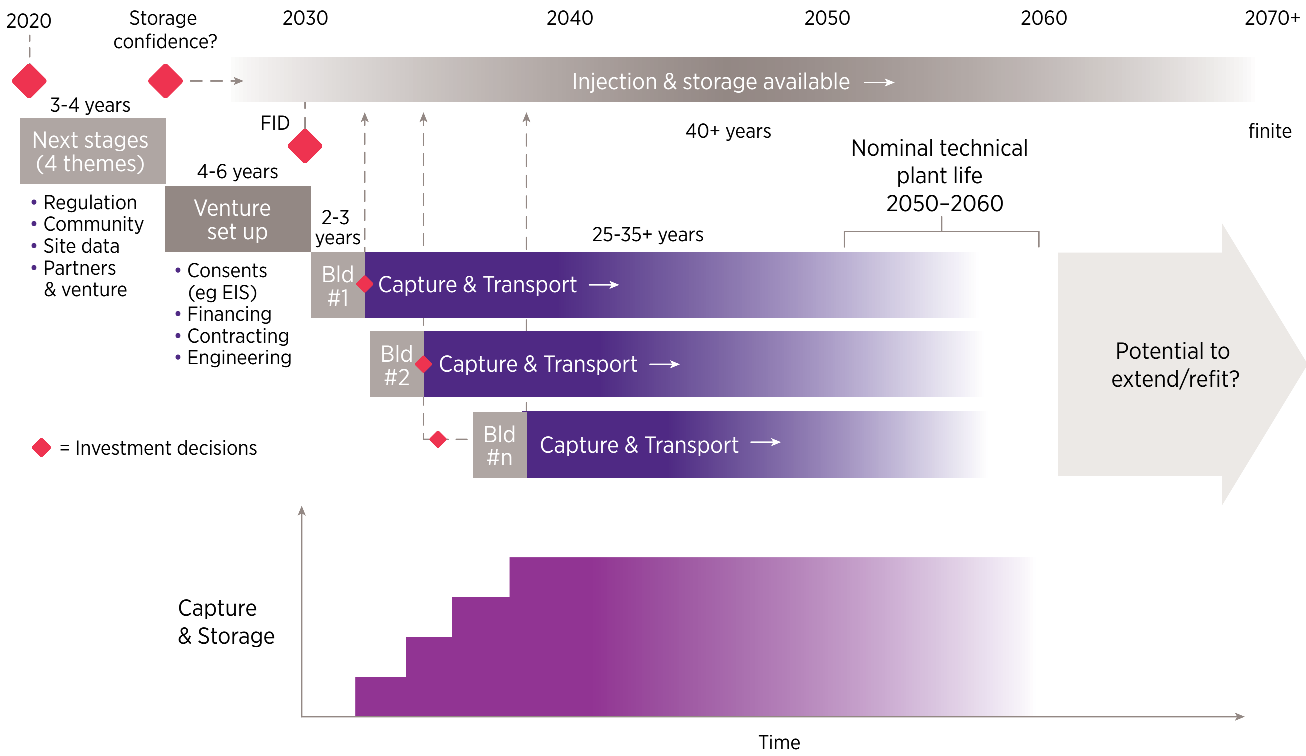
Finally, the project has also investigated a roll-out and deployment scenario that would have minimal reduction to baseload power availability, maximum learning, and plant disruption shared across locations and owners/operators. It would also manage overall risk by disaggregating one very large hub investment to several smaller investments, each of which is stage-gated and at each a decision to “halt” can be made.

Previous work has highlighted the organisational challenges in progressing large-scale CCS projects, e.g. Garnett et al. 2012 Chapter 2; Greig, Baird & Zervos 2016; Herzog 2017; Kapetaki & Scowcroft 2017; and Berly & Garnett 2018. Not least of these challenges relates to raising finance, securing large engineering contracts and undertaking complex EIS processes, while at the same time progressing the three action themes above. Finally, this leads to:

Theme 4. Setting up and growing a suitable venture company or entity.

A high-level timeline is shown in Figure 6.

Figure 6 High-level timeline to carbon abatement through retrofit.



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9. Glossary of terms, acronyms and abbreviations

Term	Definition
Abatement (carbon)	See definitions for Material Abatement and Feasible Abatement
Acentric factor	The acentric factor is a conceptual number introduced by Kenneth Pitzer in 1955, proven to be very useful in the description of matter. It has become a standard for the phase characterisation of single & pure components
Acritarchs	Acritarchs are defined as small, organic-walled microfossils of unknown biological affinity
Acoustic impedance	The ratio of the pressure over an imaginary surface in a sound wave to the rate of particle flow across the surface
AHP	Analytical hierarchy process
Allogenic	The term applied to the derived portion of a sediment, whether minerals or other constituents, which originated away from the area of sedimentation and is transported to it for final deposition
ANLEC R&D	Australian National Low Emissions Coal Research and Development
Anticline	A convex-upward formation of rock layers, which may form a trap for hydrocarbons
APCRC	Australian Petroleum Cooperative Research Centre
APLNG	Australia Pacific LNG (a joint venture between Origin, ConocoPhillips and Sinopec)
Aquifer	An underground layer of water-bearing permeable rock or unconsolidated materials (gravel, sand, silt or clay) from which groundwater can be extracted using a water well
Aquitards	An aquitard is a zone within the Earth that restricts the flow of groundwater from one aquifer to another
ASL	Above sea level
Autogenic	Internally generated, or autogenic, terrestrial and marine sediment-transport dynamics can produce depositional patters similar to those associated with climatic, tectonic, or sea level changes
Bar	Unit of pressure
Barrel	42 US Gallons
Barrels of oil equivalent	Converting gas volumes to the oil equivalent is customarily done on the basis of the heating content or calorific value of the fuel. There are a number of methodologies in common use. Before aggregating, the gas volumes first must be converted to the same temperature and pressure. Common industry gas conversion factors usually range between 1.0 barrel of oil equivalent (boe) = 5.6 thousand standard cubic feet of gas (mscf) to 1.0 boe = 6.0 mscf
Baseload power	The baseload on a grid is the minimum level of demand on an electrical grid over a span of time, for example, one week. Synchronous power
Basin	A large, natural depression on the Earth's surface in which sediments, generally brought by water, accumulate
Bedding style	A bedding plane is a surface parallel to the surface deposition, which may or may not have a physical expression
Bellona	A Norwegian NGO that works across a range of issues, including energy
BHP	Bottom hole pressure
Biofuels	A fuel derived immediately from living matter
Biostratigraphy	Biostratigraphic correlation uses fossil assemblages constrained within rock strata to establish the relative ages of the rock layers. It is one of the most widely utilised methods for determining age-relationships of sediments in geological successions
Bioturbation	The disturbance of sedimentary deposits by living organisms
BI-scale	Bioturbation index

Term	Definition
Bitumen	A highly viscous form of crude oil resembling cold molasses (at room temperature). Bitumen must be heated or combined with lighter hydrocarbons for it to be produced. Contains sulfur, metals and other non-hydrocarbons in its natural form
BoD	Basis of design
Borehole	A hole in the earth made by a drilling rig
Bouguer gravity	In geodesy and geophysics, the Bouguer anomaly is a gravity anomaly, corrected for the height at which it is measured and the attraction of terrain
Bowen Basin	The foreland, Early Permian to Middle Triassic Bowen Basin of eastern Queensland occupies about 160,000 km^2, the southern half of which is covered by the Surat Basin. It has a maximum sediment thickness of about 10,000 metres concentrated in two north-trending depocenters, the Taroom Trough to the east and the Denison Trough to the west. Deposition in the basin commenced during an Early Permian extensional phase, with fluvial and lacustrine sediments and volcanics being deposited in a series of half-graben structures in the east, and a thick succession of coals and nonmarine clastics in the west
Braided channel complex	A stream consisting of interwoven channels constantly shifting through islands of alluvium and sandbanks
BREE	Bureau of Resources and Energy Economics
C1-C6	Hydrocarbons of varying chain lengths (where C1 is methane and C2-C6 are higher chain hydrocarbons such as ethane, propane, butane etc.)
CAPEX	Capital expenditure
Capillary pressure	In fluid statics, capillary pressure is the pressure between two immiscible fluids in a thin tube, resulting from the interactions of forces between the fluids and solid walls of the tube
Cap-rock	Impermeable layer of rock providing a seal to contain the reservoir fluids
Carbon abatement	The reduction of the amount of carbon dioxide that is produced when coal and oil are burned
Carbon capture and storage (CCS)	Process by which carbon dioxide emissions are captured and removed from the atmosphere and then stored, normally via injection into a secure underground geological formation
Carbon Capture and Storage Research Development and Demonstration (CCS RD&D)	A fund set up by the Australian Government for research, development and demonstration activities in supporting Australian industry to innovate and adapt new technologies and processes, in particular for transport and storage of CO_2. UQ-SDAAP is one of the projects funded under the scheme
Carbon dioxide equivalents (CO_2e)	The quantity that describes, for a given mixture and amount of greenhouse gas, the amount of CO_2 that would have the same global warming potential (GWP) when measured over a specified timescale (generally 100 years)
Carbon sequestration	The fixation of atmospheric carbon dioxide in a carbon sink through biological or physical processes
Carbonic acid	Is a chemical compound with the chemical formula H_2CO_3 (equivalently $OC(OH)_2$). It is also a name sometimes given to solutions of carbon dioxide in water (carbonated water), because such solutions contain small amounts of H_2CO_3
Carboniferous	A period named from the widespread occurrence of carbon in the form of coal in these beds. It extends from 345 to 280 m.y. and has a duration of 65 m.y.
Casing	Thick walled steel pipe placed in wells to isolate formation fluids (such as fresh water) and to prevent borehole collapse
CCGTs	Combined cycle gas turbines (Condamine & Darling Downs plants in the study area)
CCS hubs	Central collection or storage distribution systems for CO_2
CCTVs	Closed circuit televisions
CCUS	Carbon capture, utilisation and storage
CDR	Carbon dioxide removal
Cement bond integrity	Cement integrity logs are run to determine the quality of the cement bond to the production casing, and to evaluate cement fill-up between the casing and the reservoir rock. A poor cement bond may allow unwanted fluids to enter the well

Term	Definition
Cementation	The process of deposition of dissolved mineral components in the interstices of sediments
Cenozoic	The Cenozoic Era meaning "new life", is the current and most recent of the three Phanerozoic geological eras, following the Mesozoic Era and extending from 66 million years ago to the present day
CH4	Methane
Clarence-Morton Basin	The Clarence Moreton Basin is a Mesozoic sedimentary basin on the easternmost part of the Australian continent. It is located in the far north east of the state of New South Wales around Lismore and Grafton and in the south east corner of Queensland
Clastic (rock)	Rock which has been formed from sediment of other rocks e.g. sandstone, shale, conglomerates, etc.
CMA	Cumulative Management Area (Office of Groundwater Impact Assessment, Queensland, terminology)
CMG GEM	GEM is CMG's reservoir simulation software. It's the equation-of-state (EoS) compositional and unconventional simulator that models the flow of three-phase, multi-component fluids
CO_2	Carbon dioxide
COIs	Communities of interest (communities strategically chosen because of their exposure to energy projects)
Completion	Completion of a well. The process by which a well is brought to its final classification - basically a dry hole, producer, or injector. A dry hole is completed by plugging and abandonment. A well deemed to be producible of petroleum, or used as an injector, is completed by establishing a connection between the reservoir(s) and the surface so that fluids can be produced from, or injected into the reservoir. Various methods are utilised to establish this connection, but they commonly involve the installation of some combination of borehole equipment, casing and tubing, and surface injection or production facilities
Condamine	Refers to the Condamine combined cycle gas turbines
Condensate	Mixture of hydrocarbons which are in a gaseous state under reservoir conditions and, when produced, become a liquid as the temperature and pressure is reduced
Conductor (casing)	Generally the first string of casing in a well
Container	For climate change mitigation to be accomplished through CCS, the large majority of CO_2 injected into the sub-surface must be securely contained indefinitely. To demonstrate containment requires the definition of a "container". The leakage risk must be analysed within the context of this defined container. A container comprises the intended injection and storage reservoir and an overlying seal or seal complex that defines a vertical extent. The container also has to have defined, lateral boundaries. If CO_2 migrates outside the defined container (i.e. above the seal complex and/or beyond the lateral boundaries), it can be considered to have leaked
Containment	Containment, where geological features limit the migration of injected CO_2 (laterally or vertically) beyond its intended location
Conventional gas	Conventional gas is a natural gas occurring in a normal porous and permeable reservoir rock, either in the gaseous phase or dissolved in crude oil, and which technically can be produced by normal production practices
COP21 NDC commitments	Australia's current Conference of Paris 21, nationally determined contributions
Core	A cylindrical sample taken from a formation for geological analysis
Coring	The process of cutting a vertical, cylindrical sample of the formations
Cretaceous	Rock formed in the last period of the Mesozoic era, between the Jurassic and the Tertiary periods
CSG	Coal seam gas. Natural gas contained in coal deposits, whether or not stored in gaseous phase
Cuttings	Small chips of rock retrieved from a well by the circulation of the mud, studied/logged by the well-site geologist
Darcy	Unit of measurement of rock permeability, the extent to which fluid will flow through it
Darling Downs	Refers to the Darling Downs combined cycle gas turbines
Decarbonisation	The reduction or removal of carbon dioxide from energy sources
Decollements	The plane of dislocation caused by an upper series of rocks folding and, in the process, sliding over a lower series of rocks, which may be unfolded or only slightly folded
DEM	Digital elevation model

Term	Definition
Density log	A wireline log parameter (measurement of density, a guide to porosity)
Depositional hiatuses	In geology a discontinuous succession of depositional layers would produce a hiatus or period of non-deposition between two orderly depositional units
Depth map	Relief map of sub-surface structure, contours relating to depths from surface datum level (i.e. sea level)
Deterministic estimate	The method of estimation of reserves or resources is called deterministic if a single best estimate is made based on known geological, engineering, and economic data
Development well	A well drilled within the proved area of an oil or gas reservoir to the depth of a stratigraphic horizon known to be productive
Deviated (well)	Well diverted from the vertical
DFIT	Diagnostic fracture injection testing
DG	Decision gates for next stage investments
Dinoflagellate cysts	Dinocysts or dinoflagellate cysts are typically 15 to 100 µm in diameter and produced by around 15–20% of living dinoflagellates as a dormant, zygotic stage of their lifecycle, which can accumulate in the sediments as microfossils. Organic-walled dinocysts are often resistant and made out of dinosporin
Drawdown	The difference between the static and the flowing bottom hole pressures
Drilling fluid	Circulating fluid, removes cuttings from wellbore to surface, cools the bit and counteracts downhole formation pressure
DST	Drill stem test. Used to test the wells production potential with a temporary completion
Dynamic storage capacity	An estimate consistent with environmental and social context, for a given the geological environment (play) and a notional field development plan; the integral over time of the sustained (highest) injection rate supported by the analyses
EAs	Environmental approvals
EC	Electrical conductivity
Effective porosity	Effective porosity is most commonly considered to represent the porosity of a rock or sediment available to contribute to fluid flow through the rock or sediment, or often in terms of "flow to a borehole"
EIB	European Investment Bank
EIS	Environmental Impact Statement
Emissions	Emission of air pollutants, notably: Flue gas, gas exiting to the atmosphere via a flue. Exhaust gas, flue gas generated by fuel combustion. Emission of greenhouse gases, which absorb and emit
EMV analysis	Expected monetary value analysis
En-échelon	In structural geology, en-échelon veins or "en-échelon gash fractures" are structures within rock caused by noncoaxial shear. They appear as sets of short, parallel, planar, mineral-filled lenses within a body of a rock
Environmental assessment	A study that can be required to assess the potential direct, indirect and cumulative environmental impacts of a project
Environmental Protection and Biodiversity Conservation Act 1999	Australian Government's central piece of environmental legislation
Environmental Protection Act 1994	The principal element of Queensland's environmental legal system
EOR	Enhanced oil recovery. One or more of a variety of processes that seek to improve recovery of hydrocarbon from a reservoir after the primary production phase
EPCM	Engineering, procurement, construction and management
Eromanga Basin	The Eromanga Basin is a large Mesozoic sedimentary basin in central and northern Australia. It covers parts of Queensland, the Northern Territory, South Australia, and New South Wales, and is a major component of the Great Artesian Basin. The Eromanga Basin covers 1,000,000 km^2 and overlaps part of the Cooper Basin

Term	Definition
Eustatic sea level	Pertaining to absolute changes in sea level, i.e. to worldwide changes and not local changes produced by local movements of land or the sea floor
Evergreen Formation	Strata of the Surat Basin
EWR	Enhanced water recovery
EWT	Extended well test
Facies	The sum total of features such as sedimentary rock type, mineral content, sedimentary structures, bedding characteristics, fossil content, etc. which characterise a sediment as having been deposited in a given environment
Fault	A fracture in rock along which there has been an observable amount of displacement
FBHP	Flowing bottom hole pressure
FDP	Field development plan
Feasible Abatement	UQ-SDAAP aimed to establish whether or not 'material' carbon Abatement was 'feasible' in the Surat Basin in southern Queensland via large-scale CCS. "Feasible Abatement" was defined to mean a combination of: Lowest risk: Non-technical risk factors are known and demonstrably minimised and there is a clear work plan to address them before any deployment High technical confidence: High level of technical confidence that a high rate can be sustained for a long duration; and, that the CO_2 will be contained indefinitely A robust, conservative capture scenario with minimum disruption to generation (minimum price impacts) Pipeline routes possible with no obvious showstoppers Reasonable cost estimates: the unit costs of carbon abatement ($/t) and LCOE ($/Mwh) are in the range of published estimates for other CCS projects or literature
FEED	Front end engineering design
FID	Final investment decision
Field	An area consisting of a single hydrocarbon reservoir or multiple geologically related reservoirs all grouped on or related to the same individual geological structure or stratigraphic condition
Flow test	An operation on a well designed to demonstrate the existence of moveable petroleum in a reservoir by establishing flow to the surface and/or to provide an indication of the potential productivity of that reservoir. Some flow tests, such as drill stem tests (DSTs), are performed in the open hole. A DST is used to obtain reservoir fluid samples, static bottomhole pressure measurements, indications of productivity and short-term flow and pressure build-up tests to estimate permeability and damage extent. Other flow tests, such as single-point tests and multi-point tests typically involve a measurement or estimate of initial or average reservoir pressure and a flow rate and flowing bottomhole pressure measurement. Multi-point tests are used to establish gas well deliverability and absolute open flow potential
Flue gas	Gas from industrial processes
Formation	A rock layer which has distinct characteristics (e.g. rock type, geologic age)
Formation damage	Reservoir damage due to plugging with mud, crumbling under pressure or high flow rate, etc.
Fossil	An organic trace buried by natural processes, and subsequently permanently preserved. The term 'organic trace' is here used to include skeletal material, impressions of organisms, excremental material, tracks, trails, and borings
Fossil fuel	A fuel source (such as oil, condensate, natural gas, natural gas liquids or coal) formed in the earth from plant or animal remains
Fracturing	Fracturing formation adjacent to well bore to improve well productivity (flow) by applying hydraulic pressure downhole
Free water level (FWL)	The free water surface is the highest elevation with the same oil and water pressure (zero capillary pressure)
Fugacity	In chemical thermodynamics, the fugacity of a real gas is an effective partial pressure which replaces the mechanical partial pressure in an accurate computation of the chemical equilibrium constant. It is equal to the pressure of an ideal gas which has the same temperature and molar Gibbs free energy as the real gas

Term	Definition
Galilee Basin	The Galilee Basin is a large inland geological basin in the western Queensland region of Australia. The Galilee Basin is part of a larger Carboniferous to Mid-Triassic basin system that contains the Cooper Basin, situated towards the south-west of the Galilee Basin, and the Bowen Basin to the east
Gamma ray	Log of the total natural radioactivity. Shales and clays are responsible for most natural radioactivity, so the gamma ray log is a good indicator of such rocks
Geobodies	Seismic bodies identified from different seismic attributes are analysed and calibrated with drilled wells to define their geological features
Geochronometric	A branch of stratigraphy aimed at the quantitative measurement of geologic time. It is considered a branch of geochronology
GEODISC	A program of APCRC that assessed and ranked sedimentary basins across Australia for their carbon storage potential relative to major point source emissions
Geomechanical	Geomechanics involves the geologic study of the behaviour of soil and rock
Geosequestration	Is the term used to describe the technology of capturing greenhouse gas emissions from power stations and pumping them into underground reservoirs. It is also referred to in some circles as carbon capture and storage (CCS)
Geothermal gradient	Increase of temperature with depth in the earth's crust
GHG	Greenhouse gas
GIS	Geographic Information Systems
Grain roundness	Rounding, roundness or angularity are terms used to describe the shape of the corners on a particle (or clast) of sediment. Such a particle may be a grain of sand, a pebble, cobble or boulder
Grain size	Grain size (or particle size) is the diameter of individual grains of sediment, or the lithified particles in clastic rocks. The term may also be applied to other granular materials. This is different from the crystallite size, which refers to the size of a single crystal inside a particle or grain
Grain sorting	Sorting describes the distribution of grain size of sediments, either in unconsolidated deposits or in sedimentary rocks
Great Artesian Basin (GAB)	The Great Artesian Basin, located in Australia, is the largest and deepest artesian basin in the world, stretching over 1,700,000 km^2, with measured water temperatures ranging from 30–100 °C. The basin provides the only source of fresh water through much of inland Australia
Greenhouse gas	Atmospheric gases that are transparent to solar (short-wave) radiation but opaque to long-wave (infrared) radiation, thus preventing long-wave radiant energy from leaving Earth's atmosphere. The net effect of these gases is a trapping of absorbed radiation and a tendency to warm the planet's surface. The greenhouse gases most relevant to the oil and gas industry are carbon dioxide, methane and nitrous oxide
Greenhouse Gas Storage Act 2009	Queensland Government Act regulating storage of greenhouse gases
GRFS	Gaussian random function simulation
Gunnedah Basin	The Gunnedah Basin is in north-eastern New South Wales, between the Bowen Basin to the north and the Sydney Basin to the south. Marine and non-marine sequences from the Permian and Triassic are present in it, and it contains Permian coal deposits
GW	Gigawatts
GWDB	The Queensland Government's Groundwater Database
GWh	Gigawatt hours
HFB	Horizontal flow barrier
HI	Hydrogen index
Highstand systems tract	A systems tract bounded below by a downlap surface and above by a sequence boundary
HM	History matching

Term	Definition
Horner extrapolation	The Horner plot is a cross-plot of build-up (or drawdown) pressure (Pi) on the Y axis versus a dimensionless time coefficient (HTi), usually called Horner Time, on a logarithmic X axis
Hunter Bowen Orogeny	Late Permian and early Triassic resulted in deformation and basin inversion with uplift of nearly 4 km
Hutton Sandstone	The Hutton Sandstone is a geological formation of the Surat Basin in Queensland, Australia. The ferruginous sandstones and coal were deposited in a floodplain environment and dates back to the Bajocian Age
Hydraulic conductivity	Is a property of soils and rocks, that describes the ease with which a fluid can move through pore spaces or fractures
Hydraulic head	Hydraulic head or piezometric head is a specific measurement of liquid pressure above a vertical datum. It is usually measured as a liquid surface elevation, expressed in units of length, at the entrance of a piezometer
Hydrocarbons	An organic compound containing only carbon and hydrogen and often occurring in nature as petroleum, natural gas, coal and bitumen or in refined products such as gasoline and jet fuel
Hydrograph	A hydrograph is a graph showing the rate of flow (discharge) versus time past a specific point in a river, channel, or conduit carrying flow. The rate of flow is typically expressed in cubic meters or cubic feet per second (cms or cfs)
Hydrostatic	Pressure/head pressure exerted by a column of liquid at a given depth
Ichnology	Is the study of trace fossils, and is the work of ichnologists. Trace fossils may consist of impressions made on or in the substrate by an organism: for example, burrows, borings (bioerosion), urolites (erosion caused by evacuation of liquid wastes), footprints and feeding marks, and root cavities
IEA	International Energy Agency
Impermeable	Rock that will not allow hydrocarbons or groundwater to flow through it
Injection	The forcing or pumping of substances into a porous and permeable subsurface rock formation. Examples of injected substances can include either gases or liquids
Injectivity	Injectivity, where the storage reservoir has sufficient permeability and thickness to accept the injected CO_2 at an economic rate for an economic duration and preferably with minimum surface footprint (not too many injection wells) without exceeding critical pressure constraints where pressures in the formation are to be managed lower than (i) the temperature adjusted fracture pressure of the sealing formations at the injection well site; (ii) fault reactivation or fault valving pressures for any naturally occurring faults in the Play; and (iii) the CO_2 capillary entry pressure at the seal
Intermittent power	An intermittent energy source is any source of energy that is not continuously available for conversion into electricity and outside direct control because the used primary energy cannot be stored. Intermittent energy sources may be predictable but cannot be dispatched to meet the demand of an electric power system. Non-synchronous power
Intracratonic	Intracratonic sag sedimentary basins occur in the middle of stable continental or cratonic blocks. They are rarely fault bounded, although strike-slip faulting can occur within them
IPCC	Intergovernmental Panel on Climate Change
Isochores	A contour connecting points of equal true vertical thickness of strata, formations, reservoirs or other rock units
Jurassic	Rock formed in the second period of the Mesozoic era, between the Triassic and Cretaceous periods
Kogan Creek	A modern supercritical power plant located in the study area
Kriging	In statistics, originally in geostatistics, kriging or Gaussian process regression is a method of interpolation for which the interpolated values are modelled by a Gaussian process governed by prior covariances
LCOE	Levelised cost of electricity
Lease	A legal document executed between a mineral owner and a company or individual that conveys the right to explore for and develop hydrocarbons and/or other products for a specified period of time over a given area
Liquefied natural gas (LNG)	Natural gas that has been converted to a liquid by refrigerating it to 260°F. Liquefying natural gas reduces the fuel’s volume by 600 times, enabling it to be shipped economically from distant producing areas to markets
Listric fault	A term applied to fracture planes which curve, either to near-horizontal ones which steepen, or to near-vertical ones which become less steep

Term	Definition
Lithology	A term usually applied to sediments, referring to their general characteristics
Lithostratigraphic unit	Lithostratigraphic units are bodies of rocks, bedded or unbedded, that are defined and characterised on the basis of their lithologic properties and their stratigraphic relations. Lithostratigraphic units are the basic units of geologic mapping
Logging (well)	Recording of information of subsurface formations. Logging includes records kept by the driller and records of mud and cutting analyses, core analyses, drill stem tests, and electric, acoustic and radioactivity logging
LOT	Leak-off test
Lowstand systems tract	A systems tract overlying a sequence boundary and overlain by a transgressive surface. Characterised by a progradational to aggradational parasequence set, this systems tract commonly includes a basin-floor fan, a slope fan and a lowstand wedge
LQC	Log quality control
M&V	Monitoring and verification
Machine learning	Machine learning is an application of artificial intelligence (AI) that provides systems the ability to automatically learn and improve from experience without being explicitly programmed. Machine learning focuses on the development of computer programs that can access data and use it learn for themselves
Magmatic arc	A magmatic/volcanic arc is a chain of volcanoes formed above a subducting plate, positioned in an arc shape as seen from above. Offshore volcanoes form islands, resulting in a volcanic island arc
Magnetics	Geophysical datasets used to depict regional structural grain or patterns using natural occurring rock magnetism
MAR	Managed Aquifer Recharge. Trials using fresh water from reverse osmosis plants. Using either the reinjection of water or CO_2 to raise water levels in the basin
Markov chain analysis	A Markov chain is a stochastic model describing a sequence of possible events in which the probability of each event depends only on the state attained in the previous event
MARPD	MAR Petrophysics Database
Material Abatement	UQ-SDAAP aimed to establish whether or not 'material' carbon abatement was 'feasible' in the Surat Basin in southern Queensland via large-scale CCS "Material Abatement" was defined initially as *at least* 5 Mtpa for *at least* 20 years, roughly equivalent to the emissions of one of the large supercritical power stations *Note: In the event, a working plateau rate of ~13 Mtpa was found technically robust. This was used as a reference case, representing the full retrofit of Millmerran and Kogan Creek and a partial retrofit at Tarong North. All reservoir models were run for longer than the lifetime of these plants indicating surplus dynamic capacity*
Maximum flooding surface (MFS)	In sequence stratigraphy, a maximum flooding surface is the surface that marks the transition from a transgression to a regression. Maximum flooding surfaces are abbreviated by MFS, synonyms for them include final transgressive surface, surface of maximum transgression and maximum transgressive surface
MCPD	Myall Creek Petrophysics Database
MEA	Monoethanolamine (MEA), an amine solvent used to remove CO_2 from flue gas (CO_2 scrubbing process). The process principle is based on the thermally reversible reaction between components in the liquid absorbent and CO_2 present in the flue gas
MEMs	Mechanical earth models
MFS	Maximum flooding surfaces
MICP	Mercury injection capillary pressure
Migration	Movement of hydrocarbons from source rock either into a reservoir or seeping to the earth's surface
Millmerran	A modern supercritical power plant located in the study area
Mimosa Syncline	The north-south axis along which the Surat Basin is aligned
MKTMK scenario	The highest rate scenario modelled has considered the partial sequential retrofitting of Millmerran, then Kogan Creek, then Tarong North, Millmerran and finally Kogan Creek
ML	Megalitres

Term	Definition
MMV	Measurement, monitoring and verification
Modflow	The U.S. Geological Survey modular finite-difference flow model, which is a computer code that solves the groundwater flow equation. The program is used by hydrogeologists to simulate the flow of groundwater through aquifers
Modflow-6 code	Modflow-6 is the most recent version of Modflow, one of the groundwater industry's standard codes that has been continually developed by the US Geological Survey since the late 1970s. It represents 3D fluid flow of a single water phase, with a wide variety of boundary condition options available
Monocline	Is a step-like fold in rock strata consisting of a zone of steeper dip within an otherwise horizontal or gently-dipping sequence
Monte Carlo simulation	A type of stochastic mathematical simulation which randomly and repeatedly samples input distributions (e.g. reservoir properties) to generate a results distribution (e.g. recoverable petroleum volumes)
MTPA	Millions of tonnes per annum
MWh	Megawatt hours
Natural gas	Natural gas is the portion of petroleum that exists either in the gaseous phase or is in solution in crude oil in natural underground reservoirs, and which is gaseous at atmospheric conditions of pressure and temperature. Natural gas may include amounts of non-hydrocarbons
NEM	National Electricity Market
NeuraLog™	Software used to digitise a significant number of legacy wireline logs
Neutron log	Normally synonymous with a neutron porosity log, however, the term is sometimes broadened to include an activation log. Guide to rock porosity
New England Fold Belt	The New England Fold Belt of eastern Australia comprises a number of variably deformed terrains, ranging in age from Early Palaeozoic to Late Triassic
NNM	Not normally manned
Normal fault	A fault with a major dip-slip component in which the hanging wall is on the downthrown side. See fault
Notional injection sites	Areas that may support large-scale injection and securely store by injecting into the deepest, lowermost aquifer of the Surat Basin. However, more site-specific data is required from these notional injection sites to increase technical confidence before development decisions can be made
NOx	Oxides of nitrogen, especially as atmospheric pollutants
nRMS	Normalised root mean square error
NTG	Net to gross
OECD	The Organisation for Economic Co-operation and Development is an intergovernmental economic organisation with 36 member countries, founded in 1961 to stimulate economic progress and world trade
Offset well location	Potential drill location adjacent to an existing well. The offset distance may be governed by well spacing regulations. Proved volumes on the existing well are indicated by either conclusive formation test or production. For proved volumes to be assigned to an offset well location there must be conclusive, unambiguous technical data which supports the reasonable certainty of production of hydrocarbon volumes and sufficient legal acreage to economically justify the development without going below the shallower of the fluid contact or the lowest known hydrocarbon
OGIA	Office of Groundwater Impact Assessment, Department of Natural Resources, Mines and Energy, Queensland
Open-hole	An uncased section of well borehole
Operator	The entity responsible for managing operations in a field or undeveloped acreage position.
OPEX	Operating expenditure
Organic	Substances derived from living organisms, such as oil in the natural state
Outcrop	The appearance of a rock formation at the surface
OzSEEBASE Map	Shows regional structural trends inferred from gravity maps

Term	Definition
P&A	Plugged and abandoned
pa	per annum
P50	P50 is defined as 50% of estimates exceed the P50 estimate (and by definition, 50% of estimates are less than the P50 estimate). It is a good middle estimate
Palaeozoic	The era ranging from 600-230 million years, a duration of 370 million years
Paleodepositional	Ancient depositional environment
Palynology	The study of fossil spores and pollen
Palynomorphs	Palynomorphs are broadly defined as organic-walled microfossils between 5 and 500 micrometres in size. Palynomorphs may be composed of organic material such as chitin, pseudochitin, sporopollenin and dinosporin
Paralic lakes	Of, relating to, or being interfingered marine and continental sediments
PCC	Post combustion capture refers to the separation of CO_2 from flue gas derived from the combustion of carbon-based fuel
Perforation	Holes shot through the casing in the pay zone (producing zone)
Permeability	The permeability of a rock is the measure of the resistance to the flow of fluid through the rock. High permeability means fluid passes through the rock easily
Permo-Triassic	Relating to the Permian to Triassic periods
Petrel	Software used for geological and reservoir engineering models
Petroleum	Petroleum is a naturally occurring mixture consisting predominantly of hydrocarbons in the gaseous, liquid or solid phase
Petrology/ Petrophysics	The study of rocks, their origin, chemical and physical properties and distribution
PHIE	Effective porosity
PHIT	Total porosity
Photoelectric factor	A wireline log parameter
PI	Well productivity index. PI defines the well deliverability, showing the flow rate of formation fluid that can be produced from the reservoir per unit pressure drawdown
Pilot project	A small-scale test or trial operation that is used to assess the suitability of a method for commercial application
Pipeline	A system of connected lengths of pipe, buried or surface laid for the transportation of fluids
Play	Recognised prospective trend of potential prospects, but which requires more data acquisition and/or evaluation to define specific leads or prospects
Plug/Plug and abandon	To seal a well with cement, e.g. before producing from a higher formation, side-tracking, or leaving the well permanently sealed and abandoned
Poro-perm	Porosity - permeability relationships
Porosity	The measure of a rock's ability to hold a fluid. Porosity is normally expressed as a percentage of the total rock which is taken up by pore space
PPA	Power purchase agreement
PPC	Post combustion capture
Precipice Sandstone	Strata of the Surat Basin. Considered to be the lowermost aquifer of the Great Artesian Basin
Present value	Also known as present discounted value, is a future amount of money that has been discounted to reflect its current value, as if it existed today
Produced water	Groundwater produced in connection with oil and natural gas exploration and development activities. Also known as formation water
Production casing	Innermost steel lining of a well cemented in place and perforated for production in the pay zone

Term	Definition
psi	pounds per square inch; a unit of pressure
PTA	Pressure transient analysis
Python	A programming language
QDEX	Queensland Digital Exploration Reports
QGC	Queensland Gas Company
QPED database	Queensland Petroleum Exploration Data
Regional Geological Model	The UQ-SDAAP research created a Regional Geological Model of the Precipice Sandstone to Evergreen Formation strata in the Surat Basin. It integrates existing seismic data, well data, and their associated geological interpretations using Petrel 2016 software. The aim was to produce a 3D geological model that combines all the subsurface geological understanding to depict the spatial distribution of reservoirs and seals that is consistent with all available data. Subsurface data integration supported a conceptual geological model creation. In addition, using the play concept developed for the Precipice Sandstone and Evergreen Formation, subsurface fluid flow and its implications for CO_2 storage can then be assessed. Constructing large-scale models for the Surat Basin has limitations relating to areas of sparse data and this carries with it a relatively high degree of uncertainty. However, the uncertainty was mitigated by using our conceptual understanding of the geology to infill data gaps in a geologically consistent manner. The Regional Geological Model is used as the base case reference for the Regional Groundwater and Notional Injection Sector dynamic simulations
Reserves	Estimated remaining quantities of oil and gas and related substances anticipated to be economically producible, as of a given date, by application of development projects to known accumulations. In addition, there must exist, or there must be a reasonable expectation that there will exist, the legal right to produce or a revenue interest in production, installed means of delivering oil and gas or related substances to market and all permits and financing required to implement the project
Reservoir	A subsurface rock formation containing one or more individual and separate natural accumulations of moveable petroleum that is confined by impermeable rock and is characterised by a single-pressure system
Reservoir pressure	The pressure at reservoir depth in a shut-in well
Resistivity log	A log of the resistivity of the formation made by an electrode device such as a laterolog, in this sense the term is used to distinguish the log from an induction measurement, which responds more directly to conductivity
Resources	Quantities of oil and gas estimated to exist in naturally occurring accumulations. A portion of the resources may be estimated to be recoverable, and another portion may be considered to be unrecoverable. Resources include both discovered and undiscovered accumulations
Reverse fault	A fault with a major dip-slip component in which the hanging wall is on the downthrown side
Rig (drilling)	The machine used to drill a wellbore
Risk	The probability of loss or failure. As “risk” is generally associated with the negative outcome, the term ‘chance’ is preferred for general usage to describe the probability of a discrete event occurring
ROI	Radius of investigation
Roma Shelf	Western margin of the Surat Basin
RTUPE	Real terms unit price earned (which would risk-cover the development, operating and appraisal costs)
SCADA	Supervisory control and data acquisition (SCADA) is a system of software and hardware elements that allows industrial organisations to control industrial processes locally or at remote locations. It is used to monitor, gather, and process real-time data
Schlumberger’s Techlog	Petrophysical analysis software
SDPD	Southern Depocenter Petrophysical Database
Seal	A relatively impermeable rock, commonly shale, anhydrite or salt, that forms a barrier or cap above and around reservoir rock such that fluids cannot migrate beyond the reservoir
Sedimentary rock	Rock composed of weathered materials transported by wind or water that have undergone lithification, e.g. sandstone, shale and limestone
Sedimentological	Relating to sedimentary rock forming processes. See Sedimentary rock

Term	Definition
Seismic survey	Exploration method in which strong, low-frequency sound waves are generated on the surface or in the water to find subsurface rock structures that may contain hydrocarbons
Seismogram	A seismogram is a graph output by a seismograph. It is a record of the ground motion at a measuring station as a function of time. Seismograms typically record motions in three cartesian axes (x, y, and z), with the z axis perpendicular to the Earth's surface and the x- and y- axes parallel to the surface.
SEM image	Image produced from a scanning electron microscope
Sequence stratigraphic	Critical to confidence in injection and containment prediction is the lateral prediction of properties away from well control. Rather than rely on historic correlations, UQ-SDAAP has undertaken a fundamental revision of the lowermost Jurassic stratigraphy that comprise the storage play into a sequence stratigraphic framework. This has led to increased confidence in both injection and sealing prediction and performance
SGS	Sequential Gaussian Simulation
SIS	Sequential Indicator Simulation
Skid	Steel framework used to contain equipment or mount equipment for transport
Skin factor	Is a term introduced to account for any deviation from radial flow in the near well bore region and quantifies the pressure drop (positive skin) near the well bore due to formation damage induced during drilling operations, or flow improvement (negative skin) because of well stimulation such as acidisation
Solar PV	Solar photovoltaics
Sonic	A type of acoustic log that displays travel time of P-waves versus depth. Sonic logs are typically recorded by pulling a tool on a wireline up the wellbore. The tool emits a sound wave that travels from the source to the formation and back to the receiver
Source rock	Sedimentary rock with organic deposits that form into hydrocarbons
SOx	Oxides of sulfur, especially as atmospheric pollutants
Spacing	The distance between wells producing from the same reservoir. Spacing is often expressed in terms of acres (e.g. 8-acre spacing) and is often established by regulatory agencies
SPE	Society of Petroleum Engineers
SSSV	Subsurface safety valves
Static models	Static models can be defined as models that represent a phenomenon at a given point in time or that compare the phenomenon at different points in time
Stochastic	Adjective defining a process involving or containing a random variable or variables or involving chance or probability such as stochastic simulation
STOOIP	Stock-tank original oil in place, the volume of oil in a reservoir prior to production
Storage capacity	Storage capacity, where there is sufficient accessible pore space within the injection reservoir to accommodate the volume to be stored
Subsidence	Subsidence is the sudden sinking or gradual downward settling of the ground's surface with little or no horizontal motion. The definition of subsidence is not restricted by the rate, magnitude, or area involved in the downward movement. It may be caused by natural processes or by human activities
Supercritical power plant	A supercritical steam generator is a type of boiler that operates at supercritical pressure, frequently used in the production of electric power. In contrast to a subcritical boiler in which bubbles can form, a supercritical steam generator operates at pressures above the critical pressure – 3,200 psi or 22 MPa
Surat Basin	The Surat Basin is a geological basin in eastern Australia. It is part of the Great Artesian Basin drainage basin of Australia. The Surat Basin extends across an area of 270,000 km^2 and the southern third of the basin occupies a large part of northern New South Wales, the remainder is in Queensland
Syncline	A downward, trough-shaped configuration of folded, stratified rocks. Compare with anticline
Tarong North	A modern supercritical power plant located in the study area
Taroom Trough	Bowen Basin major depocenter with up to 7km of burial

Term	Definition
TD	Total depth i.e. the drilled depth in a well at any one time
TDR	Time-depth relationship
TDS	Total dissolved solids
Tectonics	The process of formation and evolution of the earth's solid surface crust
Tectono-stratigraphy	The degree to which local structures may have influence stratigraphy
Thermogenic hydrocarbon	The manufacture of thermogenic hydrocarbon gases usually occurs at sub-bottom depths exceeding 1000 m. These hydrocarbon gases are produced under conditions of high temperature and great pressure from kerogens (which are derived from organic matter)
Tidal flats	Mudflats or mud flats, also known as tidal flats, are coastal wetlands that form when mud is deposited by tides or rivers. They are found in sheltered areas such as bays, bayous, lagoons, and estuaries
TOC	Total organic content
Toriacian to Bajocian	A period in the Early to Middle Jurassic
Total porosity	Total porosity is defined as the ratio of the entire pore space in a rock to its bulk volume. Effective porosity is the total porosity less the fraction of the pore space occupied by shale or clay. In very clean sands, total porosity is equal to effective porosity. See Porosity
Transgression	A marine transgression is a geologic event during which sea level rises relative to the land and the shoreline moves toward higher ground, resulting in flooding. Transgressions can be caused either by the land sinking or the ocean basins filling with water (or decreasing in capacity)
Transgressive surface	This is a marine-flooding surface that forms the first significant flooding surface in a sequence
Transgressive systems tract	The transgressive systems tract comprises the deposits accumulated from the onset of coastal transgression until the time of maximum transgression of the coast, just prior to renewed regression
Triassic	The period extends from 252 - 201 million years ago, a duration of ~40 million years. It marks the beginning of the Mesozoic Era
TVD	True Vertical Depth; the vertical distance below surface datum reached by a deviated well
TVDSS	True vertical depth sub-sea
TWT	Two-way time
UCG	Underground coal gasification
Ultimate Seal	Acts as the final cap-rock which retains the CO_2
Uncertainty	The range of possible outcomes in an estimate
Unconformity	An unconformity is a buried erosional or non-depositional surface separating two rock masses or strata of different ages, indicating that sediment deposition was not continuous
Unit play segment appraisal costs (UPSAC)	Unit costs for a specific plateau rate which probably uses the majority of the dynamic capacity appraised and is not limited by the project lifetime, again with the denominator as discounted injection rates. This could also be additive to UTC and assumes that, at some future point, additional sources of CO_2 are found to "use up" all of the storage resource
Unit project appraisal costs (UPAC)	Unit costs of appraisal for a specific project (which may not "use" the entire dynamic capacity appraised), limited by the project lifetime, with the denominator as discounted injection rates. This could be additive to UTC, but the capital spent has likely appraised more storage than the project has 'used'. It has benefited other future investors
Unit resource finding costs (URFC)	Unit costs of appraising a certain resource "volume", which is calculated as the integral of the maximum injection rate over time modelled with given pressure constraints and undiscounted rates over time. This is not additive to UTC
UPS	Uninterruptible power supply
UQ Centre for Coal Seam Gas Fault and Fractures project	Structural data and interpretations from the north were consolidated from the fault and fractures project

Term	Definition
UQ-SDAAP	The University of Queensland Surat Deep Aquifer Appraisal Project. is part of the ongoing development of carbon capture and storage (CCS) to help reduce emissions from fossil fuel in Australia
UTC	Unit technical cost
Variogram	A variogram is a description of the spatial continuity of the data. The experimental variogram is a discrete function calculated using a measure of variability between pairs of points at various distances. The exact measure used depends on the variogram type selected
Vegetation Management Act 1999	Queensland Government Act
Vent	Pipe/fitting on a vessel that can be opened to atmosphere
Vent stack	Open pipe and framework for discharging vapours into the atmosphere at a safe location without combustion
Viscosity	Property of fluids/slurries indicating their resistance to flow, defined as the ratio of shear stress to shear rate
VIT	Vertical interference test
Vitrinite reflectance	Thermal maturation indicators
VSMOW	Vienna Standard Mean Ocean Water (VSMOW) is a water standard defining the isotopic composition of fresh water
WACC	Weighted average cost of capital
Walloon Coal Measures (WCM)	The Walloon Coal Measures is an Aalenian to Oxfordian geologic formation in Queensland, Australia
Waste Reduction and Recycling Act 2011	Queensland Government Act
Water Act 2000	Queensland Government Act
Water drive	When the hydrocarbon reservoir in contact with underlying water table, the formation pressure will drive the water into the rock pores vacated by produced oil, thus maintaining reservoir pressure and aiding production
Water injection	The injection of water in order to maintain reservoir pressure and boost production
Water reinjection	Disposal of produced water into a disposal well as opposed to dumping to the environment (not for boosting the reservoir pressure)
Water saturation	Proportion of water in the pore spaces of a reservoir. See Porosity
Water table	The level in the earth below which rock pores are saturated with water
Well abandonment	The permanent plugging of a dry hole or of a well that no longer produces petroleum or is no longer capable of producing petroleum profitably. Several steps are involved in the abandonment of a well: permission for abandonment and procedural requirements are secured from official agencies; the casing is removed and salvaged if possible; and one or more cement plugs and/or mud are placed in the borehole to prevent migration of fluids between the different formations penetrated by the borehole
Well pad	A temporary drilling site, usually constructed of local materials such as gravel, shell or even wood
Well testing	Testing of an exploration or appraisal well to aid the estimation of reserves in communication with the well and well productivity. Testing in a production well also monitors the effects of cumulative production on the formation
Wellbore	The hole drilled by a drilling rig to explore for or develop oil and/or natural gas. Also referred to as a well or borehole
Wellhead	The "Wellhead" is descriptive of a location or function (including the 'Christmas tree' and hang offs) rather than a specific item of equipment Permanent equipment used to secure and seal the casings and production tubing and to provide a mounting for the Christmas tree. The Christmas tree is an assembly of valves, spools and fittings used to regulate the flow in all types of oil, gas and water wells (extraction and injection)
Wettability	Wettability is the tendency of one fluid to spread on, or adhere to, a solid surface in the presence of other immiscible fluids. Wettability refers to the interaction between fluid and solid phases. In a reservoir rock the liquid phase can be water or oil or gas, and the solid phase is the rock mineral assemblage

Term	Definition
WHP	Wellhead pressure
Wireline	Small-diameter metal line used in wireline operations; also called a slick line. A system in which a flexible cable and reel is used to lower a log or maintenance equipment into a well, rather than a rigid drill string, offering considerable savings of equipment, manpower and time
Wireline logs	See logging (wells)
WLF	Wireline log facies
WMIP	The Queensland Government's online Water Monitoring Information Portal
Zerogen Project	The ZeroGen Project was a Queensland Government initiative established to develop, construct and operate an Integrated Gasification Combined Cycle (IGCC) and carbon dioxide capture and storage (CCS) power plant and storage facility in Central Queensland, Australia
Zone	Interval between two depths in a well containing reservoir or other distinctive characteristics

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