Australia's National Science Agency

CO_2 Utilisation Roadmap

Citation

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Acknowledgments

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We are grateful for the time and input of the stakeholders from industry, government, academia who were consulted throughout this project. A full list of stakeholders consulted may be found in Appendix A.

Sponsors and supporting organisations

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Foreword

Australia's journey to net zero emissions represents one of the largest and most complex industry shifts we're likely to see in our lifetimes.

We need energy and products that are low emissions and sustainable, but that are also economically viable to give our industries a competitive edge.

Fortunately, Australia has a world-class science sector innovating in low-emissions technology.

Australian science invented the low-cost solar cell design that is used around the world today.

Australian science invented the hydrogen cracker to enable a liquid renewable fuel for transport and industry.

And Australia has demonstrated it can deploy 5GWs of variable renewables per year, like wind and solar PV, to put us in a great position to contribute to global emissions reduction.

But despite this, there are a range of industries critical to our daily lives that still draw heavily on fossil fuels. These 'hard to abate' industries, like cement, steel, plastics, and transport (among others) are big emitters – they account for about a sixth of Australia's emissions and represent around a third of global emissions.

Unfortunately, these industries can't easily be decarbonised with renewables alone. Some rely on fossil fuels as building blocks for products, some require fossil fuels to deliver high density energy and fuels, and some have CO_2 emissions inherent in their processes, like when making cement. They are among the hardest industries to decarbonise, and with limited near-term options, we need to look at other solutions.

As the national science agency, CSIRO is working with the Australian government and industry to catalyse Australia's transition towards net zero emissions.

We are working on a broad range of low emissions technologies including clean hydrogen, energy storage, low carbon materials, carbon capture and storage, and carbon stored in soils.

An important emerging technology is carbon capture and utilisation, or CCU. Using this technology, we can take CO_2 emissions from the atmosphere or from industrial processes and convert them into useful commercial products, like synthetic fuels, chemicals, carbon fibre, or building materials.

Delivered with the support of the Department of Industry, Science, Energy and Resources, this Roadmap brings together research, industry, and government to lay a pathway to CCU opportunities for Australian industries, and for our economy.

It looks at how we can use CCU to convert CO_2 from hard to abate industries into a valuable resource, while lowering their emissions and expanding Australia's low-carbon offering to the world.

CCU is an emerging area of science and technology, and further work is needed to bring down costs, but international interest in this technology continues to grow. This Roadmap aims to provide a framework for discussion about how Australia could become a leader in this area, and reduce the emissions, but not the profits, from our industries.

No single technology will take us to net zero – the scale of our challenge in adapting to climate change and decarbonising our industries requires us to draw on every available tool.

The development and demonstration of high abatement technologies like CCU has the potential to have a significant impact, as part of our broader efforts to both reduce emissions and lift the competitiveness of our industries.

Dr Larry Marshall
Chief Executive, CSIRO

Contents

Executive summary

The global climate challenge is shaping the 21st century and with over 33 gigatonnes of carbon dioxide (CO_2) emitted globally in 2019 alone, significant change is required.[1] However, carbon based products remain part of society and there are a broad range of industries that are difficult to decarbonise with renewable technologies alone. These industries often rely on fossil fuels as a building block for products (such as the thousands of everyday products created by the plastics and chemicals industry); they require fossil fuels for the high density energy required for long-distance transport (such as commercial aviation); or have CO_2 emissions inherent in their processes (such as those required to produce cement and steel).

These industries face significant challenges as demand for their products is expected to continue growing and as the world embraces net zero emission goals. They are often described collectively as difficult or hard-to-abate industries[2] and account for approximately 16% (almost 82Mt of CO_2-e) of emissions in Australia[3] and are responsible for almost one third of global emissions.[4]

The global challenges related to climate change raises the question of how continued demand for these products that are embedded in society can be supported, while addressing CO_2 emissions.

Carbon capture and utilisation (CCU) is defined as the conversion of CO_2 captured from emissions sources or the atmosphere into valuable lower or zero emission products.

This differs from carbon capture and storage (CCS) where CO_2 is captured, transported, and buried in underground geological formations for permanent storage.

Carbon capture and utilisation (CCU) is shifting CO_2 from a cost or a waste product to an opportunity – supporting global decarbonisation efforts, the transition to lower-emissions products and creating potential revenue streams from CO_2-derived products.

CCU creates the opportunity to capture emitted CO_2 and convert it for use in products (see figure to right). CO_2 is already utilised in several industries, either directly in the food and beverage industry or indirectly, through the manufacture of urea, a feedstock for fertilisers. However, expanding CCU, particularly through the conversion of CO_2, creates opportunities to reduce the amount of CO_2 emitted through the creation of chemicals and fuels and a variety of building materials and products, some with the ability to permanently lock away CO_2. In the long term, this can support the transition to lower-emissions products and processes. For example, the development of lower-emissions fuels, particularly in industries like commercial aviation where alternatives such as batteries and hydrogen are not viable in the near-term.

CCU can take advantage of CO_2 from industrial waste streams or the atmosphere via emerging direct air capture (DAC) technologies. Increased deployment of CCU can help bring down the costs of these technologies and create a revenue stream that can help to offset CO_2 capture costs.

In addition to supporting emissions reduction, CCU can provide Australia with a range of low emissions technology opportunities. These opportunities can be applied in a way that helps maintain the competitiveness of hard-to-abate domestic industries, while positioning Australia for a role in servicing the global demand for carbon-based products.

1 International Energy Agency (2021) *Net Zero by 2050*. IEA

2 The definition of 'hard-to-abate' industries varies but for the purpose of this report it refers to the following categories in the Australian Government's National Inventory Report Volume 1; industrial processes and product use (including the mining, chemicals and metals industry), manufacturing industries and construction, and domestic aviation.

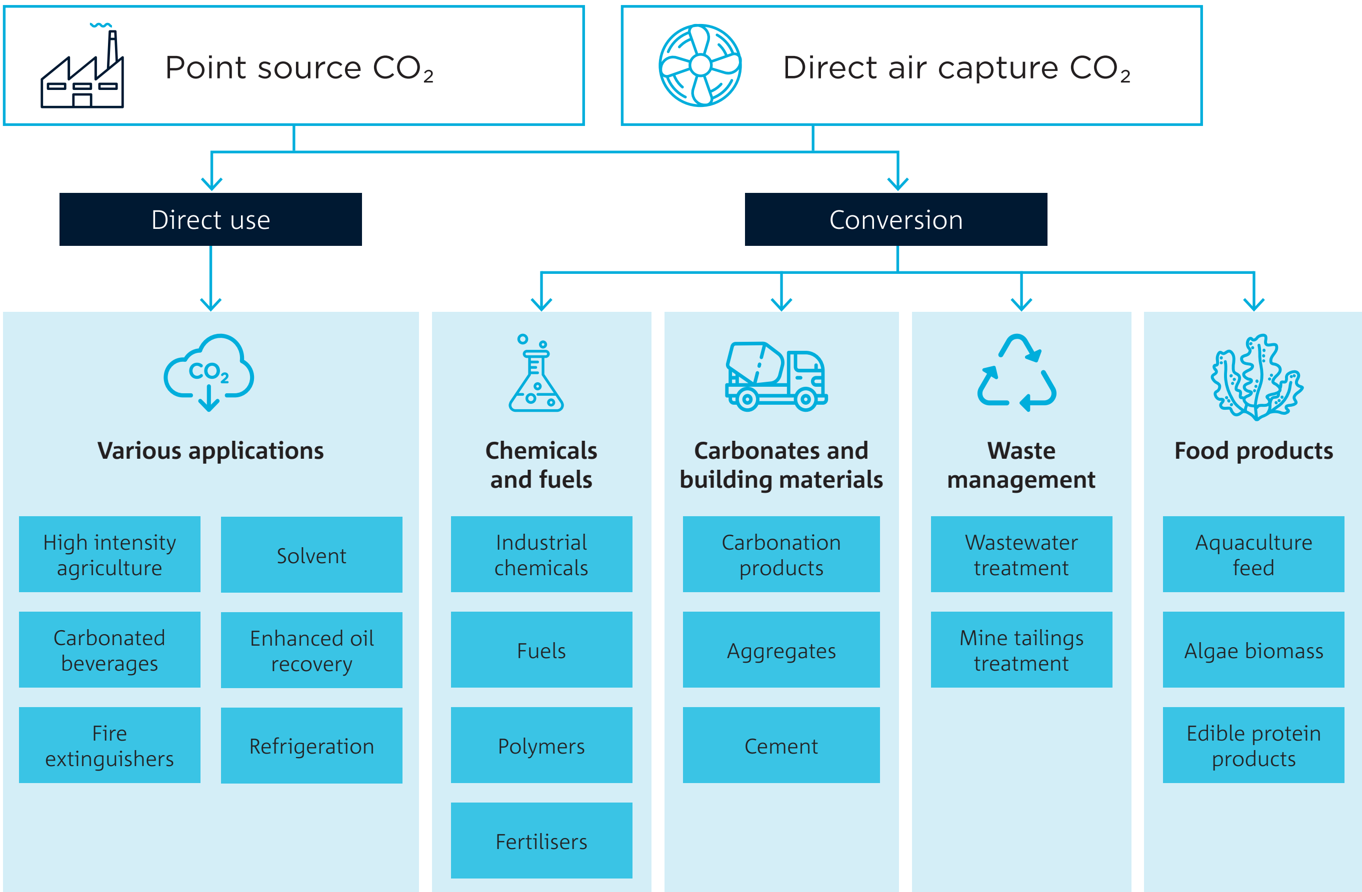
3 Australian Government Department of Industry, Science, Energy and Resources (DISER) (2021) *National Inventory Report Volume 1*. DISER

4 World Economic Forum (2020) *Tackling the harder-to-abate sectors*. Viewed 3 May 2021, https://www.weforum.org/agenda/2020/07/tackling-the-hard-to-abate-sectors-join-the-conversation/

Australia is well positioned to capitalise on the CCU opportunity and become a leader in this emerging area.

CCU can play a key role in supporting Australia's decarbonisation trajectory due to domestic comparative advantages and trends that support scale-up including but not limited to:

- **Bilateral CCU collaborations:** Australia has established bilateral agreements on low emissions technologies, including carbon capture, utilisation and storage (CCUS), with Japan and Singapore.
- **Large volumes of feedstocks:** Australia has the capacity to produce large volumes of necessary feedstocks (e.g. hydrogen and industrial waste streams), particularly within industrial hubs and precincts, as well as land availability for renewables and DAC technologies.
- **Projected low cost electricity:** Australia has the potential for internationally competitive low cost renewable electricity, supporting the deployment of low emissions technologies, including CCU.
- **Track record for exporting resources:** Australia's history of developing internationally competitive industries can be coupled with domestic CCU capabilities to service global demand for carbon-based products.
- **Decarbonisation commitments across hard-to-abate industries:** As Australian industry pursues net zero commitments, industrial sites can be used to support large scale demonstration of CCU.
- **A growing manufacturing base:** The Australian Government is building on the nation's established manufacturing base through the Modern Manufacturing Strategy, which envisages the transition to low emissions manufacturing pathways.



However, not all CCU applications are equal, requiring Australia to scale up CO_2 utilisation strategically.

Low emission and cost effective CCU applications are still emerging and far from equal. For example, different CCU applications will be developed over different time-horizons and have higher associated costs when compared to their current equivalent products and feedstocks. Effective displacement will likely require renewable energy to power processes and large quantities of hydrogen as feedstock, while some will require substantial quantities of other inputs, such as mine tailings or minerals for carbonation. In addition, different CCU applications can lock in CO_2 for different time periods which impacts their carbon abatement and storage potential. Another challenge is that the understanding of CCU is still nascent in Australia and globally; and requires clear public, industry and government communication of CCU, its role in the decarbonisation challenge and its relationship to carbon capture and storage (CCS).

As such, a strategic and well-informed approach to the scale-up of CCU will be important; one that recognises the complexity of the global decarbonisation challenge and the status of and opportunities associated with the various CCU applications.

A roadmap to scale-up

This report, through extensive consultation, modelling and analysis, has developed a roadmap to support scale-up of CCU in Australia. It has identified which CCU technologies are most viable and what are the key advantages and barriers to the deployment of each. It has considered the economic parameters and the short and long term market opportunities. It is not intended to be a definitive document, but rather to inform the debate about the associated risks and opportunities for CCU in the Australian context. To that end, the report has explored the application of CCU in four areas: Direct use of CO_2, mineral carbonation, the conversion of CO_2 to chemicals and fuels and the biological conversion of CO_2. It also provides key recommendations to facilitate the rapid deployment and upscaling of those CCU technologies identified as having the most potential.

Direct use of CO_2

Established CO_2 demand from the food, beverage and agricultural industries could be leveraged as initial offtakers for the development of new point source capture plants and demonstration of DAC and purification technologies.

Australia's current CO_2 demand is driven by food processing, beverage carbonation and agricultural industries for supporting plant growth in greenhouses. However, it faces supply constraints as these industries are currently reliant on limited capture sources. With the industry projected to be worth $250 billion in 2030,[5] CCU using new point sources, and DAC in the longer term, could play an important role in shoring up supply for these industries.

The use of CO_2 in these industries has a very short retention time before being released back into the atmosphere. Therefore, these industries must divert the source of the CO_2 towards low emission capture sources, such as DAC if they are to become low emissions. Nevertheless, the growing market for these products may be used to leverage the development of new point source capture plants and purification technologies.

5 CSIRO Futures (2019) *Growth opportunities for Australian food and agribusiness: Economic analysis and market sizing.* CSIRO

Mineral carbonation

The cost competitiveness of mineral carbonation (i.e. the conversion of CO_2 into solid, carbonate based products) in the near-term can drive opportunities to utilise waste from heavy industry and mining, lock away CO_2 for the long term and lower the carbon intensity of the building industry.

Carbonate products from CCU can be cost competitive, creating an opportunity to economically scale up existing projects in the near term. These products have a wide range of uses including as building materials such as insulation and bricks, use in chemicals and in food and nutrition. The production of carbonates can utilise industrial waste or minerals and can assist in mitigating challenges with sustainably managing waste.

The concrete sector can also benefit from carbonation by incorporating CO_2 in concrete production. By doing so, the volume of cement and aggregates required can be reduced, thus reducing carbon intensity and feedstock costs. Australian demand for concrete is projected to grow; and as CO_2 is stored permanently in these products, it presents a near-term opportunity to reduce emissions.

Conversion of CO_2 into chemicals and fuels

With Australia's emerging hydrogen industry and its history as an energy exporter, it is well positioned to support the long-term transition to lower-emissions chemicals and fuels, but high green premiums in the near-term may require strategic investment.

Demand for chemical feedstocks and fuels is expected to continue to grow both domestically and regionally. These products require a source of carbon which is currently principally derived from imported fossil fuels. While carbon offsets could be considered to support long-term net zero targets for these industries, low emission CCU alternatives can provide a pathway that could support the transition to lower-emissions products while maintaining domestic supply.

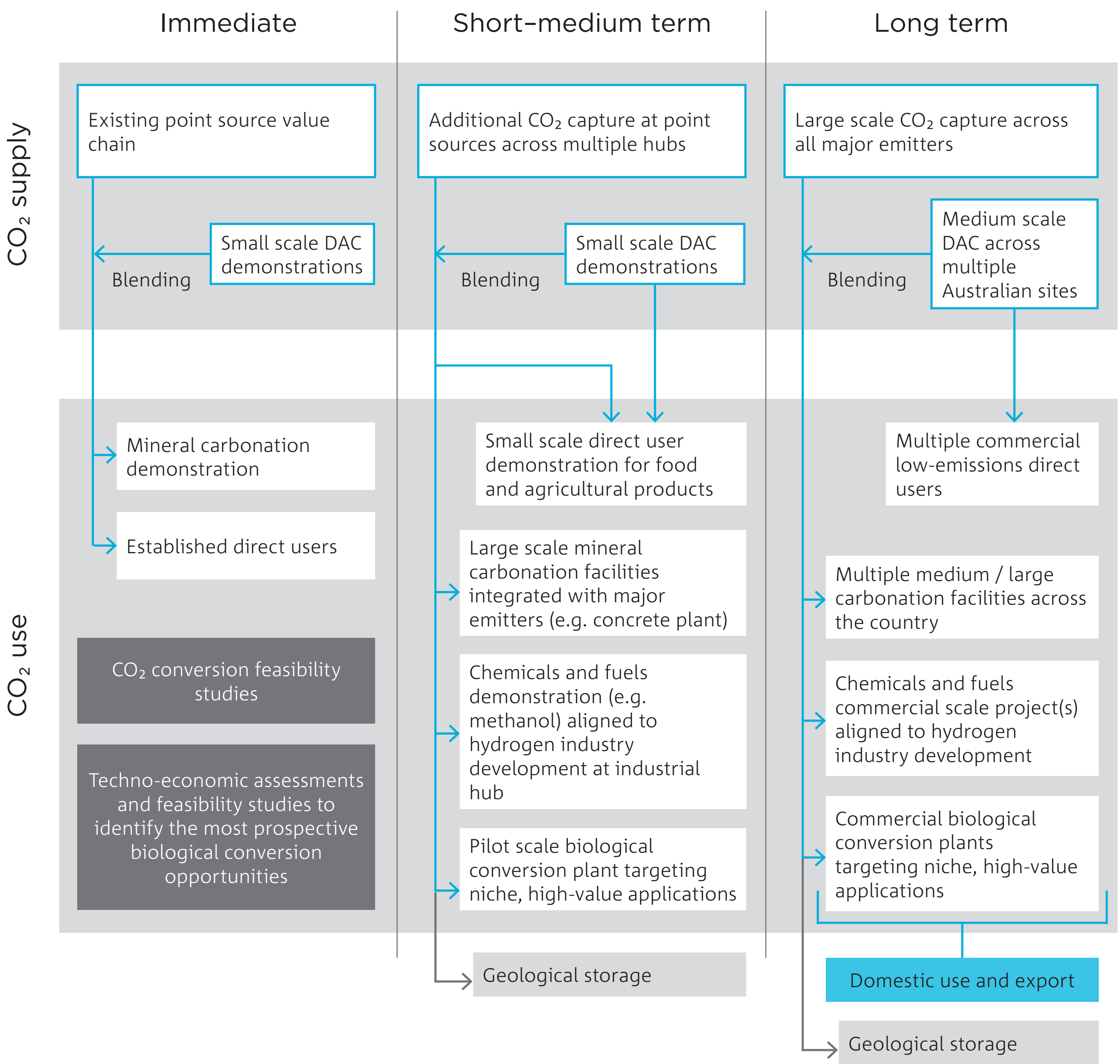
This report focuses on opportunities for the creation of methanol, electrofuel (synthetic jet fuel), olefins (for use in the plastics industry) and synthetic natural gas. These chemicals and fuels require a readily available source of hydrogen and low emissions energy, which can be closely aligned with Australia's National Hydrogen Strategy and proposed hydrogen and CCS hubs. Consequently, there will be additional costs and risks compared to the current fossil based alternative (creating a green premium). Near-term investments in Australia will likely be driven by strategic or political motivations, such as providing fuel security or supporting the domestic plastics and chemicals industry.

Biological conversion of CO_2

Australia's role as a global food exporter presents an opportunity to capitalise on emerging biological conversion pathways, including production of niche, high value products.

Biological conversion of CO_2, which can be enhanced by synthetic biology, is the use of microorganisms to produce a range of products. Although low volumes of CO_2 would be utilised, niche, high value products provide a cost competitive pathway to further develop the biological conversion pathway in Australia. Given many niche, high value products respond to challenges facing the food and agricultural sectors (e.g. alternative feed for livestock) there is potential for the biological conversion of CO_2 to focus on global food export opportunities initially.

In future, it is possible that biological systems could produce many bulk and high value chemicals on demand to meet changing supply needs. These products would need to compete with other CCU processes, such as thermochemical production. However, Australia has a strong synthetic biology research base, emerging start-ups and national and state-level biofoundry investments that could be leveraged for the development of longer term CO_2 conversion applications.


Immediate
Short–medium term
Long term
CO₂ supply
CO₂ use
Existing point source value chain
Small scale DAC demonstrations
Blending
Additional CO_2 capture at point sources across multiple hubs
Small scale DAC demonstrations
Blending
Large scale CO_2 capture across all major emitters
Medium scale DAC across multiple Australian sites
Blending
Mineral carbonation demonstration
Established direct users
CO_2 conversion feasibility studies
Techno-economic assessments and feasibility studies to identify the most prospective biological conversion opportunities
Small scale direct user demonstration for food and agricultural products
Large scale mineral carbonation facilities integrated with major emitters (e.g. concrete plant)
Chemicals and fuels demonstration (e.g. methanol) aligned to hydrogen industry development at industrial hub
Pilot scale biological conversion plant targeting niche, high-value applications
Geological storage
Multiple commercial low-emissions direct users
Multiple medium / large carbonation facilities across the country
Chemicals and fuels commercial scale project(s) aligned to hydrogen industry development
Commercial biological conversion plants targeting niche, high-value applications
Domestic use and export
Geological storage

Key recommendations

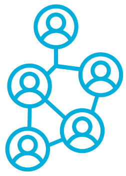
1. Diversify and engage across the value chain and multiple CCU applications
2. Use CCU as part of a portfolio of decarbonisation solutions
3. Explore incentives and minimise barriers to entry
4. Use CCU to support or de-risk investment in existing and planned infrastructure

1 Diversify and engage across the value chain and multiple CCU applications

This report identified over 50 different use cases or products possible for CO_2 utilisation grouped into broad areas: direct use of CO_2, mineral carbonation, conversion of CO_2 into chemicals and fuels, and biological conversion of CO_2. This diversity of applications is important and can be leveraged to:

- Provide flexibility to pursue/enter a range of green markets as CCU technologies evolve: A diversification strategy creates flexibility to pivot as global green markets develop and associated carbon policies evolve.
- Provide optionality for a broad range of emitters: The many ways to utilise CO_2 provides optionality for organisations (with different emissions profiles) to incorporate CCU in their strategies for decarbonisation. This could enable reduced emissions from hard-to-abate processes and activities and create opportunities to generate commercial value from captured CO_2.
- Create options for industries with no current viable option for fuel switching: For example, the commercial aviation industry has announced ambitious goals to curb emissions. With battery and fuel cell technology and its supporting infrastructure some time away, carbon fuels from low emissions sources are needed in the interim.
- Reduce the risk of flooding markets with CO_2-derived products given excess CO_2 available: As CO_2 capture and utilisation scales up, diversification can be used in part to help avoid flooding markets with more product than is required.

To avoid duplication, attract investment and improve outcomes, it is important that scale-up of different CCU applications is supported:



Engagement and close collaboration across the CO_2 value chain in Australia and overseas can avoid duplication, minimise risk and attract investment. To maximise impact and reduce investment risk, it is important to encourage collaboration across the CO_2 value chain. This extends to leveraging existing ecosystems at industrial hubs, including new CCS and hydrogen hubs that are under development. This will enable the integration of CCU at lower costs due to shared infrastructure and expertise.

Clear communication of CCU and its role in the decarbonisation challenge will be vital. A strong understanding of the potential benefits and limitations of CCU will be essential to maintain public support for CCU demonstration projects and encourage industry uptake of new technologies. Given the range and complexity of CCU technologies, clear communication of how CCU technologies could reduce emissions for specific applications will be important. Equally, the relationship between CCU and CCS should be made clear.

Engagement and integration with existing strategies and green mechanisms, such as the development of the circular economy, will promote CCU uptake. CCU is complementary to many existing goals and strategies already being pursued. Educating stakeholders on how CCU can be integrated into these will raise the profile of CCU and its potential. In terms of the circular economy, continued investment in closed loop systems can also accelerate investment in CO_2 utilisation technologies.

2 Use CCU as part of a portfolio of decarbonisation solutions

Globally, hard-to-abate industries including cement, steel, plastics, long haul trucking, shipping and aviation are responsible for almost one third of global emissions.[6] In Australia, when excluding trucking and shipping, they account for approximately 16% (almost 82Mt of CO_2-e) of emissions.[7]

CCU can be used as part of the portfolio of decarbonisation approaches for these difficult to abate or unavoidable emissions, alongside the adoption of renewables, process change, sequestration and negative emissions technologies. This can help Australian hard-to-abate industries remain competitive by providing another option to achieve their net zero commitments while also supporting the transition to lower-emissions products. Importantly, any CCU investment should be paired with product lifecycle assessments and energy efficiency evaluations to ensure and provide transparency on emissions reductions. Using CCU as part of a decarbonisation portfolio would help to:

- Pro-actively position CCU as complementary, rather than competitive, with investment in other vital decarbonisation technologies;
- Develop world class sites and demonstrations for CCU investment to support the transition to lower-emissions products and contribute to global decarbonisation efforts, focusing on the third of global emissions that have limited decarbonisation alternatives;
- Scale up CCU projects with manageable infrastructure and feedstock requirements, maintaining alignment with Australia's National Hydrogen Strategy and investment in hubs; and
- Position the country for further scale-up aligned to the longer term CCU related resources and technology export opportunities.

To illustrate this strategy and support further discussion, three scenarios have been developed exploring how a portion of annual hard-to-abate emissions could be managed via deployment of various CCU applications. In particular, it demonstrates the scale of infrastructure that would be required for large scale deployment of CCU.

- Low CCU adoption: The low CCU adoption scenario explores slow CCU uptake that is not well integrated in national and industry strategies.
- Moderate CCU adoption: The moderate CCU adoption scenario explores proactive use of CCU as part of Australia's decarbonisation strategy.
- Stretch CCU adoption: The stretch CCU adoption scenario explores how CCU could be used to achieve decarbonisation objectives as well as position Australia for long-term export outcomes.

6 World Economic Forum (2020) *Tackling the harder-to-abate sectors*. Viewed 3 May 2021, https://www.weforum.org/agenda/2020/07/tackling-the-hard-to-abate-sectors-join-the-conversation/

7 The definition of 'hard-to-abate' industries varies but for the purpose of this report it refers to the following categories in the Australian Government's National Inventory Report Volume 1; industrial processes and product use (including the mining, chemicals and metals industry), manufacturing industries and construction, and domestic aviation. Australian Government Department of Industry, Science, Energy and Resources (DISER) (2021) *National Inventory Report Volume 1*. DISER

Abatement potential	Methanol	Electrofuel	Olefins	SNG	Mineral carbonation
LOW CCU ADOPTION ~8–10% Hard to abate emissions	2.6–4.4Mt CO_2 avoided from 2 facilities				3.8Mt CO_2 permanently stored using 2 facilities
MODERATE CCU ADOPTION ~23–30% Hard to abate emissions	3.9–6.6Mt CO_2 avoided from 3 facilities	2.3–4.2Mt CO_2 avoided from 2 facilities	1.4–2.5Mt CO_2 avoided from 1 facility		11.4Mt CO_2 permanently stored using 6 facilities
STRETCH CCU ADOPTION ~39–50% Hard to abate emissions	6.5–11Mt CO_2 avoided from 5 facilities	3.6–6.3Mt CO_2 avoided from 3 facilities	1.4–2.4Mt CO_2 avoided from 1 facility	1.2–2.1Mt CO_2 avoided from 1 facility	19Mt CO_2 permanently stored using 10 facilities

Low CCU adoption:

Requirements: 3 GW of H_2 electrolyser capacity, 3.7Mt CO_2 from point sources and/or DAC

Requirements: Feedstock + 3.7Mt CO_2 from point sources and/or DAC (for negative emissions)

Moderate CCU adoption:

Requirements: 8 GW of H_2 electrolyser capacity, 11Mt CO_2 from point sources and/or DAC

Requirements: Feedstock + 11Mt CO_2 from point sources and/or DAC (for negative emissions)

Stretch CCU adoption:

Requirements: 15 GW of H_2 electrolyser capacity, 18Mt CO_2 from point sources and/or DAC

Requirements: Feedstock + 18Mt CO_2 from point sources and/or DAC (for negative emissions)

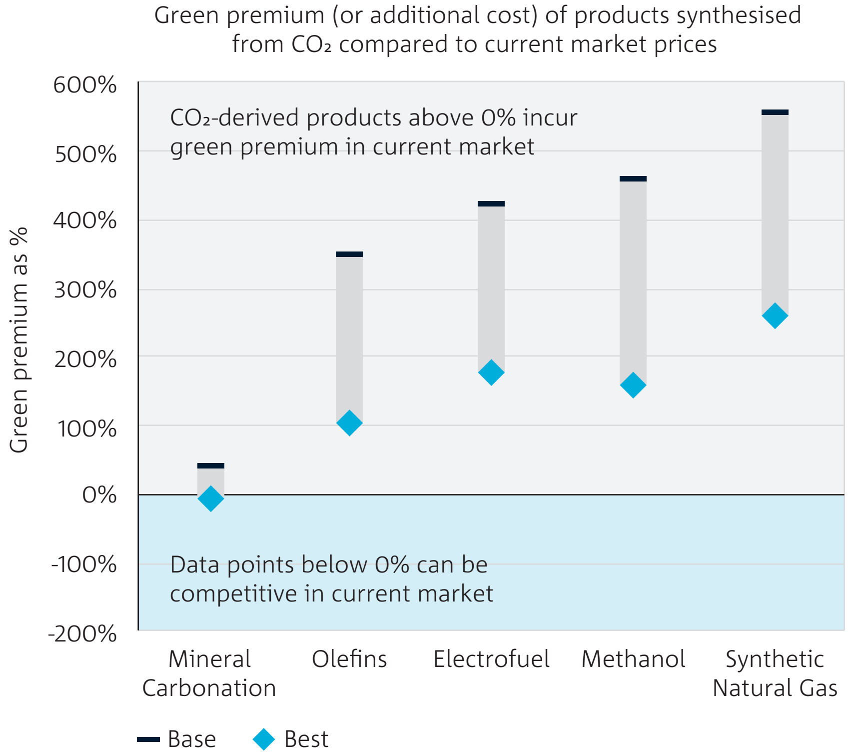
The scenarios developed are illustrative and explore the percent of hard-to-abate emissions that different levels of CCU adoption could achieve per annum. The definition of 'hard-to-abate' industries varies but for the purpose of this report it refers to the following categories in the Australian Government's National Inventory Report Volume 1; industrial processes and product use (including the mining, chemicals and metals industry), manufacturing industries and construction, and domestic aviation. Note that these scenarios describe ambitious stretch targets for CO_2 utilisation. Achieving these outcomes would require substantial action to scale up CCU in the near future. CO_2 abatement potential uses production as a boundary condition and does not consider full lifecycle emissions. See full report and Appendix D for details and assumptions.

3 Explore incentives and minimise barriers to entry

Creating the right incentives and minimising barriers to entry will be key for scale up, as almost all near term CCU applications will incur a green premium (i.e. the additional cost of choosing the low-carbon alternative). An exception is mineral carbonation which could be competitive in the near-term depending on the use case. The commercial potential of CCU applications will hinge on the speed at which green premiums can be reduced, and how incentives and policy and regulatory mechanisms can be used to bridge the remaining gap.

Green premiums can be reduced by driving down the cost of CCU production, by rising costs for the carbon intensive incumbent, or a combination of both.

The diagram below shows the green premiums or additional costs of products synthesised from CO_2 compared to current market prices. These green premiums highlight the challenges that exist, particularly in the global transitions to low emissions chemicals and fuels. However, these green premiums are not static and the competitiveness of CCU can be altered in various ways. For example, the cost of CCU derived products can be reduced through technology breakthroughs, larger production volumes and lower cost feedstocks. At the same time, the cost of the carbon intensive incumbent can increase based on carbon pricing, changes in demand and geopolitics.



Cost of low carbon CCU derived products can be reduced as a result of:

- Carbon intensity accreditation, guarantees and offsets
- Increasing production scale
- Lowering feedstock costs (e.g. electricity prices, CO_2, hydrogen, mineral carbonates)
- Technology (e.g. direct synthesis)
- Improved utilisation of existing infrastructure (e.g. hubs)

Cost of carbon intensive incumbent can increase to make CCU more competitive as a result of:

- Global or domestic carbon prices or tariffs
- Increased demand and prices for high quality carbon offset
- Electrification and fuel switching (which could impact petrochemical refinery margins and costs)
- Geopolitics and supply chain disruptions

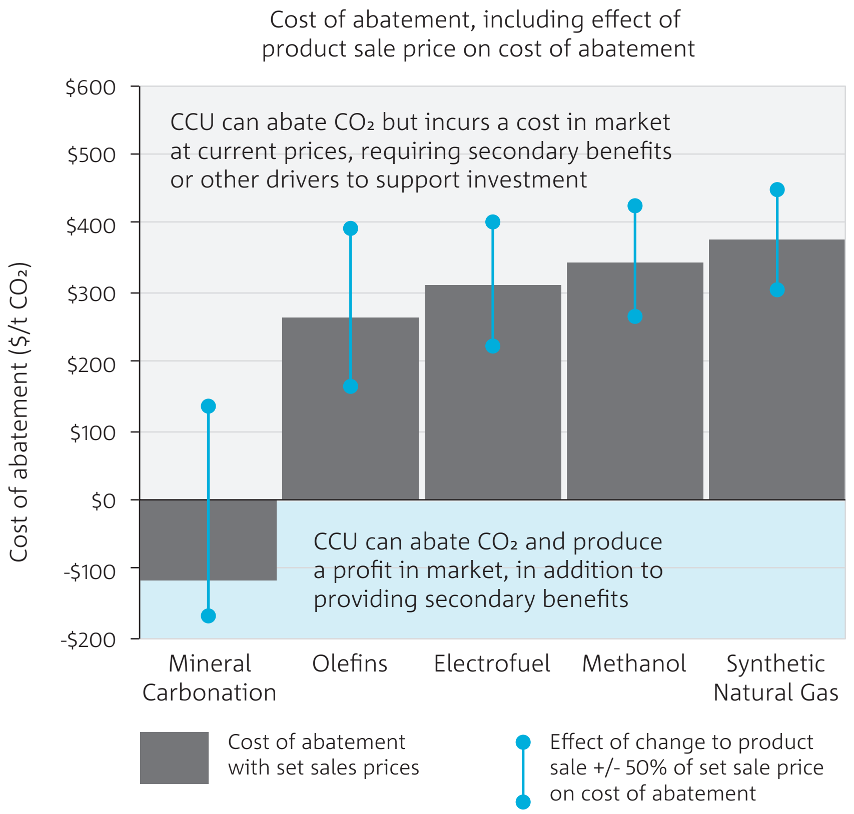
This diagram shows the green premium for each CCU application modelled. For each application, base and best case results are shown. The base case result is assessed on mature technologies available today, with the best case considering projects currently in development and projections for technology capacity in the medium term. A green premium of greater than 0% indicates the low emissions alternative is more expensive than the incumbent product. Carbon pricing, such as through ACCUs, can lower green premiums. Assumed sales prices are as follows: Mineral Carbonation (Silica:$40/t, MgCO3:$100/t), Olefins ($1000/t), Jet Fuel ($85/bbl), Methanol ($250/t), SNG ($8/GJ). See full report for all assumptions and other modelled CO_2 sources.

CO_2 abatement costs should be considered alongside technology improvements, revenue potential, secondary benefits and lifecycle assessments.

In many cases, to achieve net zero targets, extra costs will need to be absorbed by organisations. To do so, emitters will seek the most cost-effective method to achieve the goals they have set out, aiming for the lowest cost of abatement available considering the different CO_2 lock-in potentials. However, it is important to consider the broader value proposition beyond managing CO_2 liabilities, such as the co-benefits of CCU products. For example, mineral carbonation can permanently store CO_2 compared to other applications and also aid in neutralising mine waste. Further, synthetic fuels burn more efficiently and with fewer contaminants.[8]

With a minimised green premium, mechanisms and incentives can help to bridge the final gap. There are a broad range of international industry and policy examples that could support adoption. Examples include:

- Tax credits and subsidies
- CCU related carbon intensity accreditation and guarantees to reward low carbon investments
- Quotas to guarantee offtake of CO_2-based products
- Commercial mechanisms to demonstrate and scale technologies.



Investment considerations:

- Investment in lowering production costs for CCU applications can lead to a negative cost of abatement result (i.e. a profit from abatement), in addition to reducing liabilities related to CO_2.
- Understanding changes in product sales prices can influence the cost of abatement or create new revenue streams. However, even if a green premium exists, the cost of abatement can still be low and the cheapest way for an organisation to decarbonise.
- Considering secondary benefits can support investment. For example, mineral carbonation can neutralise mine waste, and synthetic fuels burn more efficiently.
- Analysis of lifecycle emissions are required to help qualify products for carbon intensity accreditation or incentive schemes.

Cost of abatement calculates how much each tonne of CO_2 costs to avoid. The diagram examines each CCU application's best case with high partial pressure capture, where 5,000t/day of CO_2 is consumed, with the products sold at a set market price. Assumed sales prices are as follows: Mineral Carbonation (Silica:$40/t, MgCO3:$100/t), Olefins ($1000/t), Jet Fuel ($85/bbl), Methanol ($250/t), SNG ($8/GJ). The products to the left have the lowest cost of abatement and from an emitter's perspective are likely to be pursued first.

8 Argonne National Labs (2012) *Life Cycle Analysis of Alternative Aviation Fuels in GREET*. US DOE

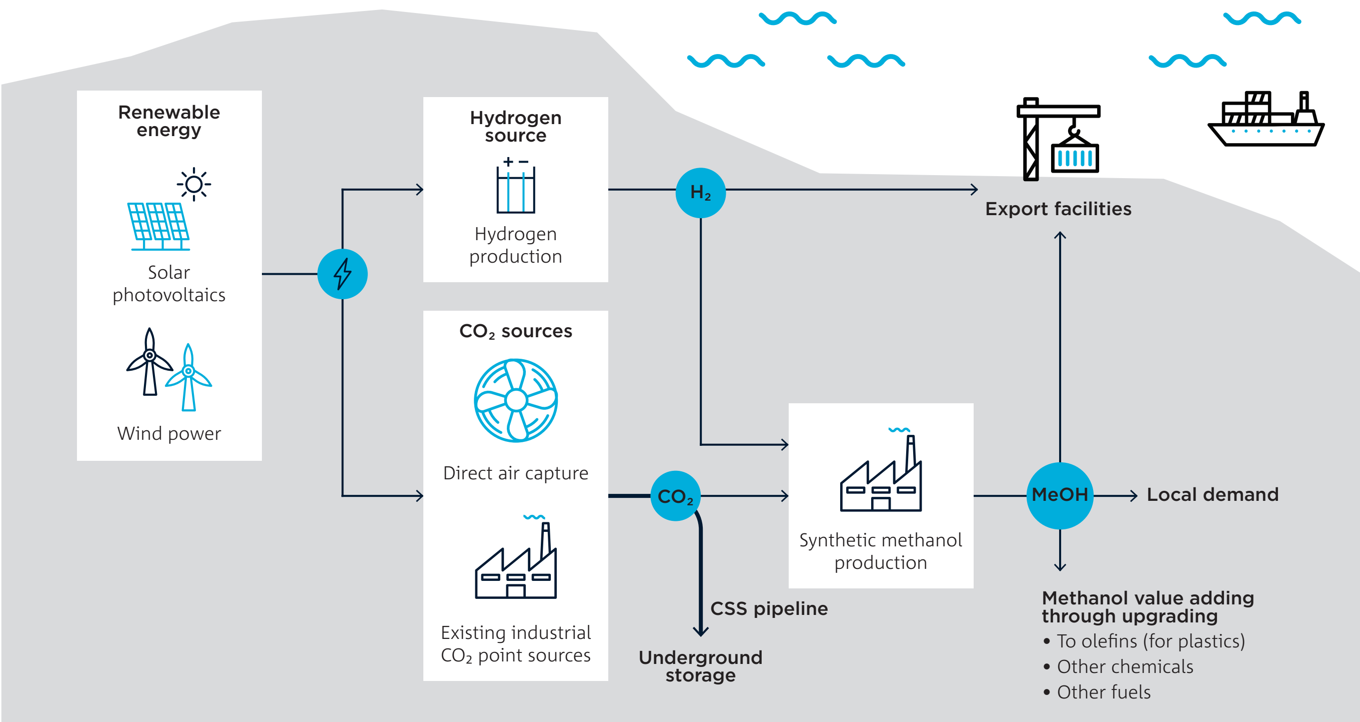
4 Use CCU to support or de-risk investment in existing and planned infrastructure

All CCU applications require infrastructure to capture, distribute and utilise CO_2, as well as substantial quantities of renewable energy to carry out each of these processes. The most efficient deployment of CCU technologies will be at sites where it can leverage infrastructure that already exists or is planned for construction. As such, deployers should consider how CCU can add value to industrial and energy hubs, and de-risk investment.

CCU can be used to offset some of the costs of CO_2 capture through revenue generated from utilisation and add value to infrastructure investment. In the case of CO_2 conversion to chemicals and fuels, CCU can become a CO_2 and hydrogen offtaker, allowing the creation of a higher value-added product (e.g. methanol, fuels) that could support hydrogen generation and energy storage.

The figure below describes a concept for a methanol hub, which makes use of hydrogen and CO_2 capture infrastructure to produce methanol and subsequently upgrade methanol to other value-added products.

Methanol hub: Scale-up alongside existing/planned infrastructure to complement and de-risk investment



Energy and land requirements

The table below describes the requirements for a methanol plant operating at a capacity of 3,182 tonnes/day, which consumes 5,000 tonnes of CO_2, obtained from point source industrial emissions. Roughly 5,000MW of solar power is estimated to be required, largely to power hydrogen production, with smaller amounts of energy needed for the methanol synthesis facility and CO_2 capture.

For perspective, the Star of the South project could generate up to 2,200MW of offshore wind renewable capacity on Victoria's coast,[9] the proposed Asian Renewable Energy Hub in Western Australia could generate 26,000MW of offshore wind and solar capacity, and the recently proposed Western Green Energy Hub could see the production of up to 50,000MW of hybrid wind and solar power.[10]

The 120km² land required for 5,000MW solar PV capacity is approximately 3 times the land size of the average Australian farm.[11] Land use requirements depend on the capacity factors of the renewables, which is reflected in the ranges shown in the table below. With Australia's vast land resources, this requirement can be accommodated, with the appropriate land rights and environmental approvals.

SCENARIO	HYDROGEN REQUIRED	RENEWABLE ENERGY CAPACITY REQUIRED	LAND USE FACTOR[12]	LAND REQUIRED
Solar PV (high-low capacity)	~670 t/day	4.6–5.2 GW	2.5 ha/MW	112–126 km²
Wind (high-low capacity)	~670 t/day	3.1–3.7 GW	18.1 ha/MW	549–659 km²

Land required relates to overall land requirements, however only about 3% of the land for wind power will be used for development of turbines and supporting infrastructure.[13] Land use factors are high level estimates only and vary depending on location.

9 Star of the South Wind Farm (2020) *Project Overview*. Viewed 11 June 2021, https://www.starofthesouth.com.au/project-overview

10 The Western Green Energy Hub (2021) *Western Green Energy Hub in Australia set to transform global green fuels production in historic partnership with the Mirning People*. Viewed 20 July 2021, https://intercontinentalenergy.com/announcements/WGEH-PressRelease-20210713.pdf

11 Australian Bureau of Statistics (ABS) (2017) *7121.0 – Agricultural Commodities, Australia, 2015–16*. ABS.

12 National Renewable Energy Laboratory (NREL) (2021) *Land Use by System Technology*. Viewed 13 July 2021, https://www.nrel.gov/analysis/tech-size.html

13 LDC Infrastructure (2021) *Australia Wind Power – Wind Turbine Leases Explained*. Viewed 13 July 2021, https://ldcinfrastructure.com.au/wind-energy-lease-explained/

Introduction

Climate change and its effects is one the greatest challenges of the 21st century, with global emissions reaching over 33 gigatonnes of carbon dioxide (CO_2) in 2019 alone.[14] The scale and complexity of this challenge requires a number of decarbonisation solutions to reduce ongoing CO_2 emissions, transition toward low-emissions products, and remove atmospheric CO_2.

However, carbon based products remain part of society. In Australia, out of the 518.9Mt of carbon dioxide equivalent (CO_2-e) emitted in 2019, approximately 16% (almost 82Mt of CO_2-e) of emissions were roughly linked to hard or difficult to abate industries that play a major role in society (as shown in Figure 1). These industries are not easy to decarbonise with renewable technologies alone as they:

- **Rely on carbon from fossil fuels as building blocks for a broad range of products:** This includes the chemicals industry which requires carbon to create thousands of everyday products including plastics, adhesives, clothing, consumer items and construction materials.
- **Require high energy density fuels for long-distance transport:** For the distances required, electrification is not technologically feasible in the short to medium term. Therefore so sustainable fuels in industries such as commercial aviation are required.
- **Produce CO_2 emissions inherently in their processes:** For example, up to 60% of emissions from cement production are due to process emissions associated with converting limestone to clinker, one of the key components of cement.[15]

Although Australia's emissions for these industries are relatively low, the challenge is global with these industries accounting for almost one third of global emissions.[16]

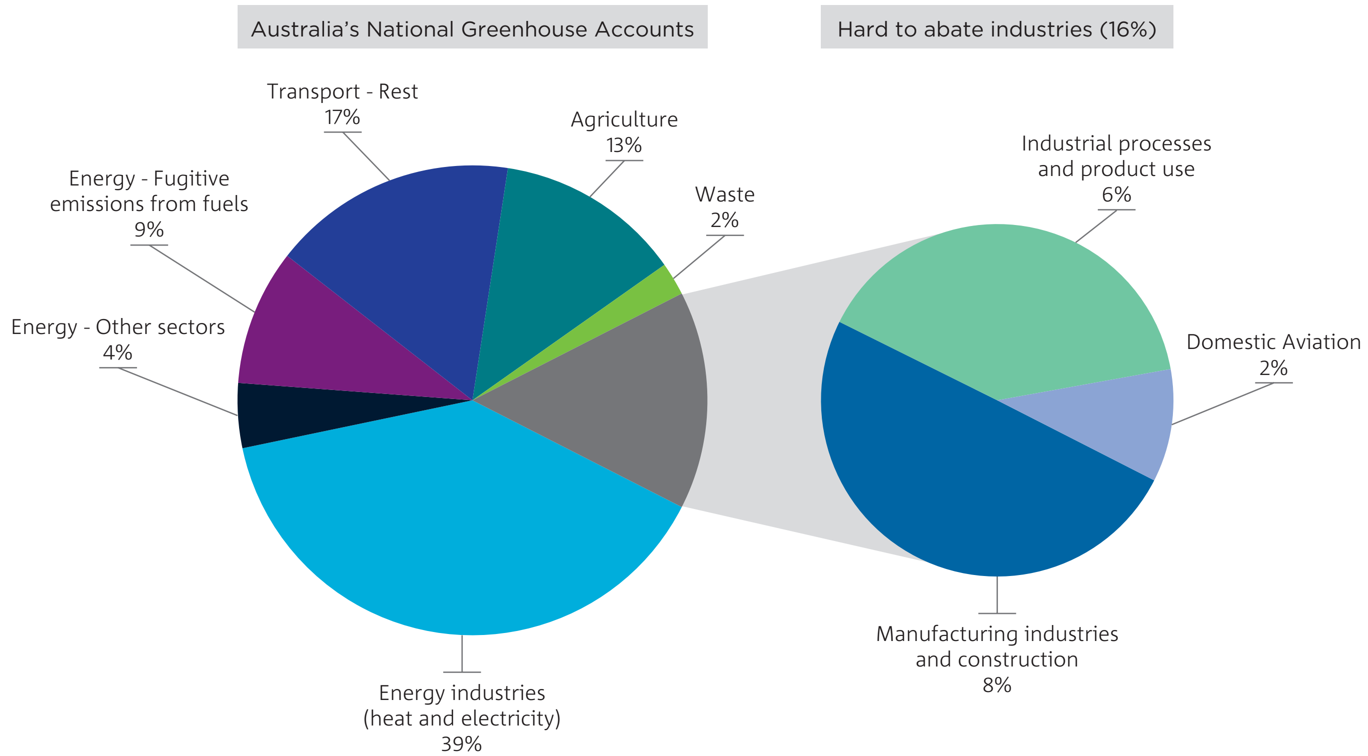


Figure 1: Understanding where emissions from industry face barriers to abatement in Australia

For the purposes of highlighting the abatement challenges across industries, land use, land use change and forestry have been removed as these industries can produce negative emissions. Hard-to-abate industries in Australia include industrial processes and product use (including the mining, chemicals and metals industry), energy related to manufacturing industries and construction and energy related to domestic aviation. See the National Inventory Report Volume 1[17] for more information. The definition of 'hard-to-abate' industries varies but for the purpose of this report it refers to those industries examined in this figure.

14 International Energy Agency (2021) *Net Zero by 2050*. IEA

15 Cement Industry Federation (2020) *Australian Cement Report*. Cement Industry Federation

16 World Economic Forum (2020) *Tackling the harder-to-abate sectors*. Viewed 3 May 2021, https://www.weforum.org/agenda/2020/07/tackling-the-hard-to-abate-sectors-join-the-conversation/

17 Australian Government Department of Industry, Science, Energy and Resources (DISER) (2021) *National Inventory Report Volume 1*. DISER

With no change, demand for these carbon-based products and industries will continue to increase and rely on the extraction of fossil fuels. One example of this is plastics, which are predominantly derived from fossil fuels and are ubiquitous in households, workplaces and industries. Demand for plastic products is expected to double by 2050, even with recycling rates increasing from today's 14% to more than 55%, demonstrating the need for new sustainable feedstocks to meet demand.[18]

The global challenges related to climate change raises the question of how continued demand for these products that are embedded in society can be supported, while addressing CO_2 emissions.

The carbon capture and utilisation (CCU) opportunity

CCU creates the opportunity to capture emitted CO_2 and convert it for use, avoiding or reducing further emissions, minimising risks or liabilities related to CO_2, and supporting the transition to low emissions products.

CO_2 is already utilised in a number of industries. The Australian food and beverage industry has been using CO_2 for decades in beverages, such as soft drinks, beer and sparkling drinks, to create their effervescence and increase shelf life. CO_2 is also used indirectly through the manufacture of urea, a feedstock for fertilisers, and salicylic acid which is used to make aspirin.

Scaling up CCU, particularly through the conversion of CO_2, creates a pathway to use large quantities as a feedstock. Emerging opportunities to convert CO_2 include the production of chemicals (e.g. plastics and synthetic rubber), building materials (e.g. concrete) and fuels (e.g. diesel and aviation fuels). Doing so supports decarbonisation efforts, creates a revenue stream that can help offset CO_2 capture costs and helps to service the ongoing demand for carbon-based products.

The available applications for CCU are broad (see Figure 2) and can make use of existing CO_2 in industrial waste streams or the atmosphere. As discussed throughout this report, CCU is a complementary, low emissions technology and can be used in parallel with renewables, hydrogen, carbon, capture and storage (CCS), solar thermal and emerging negative emissions technologies.

While promising, CCU applications are still emerging and will require significant investment to be economic at scale. Therefore, the case for CCU in Australia can be characterised by considering:

- The potential for CCU to reduce emissions and support the transition towards lower-emissions products;
- The global momentum surrounding CCU projects, supported by broader government and industry commitments to achieve net zero emissions; and
- Australia's position to capitalise on the CCU opportunity and become a leader in this emerging market – and do so in a way that supports near- and long-term national decarbonisation objectives and economic outcomes.

As CCU continues to evolve, clarity around terminology and points of overlap between CCU and carbon capture and storage (CCS) is required for translation across global systems (see Box: Defining CCU in the Australian landscape).

18 Ellen MacArthur Foundation (2016) *The New Plastics Economy Rethinking the future of plastics.* World Economic Forum

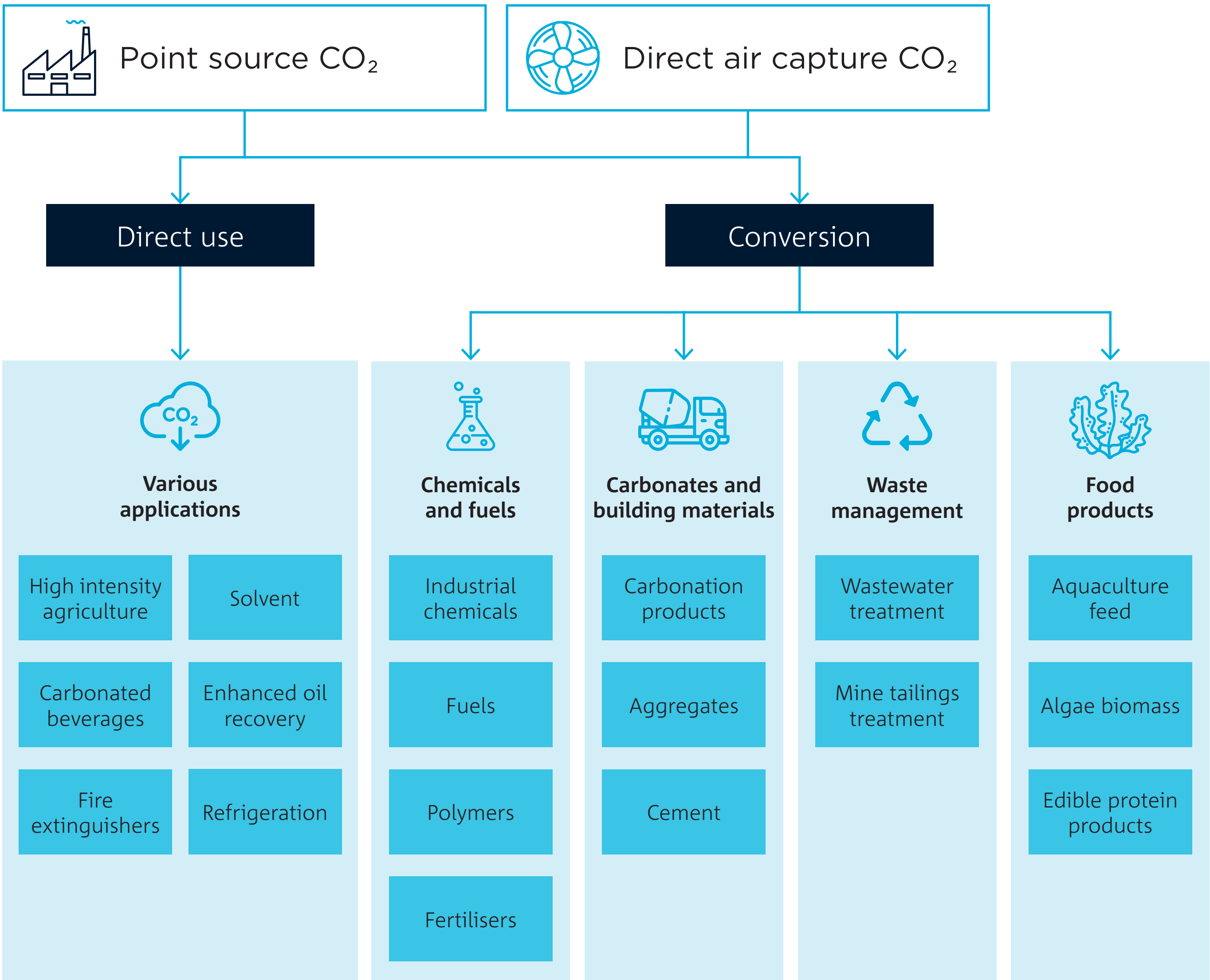


Figure 2: Summary of carbon capture and utilisation applications

Defining CCU in the Australian landscape

Carbon capture and utilisation (CCU) is defined as the conversion of CO_2 captured from emissions sources or the atmosphere into valuable low or zero emission products.

This differs from carbon capture and storage (CCS) where CO_2 is captured, transported, and buried in underground geological formations for permanent storage.

CCU and CCS both capture carbon and can make use of distribution infrastructure. However, the last stage of utilisation and storage differs. Therefore, CCU and CCS should be viewed as complementary, rather than competing technologies. As hydrogen is required in many CCU processes, CCU and hydrogen should also be viewed as complementary.

Carbon capture, utilisation, and storage (CCUS) is an umbrella term used to group both CCU and CCS.

The categorisation of some processes differs globally. Enhanced Oil Recovery (EOR) for example, where CO_2 is pumped underground to recover hydrocarbons with permanent CO_2 storage, is considered by some as CCS rather than CCU whereas some international markets consider EOR in the context of CCU. Mineral carbonation can also be used to support the remediation of mine tailings dams whereby the CO_2 would be stored permanently as part of waste management. These distinctions create some overlap between CCU and CCS as shown in Figure 3.

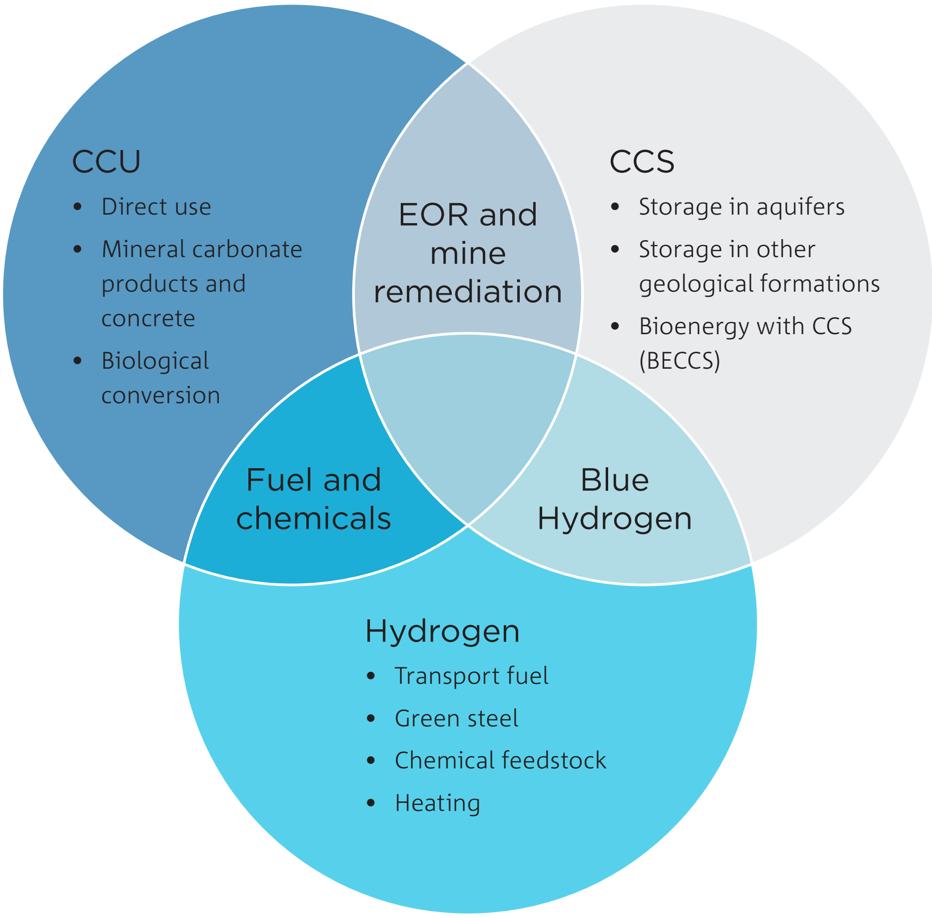


Figure 3: The relationship between CCU, CCS and the hydrogen industry

The potential for CCU to reduce emissions and support the transition towards lower-emissions products

The potential role of CCU in global decarbonisation efforts requires understanding of the nuances that exist when considering different CO_2 capture sources and different product lifespans.

CO_2 capture sources can include point source emissions from industrial waste streams or the capture of CO_2 from the atmosphere through direct air capture (DAC) technologies. Point source CO_2 capture is reasonably mature, however uptake is limited due to cost barriers and lack of incentives. CO_2 capture from the atmosphere is nascent and has not yet been demonstrated at scale.

Product lifespans provide a useful metric to consider the length of time CO_2 is locked away. For example, some CCU applications can store CO_2 away for the long term, such as some high value polymers; or permanently in the case of most mineral carbonation applications, where CO_2 is reacted with naturally minerals to form solid carbonates. Products with shorter lifespans include fuels where the CO_2 contained within the product is released to the atmosphere when that product is used.

While simplistic, Figure 4 helps explore theses nuances using three examples:

- **Typical pathways for fossil fuels and fossil fuel-based products:** In this example, carbon flows from fossil fuels that are extracted from the ground and released to the atmosphere in the form of CO_2 when the product is used. This scenario entails high carbon intensity products and processes.
- **CCU with CO_2 captured from an industrial waste stream:** In this example, carbon flows from the ground to an industrial user, then the CO_2 generated is captured and utilised again through conversion into products. This theoretically reduces the overall carbon intensity of the products and processes as the carbon molecules are being used more than once. The consideration of product lifespan plays an important role under this example. For short lifespan CCU products such as fuels, the CO_2 is released back into the atmosphere. Although there is a reduction in the total amount of CO_2 theoretically entering the atmosphere, a fuel derived from CCU results in CO_2 avoidance and the product cannot be considered carbon neutral under this example. In contrast, products with longer lifespans can result in the CO_2 being locked away, resulting in CO_2 abatement through the permanent storage of CO_2.
- **CCU with CO_2 sourced from the atmosphere such as through (DAC) technologies:** In this example, the carbon is captured from the atmosphere and flows to an industrial user, where it is converted into a product. Products with short lifespans result in the carbon being released again upon use. This could theoretically classify the product as carbon neutral, as the carbon's flow is a closed loop. When CO_2 from the atmosphere is converted for use in a longer lifespan product, it has the potential to result in negative emissions.

CCU technologies can play an integral role in a circular carbon economy, as it promotes recycling and reuse of CO_2 as a raw material in downstream products and fuels. Importantly, it supports the transition to low emissions products and can help reduce reliance on carbon offsets and credits, which may have constraints as global supply and demand increases (see Box: The challenge with over-reliance on carbon offsets).

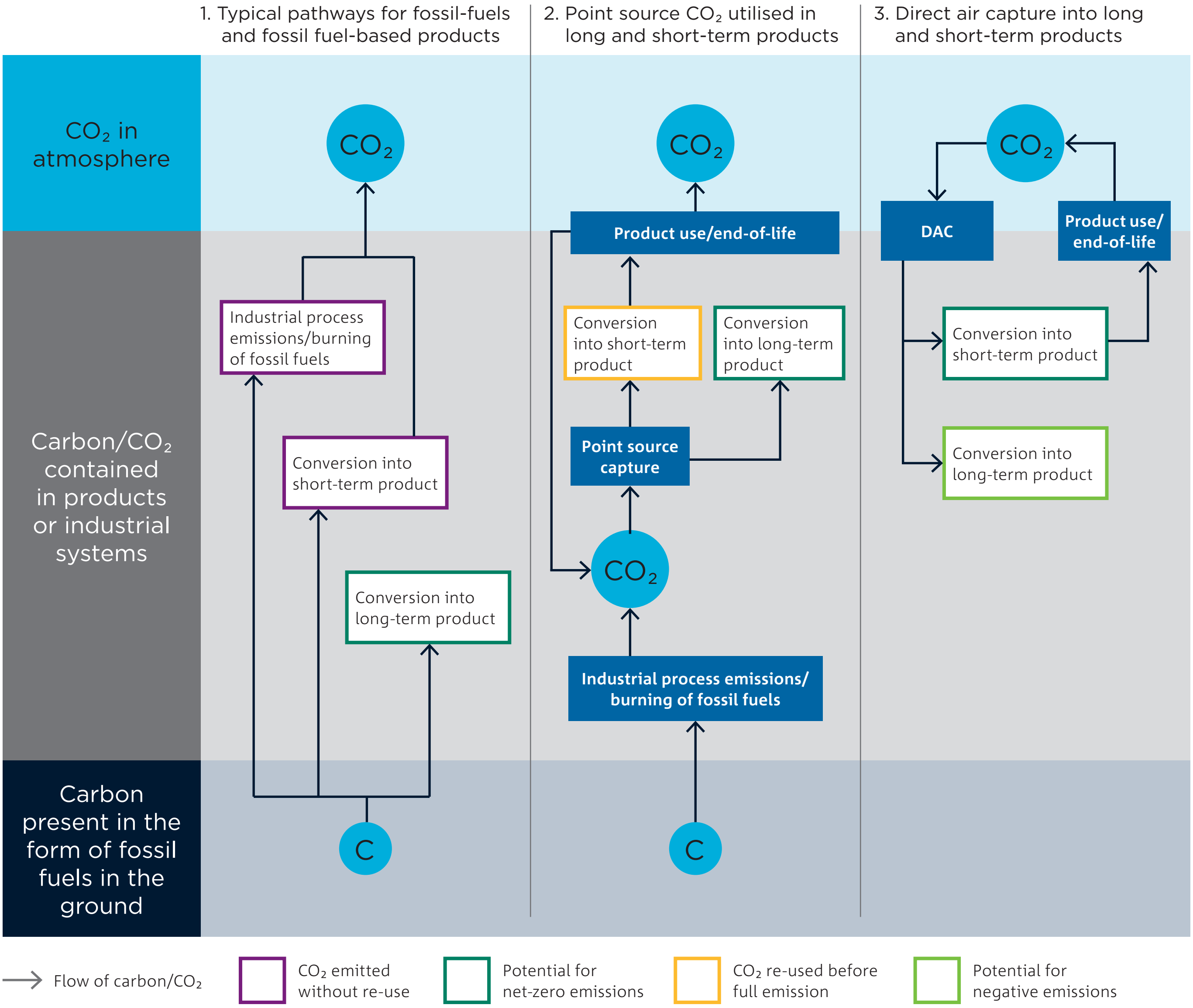


Figure 4: Summary of the potential of CCU

The figure synthesises information presented by the Science Advice for Policy by European Academies (2018).[19] The extent to which carbon is abated/avoided or the overall emissions intensity of products are reduced is dependent on the CO_2 source and its end use. Using CO_2 captured from a point source (2) for short-term applications leads to an overall reduction in emissions intensity, however net CO_2 is still released into the atmosphere. Using CO_2 capture from the atmosphere (3) for short-term applications can result in closed-loop net zero emissions products.

19 Science Advice for Policy by European Academies (SAPEA) (2018). *Novel carbon capture and utilisation technologies: research and climate aspects*. SAPEA

The challenge with over-reliance on carbon offsets

Carbon prices globally are projected to increase as a result of demand and environmental regulatory change. Carbon price projections indicate advanced economies may be paying up to $362 per tonne of CO_2 by 2050.[20] This presents a risk for hard-to-abate industries that may be subjected to paying carbon prices for a portion of their current emissions.

Carbon credits (or offsets) are also an important lever for industry to reduce greenhouse gas emissions. A 'carbon credit' is a verification that one tonne of carbon dioxide equivalent has been prevented from being emitted, or has been removed from the atmosphere.[21] In response to the proliferation of emissions targets, there is likely to be increased demand for carbon offsets. Pressure from shareholders to voluntarily adopt more aggressive emissions reduction targets is likely to cause a further spike in the voluntary carbon credits market.

As demand for carbon credits surges globally and available supply weakens, prices are projected to increase.[22] Adding complexity to this, there is likely to be greater demand for high quality carbon credits that have robust verification and accounting measures embedded across their supply chain. Land-based carbon credits are also likely to face increased pressure as they provide additional benefits beyond carbon sequestration, such as biodiversity conservation and erosion control, and global supply is finite.[23] A summary of the consequences of increased carbon prices on carbon credits supply security is shown in Figure 5.

Beyond commercial considerations, there is growing concern about the capability of carbon credits to offset current and future global CO_2 emissions, as there is finite capacity of any ecosystem to store carbon (including through reforestation).[24] As a result of price increases in carbon credits and the finite capacity of terrestrial ecosystems to absorb carbon, carbon capture and negative emissions technology are likely to be needed to support the removal of CO_2 from the atmosphere.

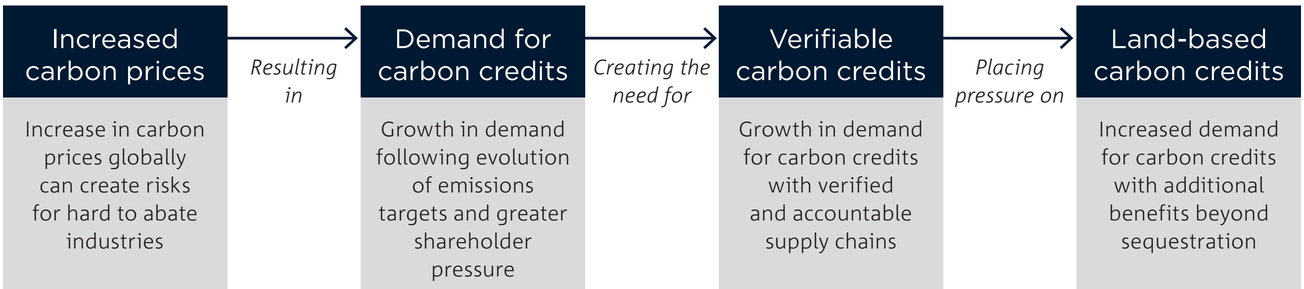


Figure 5: Potential implications of changes to carbon prices on carbon credits

20 Converted to AUD from USD using an exchange rate of 0.69. IEA (2021) *Net Zero by 2050: A Roadmap for the Global Energy Sector.* IEA

21 Blaufelder C, Katz J, Levy C, Pinner D & Weterings J (2020) *How the voluntary carbon market can help address climate change.* McKinsey & Company

22 Brinkman M (2010) *A new look at carbon offsets*. McKinsey & Company

23 Mackey, B, Prentice, C, Steffen, W, House, JI, Lindenmayer, D, Keith, H & Berry, S (2013) *Untangling the confusion around land carbon science and climate change mitigation policy.* Nature Climate Change

24 Mackey, B, Prentice, C, Steffen, W, House, JI, Lindenmayer, D, Keith, H & Berry, S (2013) *Untangling the confusion around land carbon science and climate change mitigation policy.* Nature Climate Change

The global momentum surrounding CCU projects, supported by broader government and industry commitments to achieve net zero emissions

Global commitments to achieve net zero emissions by mid-century are becoming increasingly common, with commitments doubling in less than a year, as governments and businesses prioritise climate action as part of their recovery from COVID-19.[25] These global commitments are leading to greater consideration of lifecycle emissions related to traded resources and products. For example, the European Parliament recently backed plans to consider the greenhouse gas (GHG) emissions of imported products, to avoid penalising climate action and efforts of domestic industries and governments.[26] A similar trade policy is also under consideration by the US government.[27]

Growing policy recognition and industry interest is leading to investment (see Figure 6) in CCU projects including the use of CO_2 in building materials, such as concrete and aggregates, the conversion of CO_2 into fuels, and the development of CO_2-derived polycarbonate chemicals. These investments are expected to rapidly increase, especially with countries such as the United States expressing a commitment and providing a framework to accelerate investment in CCUS technologies.[28] They are also closely tied to the broader pursuit of a circular economy by promoting the closed loop use of CO_2.

In 2021, the Australian Government announced the $50 million Carbon Capture, Use and Storage Development Fund to support the Government's Technology Investment Roadmap, with $26 million of that funding going towards mineral carbonation and concrete applications. In its statement, the government outlined carbon capture technologies, such as carbon recycling, negative emissions and direct air capture as being critical to achieving net zero emissions.[29]

Australia is well positioned to capitalise on the CCU opportunity and become a leader in this emerging market

CCU can play a key role in reducing emissions and providing Australia with a range of low emissions technology opportunities. These opportunities can be capitalised on in a way that helps maintain the competitiveness of hard-to-abate domestic industries and positions Australia for a role in servicing the long term demand for carbon-based products.

This will require action and investment to prepare Australia for the longer term global opportunity related to CCU. For example, Australia will need to scale up its ability to manufacture CO_2-derived products, increase CO_2 capture deployments and encourage complementary development of industrial hubs and investment in hydrogen, renewable energy and negative emissions technologies.

25 United Nations Framework Convention on Climate Change (2020) *Commitments to Net Zero Double in Less Than a Year.* Viewed 3 May 2021, https://unfccc.int/news/commitments-to-net-zero-double-in-less-than-a-year

26 Van Leeuwen H (2021) *European Parliament backs carbon border tax*. Viewed 27 January 2021, https://www.afr.com/policy/energy-and-climate/european-parliament-backs-carbon-border-tax-20210311-p579o9

27 United States Trade Representative (2021) *2021 Trade Policy Agenda and 2020 Annual Report.* https://ustr.gov/sites/default/files/files/reports/2021/2021%20Trade%20Agenda/Online%20PDF%202021%20Trade%20Policy%20Agenda%20and%202020%20Annual%20Report.pdf

28 White House Council on Environmental Quality (2021). *Council on Environmental Quality Report to Congress on Carbon Capture, Utilization, and Sequestration.* US Government

29 Minister for Energy and Emissions Reduction (2021) *Accelerating carbon capture technologies*. Viewed 9 June 2021, https://www.minister.industry.gov.au/ministers/taylor/media-releases/accelerating-carbon-capture-technologies

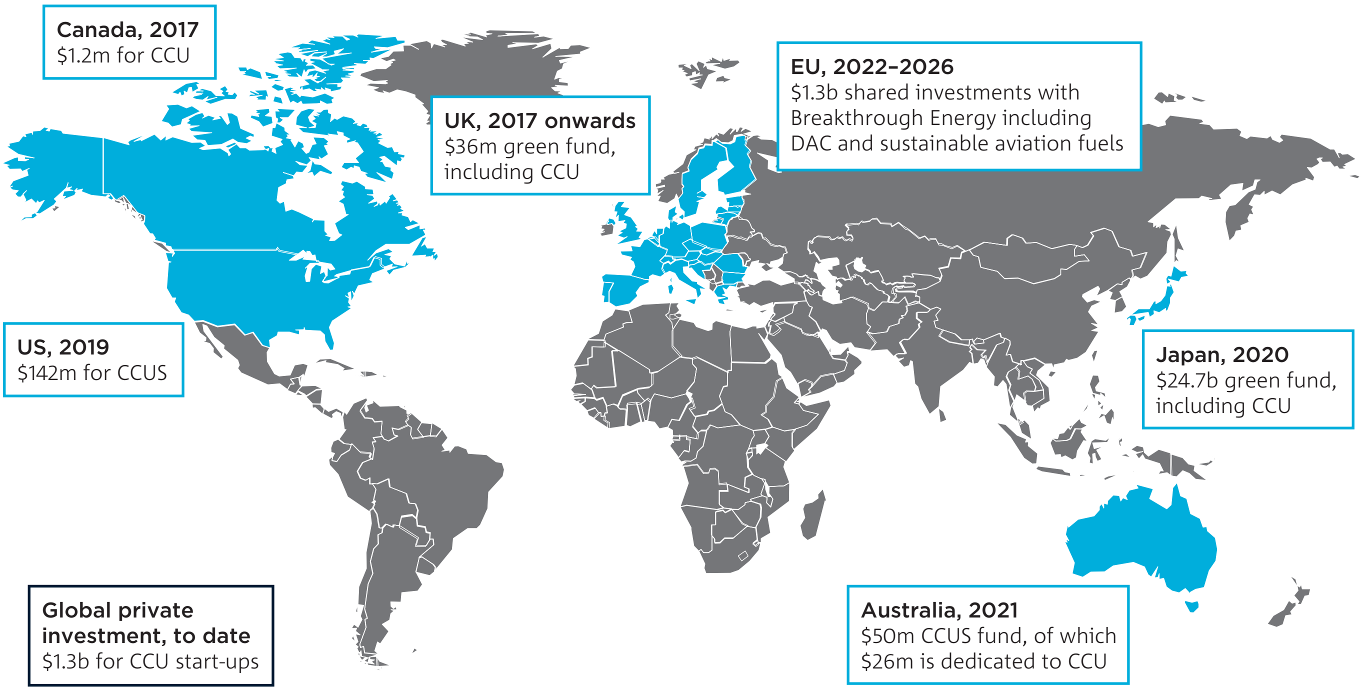


Figure 6: Major government and shared public-private investment in CCU projects[30]

Fortunately, Australia is situated to capitalise on the CCU opportunity due to domestic comparative advantages and trends that support scale-up, including:

Bilateral CCU collaborations: The Australian Government has recognised the importance of accelerating development of CCU with key trading partners, including the Australia and Japan Memorandum of Understanding (MoU) for Cooperation to explore the development of carbon recycling technologies in 2019[31] and the Australia and Singapore MoU for Cooperation on Low-Emissions Solutions announced in 2020, which includes CCUS.[32]

Large volumes of feedstocks: Australia has a number of large emitters that can act as a low-cost source of CO_2 as well as the land availability and renewable potential to capture atmospheric CO_2 using DAC technologies in the longer term. The growing commercial and government investment in hydrogen production is a key enabler of major CCU applications, such as fuels. The large volumes of industrial and mining waste products produced by Australian industry are a key input for mineral carbonate products and are available within industrial hubs and precincts across the country.

Projected low cost electricity: Australia has vast potential for low-cost renewable electricity. The nation's solar radiance and wind resources are among the best in the world, which can support internationally competitive electricity costs in the future.[33] This can be leveraged by CCU applications that often require large amounts of cost-effective renewables.

30 Nikkei Asia (2020) *Japan creates $19bn green fund to push hydrogen planes and carbon recycling*. Viewed 30 April 2021, https://asia.nikkei.com/Spotlight/Environment/Climate-Change/Japan-creates-19bn-green-fund-to-push-hydrogen-planes-and-carbon-recycling; Ministry of Economy, Trade and Industry (METI) (2019) *Roadmap for Carbon Recycling Technologies.* Japanese Government; Australian Government Minister for Energy and Emissions Reduction (2021) *$412 million of new investment in carbon capture projects*. Viewed 9 June 2021, https://www.minister.industry.gov.au/ministers/taylor/media-releases/412-million-new-investment-carbon-capture-projects; European Commission Scientific Advice Commission (2018) *Novel carbon capture and utilisation technologies.* European Commission; Department for Business, Energy and Industrial Strategy (2019) *Carbon Capture and Utilisation Demonstration (CCUD) innovation programme.* Government of United Kingdom; United States Department of Energy (2021) *Department of Energy Announces $110M for Carbon Capture, Utilization, and Storage*. Viewed 22 January 2021, https://www.energy.gov/articles/us-department-energy-announces-110m-carbon-capture-utilization-and-storage; Natural Resources Canada (2017) *Government of Canada Invests $950,000 in New Carbon Capture Technology in Richmond, B.C.* Viewed 22 January 2021, https://www.canada.ca/en/natural-resources-canada/news/2017/09/government_of_canadainvests950000innewcarboncapturetechnologyinr.html; International Energy Agency (IEA) (2019) *Putting CO2 to Use.* IEA

31 Australian Government Department of Industry, Science Energy and Resources (2019) *Australia, Japan sign carbon recycling agreement.* Viewed 30 April 2021, https://www.minister.industry.gov.au/ministers/canavan/media-releases/australia-japan-sign-carbon-recycling-agreement

32 Australian Government Minister for Energy and Emissions Reduction (2020) *Australia and Singapore to work together to accelerate low emissions technologies.* Viewed 30 April 2021, https://www.minister.industry.gov.au/ministers/taylor/media-releases/australia-and-singapore-work-together-accelerate-low-emissions

33 CSIRO Futures (2019) *Australian National Outlook 2019*. CSIRO

Track record for exporting resources: Australia has a long history of developing internationally competitive industries, which can be leveraged to export CCU products and technologies and service the ongoing global demand for carbon-based products. These industries have existing industrial ecosystems, infrastructure and capabilities that could be leveraged.

Decarbonisation commitments across hard-to-abate industries: Australia's established industries face barriers to abatement, with many of these industries providing national economic security and supply of domestic goods. CCU can provide a pathway to maintain the competitiveness of these industries over the long term, while supporting the large-scale demonstration of CCU at established industrial sites. For example, the Australian mining industry has recognised the importance of holistic decarbonisation commitments, seeking to reduce emissions beyond their own operations, including downstream use of products (scope 3 emissions).[34]

A growing manufacturing base: Building on the established manufacturing base in high value and advanced processing, the Australian Government has prioritised capability building through the Modern Manufacturing Strategy. This covers sectors that are traditionally large emitters (such as minerals processing) and considers low emissions manufacturing pathways.[35]

Analysis approach

The primary objective of this report is to assess the opportunity for CCU in present and future industries and develop a blueprint for scale-up. It was developed with support of government and industry, as well as extensive literature review and 70 consultations in Australia and overseas (for a list of consulted stakeholders see Appendix A).

As not all applications are of equal strategic value and given the nascency of CCU, this report highlights opportunities for Australia to build on existing capabilities. The technologies that underpin the CCU value chain are first assessed in terms of technology maturity, according to the Technology Readiness Level (TRL) and Commercial Readiness Index (CRI) framework (as shown in Figure 7).

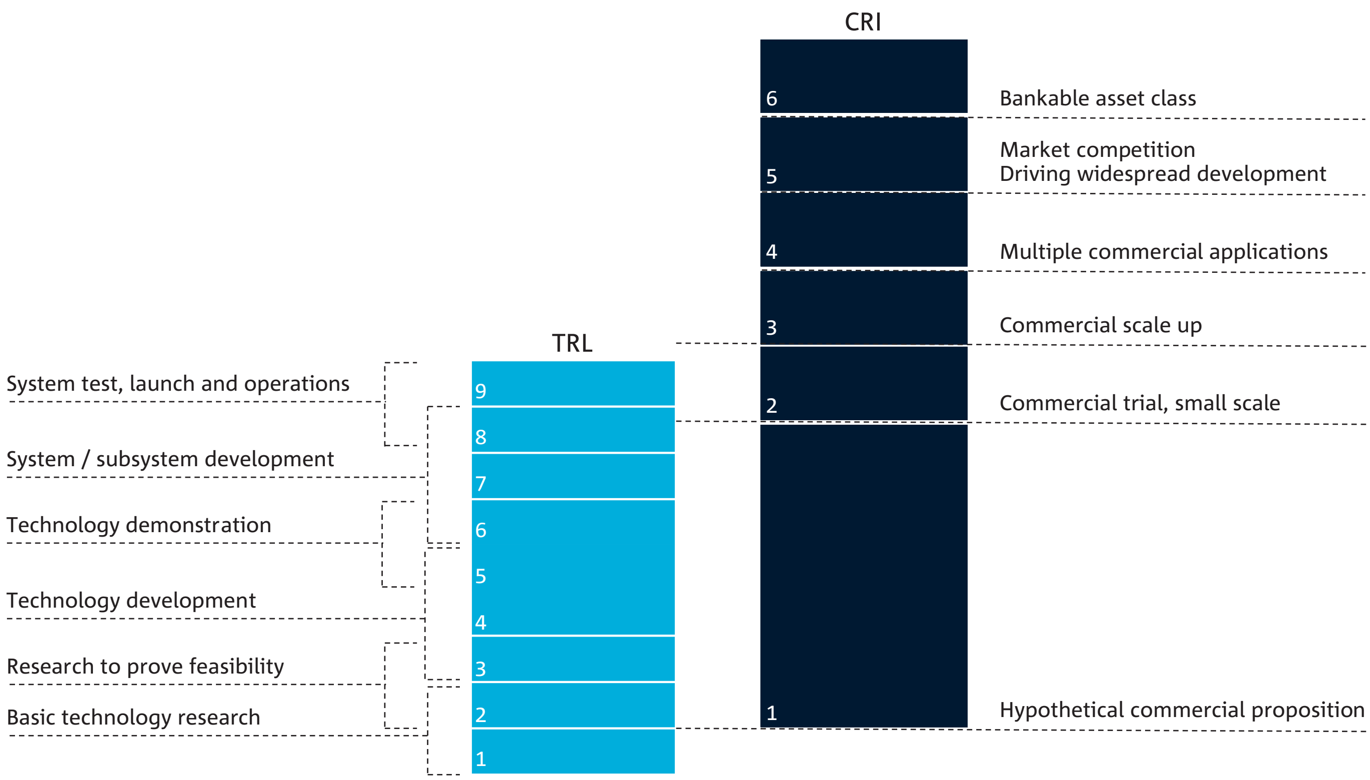


Figure 7: Technology Readiness Level and Commercial Readiness Index assessment framework[36]

34 ClimateWorks Australia (2020) *Net Zero Momentum Tracker: Resources Sector*. Viewed 30 April 2021, https://www.climateworksaustralia.org/resource/net-zero-momentum-tracker-resources-sector/

35 DISER (2020) *Our Modern Manufacturing Strategy*. DISER

36 Australian Renewable Energy Agency (ARENA) (2014) *Technology Readiness Levels for Renewable Energy Sectors.* ARENA

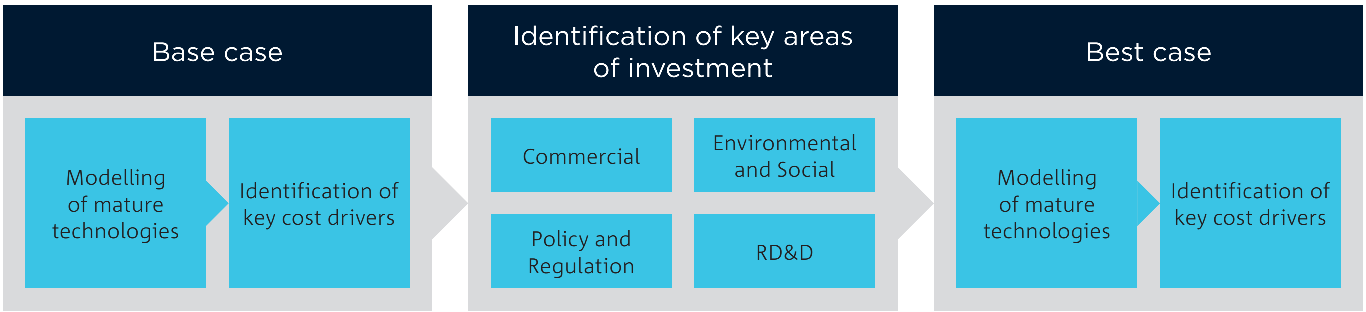


Figure 8: Assessment framework

The report utilises technoeconomic modelling to understand and communicate the key areas of investment required to scale up CCU opportunities by calculating the levelised cost of production for CO_2-derived products. Alongside technology maturity, modelling for key cost drivers is undertaken for quantifiable CCU applications, using a base to best case methodology. Technologies assessed as mature informed the 'base case' scenario for 2021. The 'best case' scenario considers projects currently in development and projections for improvements in technology capacity in the medium term.

When modelling CCU applications, the cases assume that CO_2 is sourced from high partial pressure point sources, where CO_2 concentration and pressure is highest, as this is the cheapest available CO_2 source and the likely first suppliers of CO_2. Sensitivities are shown throughout the report of how different CO_2 sources affect the levelised cost of production.

To achieve consistency across the report, the amount of CO_2 captured and used is standardised across the base and best cases. Base case assumes 1,000t/day is captured or used and the best case assumes 5,000t/day of CO_2 is captured or used. Modelling assumptions can be found in the Technical modelling appendix. All costs are presented in AUD and all figures presented in the metric system, unless stated otherwise. This report defines hydrogen as produced from renewable or low emissions sources.

This report has assessed CO_2 abatement potential from CCU quantitatively where modelling has permitted, and qualitatively in other applications, including theoretical limits to abatement potential. To quantify a theoretical net CO_2 abatement potential, the analysis considered CO_2 capture source, CO_2 consumed in each production process, production emissions, as well as the CO_2 emissions avoided from not using fossil fuel processes. This theoretical net CO_2 abatement potential is calculated per tonne of product to allow for comparison across the CCU applications.

The objective of this report is achieved via modelling as well as qualitative analysis, as detailed below:

1. **Capture and distribution (Part I):** An assessment of capture and distribution technologies and their applicability to CCU applications. This section sets out investment considerations to realise these opportunities for Australia.
2. **CCU applications (Part II):** Building on modelling, this section of the report assesses the opportunities to invest in emerging CO_2 use technologies and scale up mature industries for economic benefit. As in Part I, this section provides investment considerations to realise CCU opportunities across the following categories:
   - **Commercial:** Includes an assessment of different premiums, markets and barriers of entry to determine commercial considerations, as well as business and financing models.
   - **Policy and regulation:** Includes an assessment of policy levers and technical/economic regulations that can build capabilities and stimulate market growth. These considerations draw on experience in other countries and no attempt is made to address their application or appropriateness for Australia.
   - **Environmental and social:** Includes assessment of public awareness raising for CO_2 initiatives and consideration of environmental impacts. Lifecycle emissions are considered qualitatively given the complexity of the analysis involved.
   - **Research Development and Demonstration (RD&D):** Includes an assessment of where mature technologies can be further developed to improve efficiency, as well as emerging technologies to support the next wave of commercialisation.
3. **Roadmap to scale-up (Part III):** This section of the report provides an action plan for scaling up the development and demonstration of key technologies, including discussion of enabling market conditions. It also outlines key investment priorities for the scale up of CCU in Australia.

Part I –

Capture and distribution

1 Capture of CO_2

Carbon dioxide capture is the process of obtaining high-concentration CO_2, which can then be stored or utilised in various applications. CO_2 capture is generally divided into four categories:

- **Point source capture:** CO_2 is captured from concentrated CO_2 streams that are created as waste, from industrial processes, energy generation from fossil fuels or from oil and gas reservoirs.
- **Direct air capture:** Using engineered processes, CO_2 is extracted and captured from ambient air.
- **Biological uptake:** CO_2 is naturally taken up by biological organisms, such as trees, crops and algae, which directly convert the carbon into biomass. While valuable in atmospheric CO_2 management, this is beyond the scope of this report. However, from a utilisation perspective, the biological conversion of CO_2 directly into products using microorganisms is covered in Chapter 6.
- **Passive capture:** CO_2 can be absorbed passively in non-organic materials, such as soil carbonation, mine tailings and concrete. This passive process is beyond the scope of this report.

1.1 Point source capture

1.1.1 Overview

Point sources are stationary locations where CO_2 is emitted. The stationary locations where point source capture is mainly deployed include sites where fossil fuels are combusted for electricity generation and heat, industrial production processes that transform materials (such as cement production) and natural gas processing. Point sources can be centralised to have one emissions point or can be distributed throughout a process, resulting in numerous point sources within one facility, such as a cement production. This report refers to point source capture from flue gas streams, which describes gas entering the atmosphere via a flue (a pipe from which by-product gas is expelled).

Point sources emit CO_2 in a range of concentrations and pressures, as well as in the presence of various impurities, as shown in Table 1. Generally, the lower the pressure and concentration, the higher the cost of capture. The need to remove impurities can also add to the cost of capture as this can lead to degradation of catalysts and other materials. For simplicity, later chapters discuss point source capture in terms of high, medium and low partial pressure, which is a product of total pressure and concentration.

Table 1: Point source examples[37,38,39]

POINT SOURCE TYPE	PARTIAL PRESSURE GROUP	CO_2 PARTIAL PRESSURE (KPA)	CONCENTRATION (% BY VOL.)	IMPURITIES
Natural gas turbine	Low	3–4	3–4	H_2O, N_2, CO, NOx,
Coal power plant	Medium	12–14	12–15	H_2O, N_2, CO, NOx, SO_2
Cement factory	Medium	14–33	14–33	H_2O, O_2, CO, NO, SO_2
Natural gas processing plant	Low-Medium	50–4,400	2–65	H_2O, H_2S, CxHy
Steel making plant	Medium	15	15	CO, N_2, H_2O
Ethanol fermentation plant	High	100	~100	Ethanol, N_2, O_2
Ammonia production[40]	High	500	18	CO, H_2

37 Gale J et al. (2005) *Chapter 2: Sources of CO2. IPCC Special Report on Carbon dioxide Capture and Storage.* Intergovernmental Panel on Climate Change

38 Ho H, Iizuka A & Shibata E (2019) *Carbon Capture and Utilization Technology without Carbon Dioxide Purification and Pressurization: A Review on Its Necessity and Available Technologies.* American Chemical Society

39 Ho MT & Wiley DE (2016) *Liquid absorbent-based post-combustion CO2 capture in industrial processes.* Absorption-Based Post-Combustion Capture of Carbon Dioxide.

40 Applies to flue gas after air separation processing.

Depending on the input CO_2 stream and intended use, a series of purification steps may be required before transport and utilisation, which can add to the overall cost of supply of CO_2. For example, the stringent purity requirements on CO_2 for beverage carbonation can increase costs. CO_2 purification approaches include cooling, compression, drying and adsorption to remove impurities, such as H_2S gas or water, from the mixture.

Australia has widespread availability of CO_2 point sources. Below is a snapshot of different point source types and locations across Australia. The active status of these point sources is subject to change as plants come offline, natural resources are depleted, or emission targets evolve.

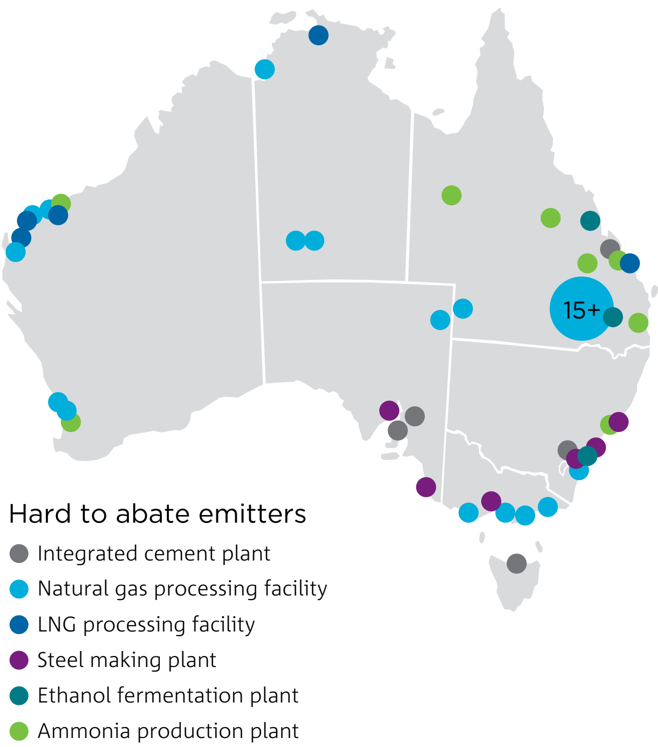


Figure 9: Point source type and locations across Australia[41]

Natural gas processing facilities feature predominantly in Figure 9. Although natural gas reserves contain mostly methane, there is a growing proportion of CO_2 found in these reserves as established methane-rich resources are depleted. CO_2 concentration has significant impacts on the value of the final natural gas streams, as the CO_2 must be separated prior to sale. This separation process produces significant volumes of CO_2 which are, at present, vented into the atmosphere. These sites provide a significant source of CO_2, presenting capture opportunities.

Australia's current market demand for CO_2 is sourced mostly from ammonia, ethylene oxide and ethanol production facilities, which offer the highest concentration and purest source of CO_2, and hence the most economical. Albeit in smaller volumes, CO_2 is also sourced from the flue gas streams of Torrens Island power station (SA) and Longford Gas Plants (VIC) , as well as from natural CO_2 gas fields.[42,43,44] Current suppliers produce CO_2 almost all year round but undergo maintenance periodically, which can impact supply.[45] During times of maintenance at these facilities, CO_2 is sourced from storage and on occasion has been imported from overseas.[46]

CO_2 captured from point sources is underpinned by mature technologies and has been deployed at commercial scale around the world including at natural gas facilities, during fertiliser production and at ethanol plants. However, there is not a one size fits all approach to CO_2 capture, which is reflected in the range of mature and emerging point source technologies (see Appendix E for details).

41 Cement Industry Federation (2020) *Australian Cement Report*. Cement Industry Federation; Geoscience Australia (2021) *Australia's Energy Commodity Resources 2021: Gas.* Viewed 18 June 2021, https://www.ga.gov.au/digital-publication/aecr2021/gas; Australian Steel Institute (2021) *Capabilities of the Australian steel industry to supply major projects in Australia*. Australian Steel Institute; Kelly A (2020) *Ethanol Fuel Production in Australia*. IBISWorld; Ammonia plant information provided by industry stakeholder.

42 AGL (2017) *ASX and Media Releases: AGL and Air Liquide partner to reduce carbon emissions.* Viewed 29 May 2021, https://www.agl.com.au/about-agl/media-centre/asx-and-media-releases/2017/may/agl-and-air-liquide-partner-to-reduce-carbon-emissions

43 ExxonMobil Australia (2021) *Gippsland Basin Joint Venture signs agreement with Air Liquide Australia that will see CO2 captured from Gippsland gas reused in Australian industries.* Viewed 29 May 2021, https://www.exxonmobil.com.au/News/Newsroom/News-releases-and-alerts/2021/GBJV-Agreement-with-Air-Liquide

44 HVAC&R Nation (2015) *The Legend of Boggy Creek*. Viewed 29 May 2021, https://www.airah.org.au/Content_Files/HVACRNation/2015/03-15-HVACR-002.pdf

45 Janda M (2012) *CO2 shortage may flatten soft drink supplies.* Viewed 1 April 2021, https://www.abc.net.au/news/2012-01-06/orica-closure-could-lead-to-soft-drink-shortage/3761750

46 Sahli M (2018) *Gas shortages to affect brewers.* Viewed 15 March 2021, https://www.brewsnews.com.au/2018/10/26/gas-shortages-to-affect-brewers/

1.1.2 Levelised cost of CO_2 capture

Technoeconomic modelling was used to calculate the approximate levelised cost of CO_2 ($LCOCO_2$) capture (base and best case) at a range of partial pressures to reflect potential emitters across Australia.

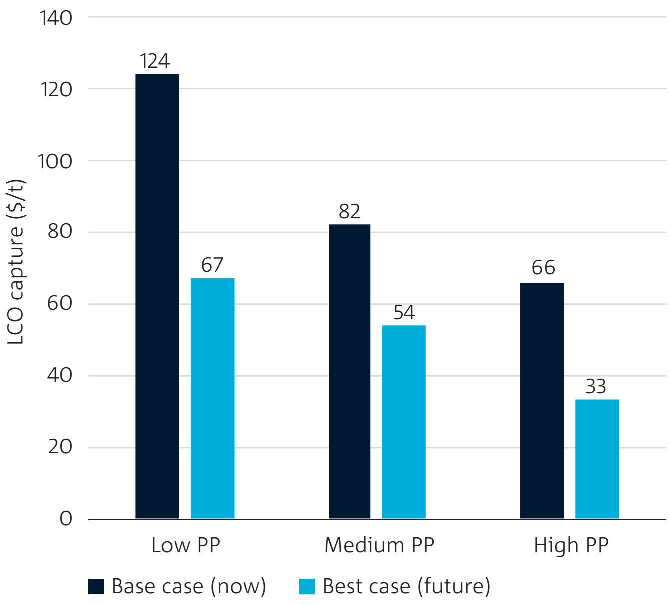


Figure 10: Levelised cost of CO_2 capture at point sources

Detailed assumptions, such as sorbent type, can be found in Appendix C. Example emitters according to partial pressure categories can be found in Table 1.

As the partial pressure increases, capture costs decrease. As such, emitters that produce CO_2 at higher concentration and pressure will be able to capture CO_2 at a lower cost.

The impact of carbon capture cost is explored in the respective CCU application chapters, showing that the effect of point source CO_2 capture on downstream production costs are relatively minor.

1.2 Direct air capture

1.2.1 Overview

Direct air capture (DAC) technologies are one of many emerging negative emissions technologies that are rapidly evolving. While not yet deployed at scale, by removing CO_2 directly from the air, DAC has the potential to result in carbon neutral products (depending on the use case) or negative emissions (if the CO_2 is stored permanently in a material or underground). DAC technologies pass air over a solid or liquid that extracts CO_2 directly from the atmosphere, where it exists at very low concentrations of approximately 415 parts per million (ppm), or 0.04%, magnitudes lower than point source capture outlined in the previous chapter.[47] Due to this low concentration, the energy requirements can be approximately three times greater compared to point source CO_2 captured from fossil fuel power generation.[48] The need for greater amounts of energy results in a high cost of capture. Further, low CO_2 concentrations require the collection columns to be larger, adding to capital costs.

As atmospheric CO_2 levels are constant globally, DAC technologies are not location-dependent and, in theory, can be established where needed rather than being reliant on point sources. If DAC can become economic at scale, the opportunity to co-locate a source of CO_2 with hydrogen and renewable energy can reduce CO_2 transport costs and enable greater cost efficiency of the DAC system. This includes the potential to optimise power, heat and water requirements for DAC systems. Australia is well positioned to demonstrate and scale up DAC due to significant land availability and access to large volumes of renewable energy through the nation's globally recognised solar and wind resources.

There are a range of technology types that are being developed to capture CO_2 from the air that broadly fit into three categories: Solution-based absorption and electrodialysis (no heat), solution-based absorption and calcination (high temp), solid-based adsorption and desorption (low temp). See Appendix E for more details.

47 NASA (2021) *Global Climate Change: Carbon Dioxide*. Viewed 3 May 2021, https://climate.nasa.gov/vital-signs/carbon-dioxide/

48 Feron P (2019) *Growing interest in CO2-capture from air*. Greenhouse Gasses: Science and Technology

1.2.2 Levelised cost of CO_2 capture

Two direct air capture technologies were modelled for this report. These technologies were chosen given literature and data availability, access to appropriate expertise and relative technological maturity:

- **Low temperature system**: Capture of CO_2 from the atmosphere using a conventional liquid-based absorption process (Monoethanolamine).
- **High temperature system:** Capture of CO_2 from the atmosphere using an aqueous potassium hydroxide (KOH) sorbent coupled to a calcium caustic recovery loop.

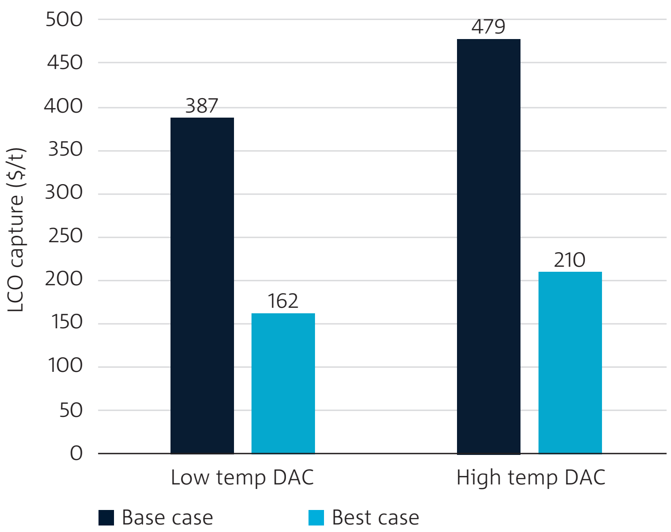


Figure 11: Levelised cost of CO_2 capture using direct air capture

Detailed assumptions can be found in Appendix C.

The plant capacity assumptions have been aligned to point source capture facilities to allow for comparison (See Appendix C). The literature referenced uses smaller plant capacities compared to this report. This can lead to a higher margin of error as assumptions are extrapolated. This margin of error is higher in the low temperature DAC case as the extrapolation is more significant. For reference, Canadian-based clean energy company Carbon Engineering (the source of the high temperature data used) are projected to build their first commercial plant by 2025 that will capture 1 million tonnes of CO_2 per year.[49] The best case modelled above assumes capture of 1.8 million tonnes per year.

1.3 Capture considerations

Commercial

Matching supply and demand: Although there are occasional shortages of supply, the current Australian market for CO_2 is small and could easily be flooded as more companies seek to capture their emissions. Therefore, commercial considerations are required to match supply and demand as new CCU applications develop. Securing long term offtake agreements will be key to transitioning from established supply to new capture sources. Through committed offtake agreements, the CO_2 supply chain can be optimised to meet demand and the capacity factor (i.e. the extent to which the asset is used) can be optimised to further lower costs.

Capture scale-up: Scale-up is a key driver to reducing capture costs, as indicated by the modelling undertaken for this report. Companies requiring large volumes of CO_2 are likely to be initially reliant on point source capture in the short to medium term. The opportunity to integrate DAC technologies into the CO_2 stream will increase as these technologies scale, potentially leading to the displacement of the point sources or increasing CO_2 supply.

Long-term offtake contracts: Establishing long-term offtake agreements will enable CO_2 suppliers to invest with confidence. These agreements could replicate power purchase agreements used by the electricity market. This allows providers to have revenue certainty over an extended period, enabling them to secure finance. While this is not currently implemented in the CO_2 market, this model would provide revenue certainty and opportunity for scale-up, while reducing costs. As a growing number of companies strive for net zero targets and reporting of CO_2 emissions comes under increasing scrutiny, long-term offtake contracts may be considered more favourably in the future.

49 Carbon Engineering (2021) *Direct Air Capture project awarded funding under Government plans to make UK world leader in Greenhouse Gas Removals.* Viewed 29 May 2021, https://carbonengineering.com/news-updates/dac-project-awarded-funding/

Policy and regulation

Incentivising CO_2 capture: While point source capture technologies are technically mature, deployment still requires investment. Incentives to support mature and emerging point source capture technologies can help increase the amount of CO_2 being captured across the economy and create opportunities for greater utilisation of CO_2. While emerging DAC technologies are more expensive than point source capture, the long-term value of DAC highlights the need to explore different incentives and models. For example, the combination of financial incentives (such as subsidies and tax rebates) alongside industry or application deployments and performance mandates could support investment and create niche markets that can support further deployments.[50] Another mechanism could include offsetting the price differential from DAC and point source capture, through offtake agreements that a set long-term price for CO_2.

Environmental and social

Investment in life cycle assessments: As new technologies are commercialised, life cycle assessments will be required to ensure environmental harm does not outweigh the benefits that come with CO_2 captured in a form suitable for utilisation. The source of electricity, heat inputs and other factors (such as land and water required) will affect the life cycle assessment (LCA) of capture technologies, in particular DAC where large input quantities are needed.[51] To assess effectiveness and environmental impacts of capture technologies, further detailed LCA is required. Development of standardised LCA methodology across capture technologies will be key for comparison between DAC and point source capture, as well as for comparing emissions from CO_2 utilisation products.[52]

Thermal recycling: The reuse of waste heat is one option that could be considered to avoid or reduce CO_2 emissions in capture technologies. For example, some technologies require high temperatures to desorb CO_2, and current operations utilise the heat produced by the combustion of methane with resulting emissions captured. Alternatively, development of heat sources that do not require burning of methane, such as waste heat from industrial processes and concentrated solar thermal, will reduce the emissions profile of capture technologies or the need to process associated emissions.[53] For example, Climeworks' initial demonstration plant in Hinwil, Switzerland uses waste heat from a municipal waste incinerator.[54]

Realising negative emissions: CCU applications, such as mineral carbonation, have the potential to achieve negative emissions when paired with DAC. Encouraging CCU deployments where a portion of CO_2 originates from DAC can help offset investment that will be required to achieve long-term deployment of DAC at scale. Permanent storage technologies will be discussed further in Part II, Chapter 4.

RD&D

There are a range of emerging capture technologies (highlighted in Table 2) for both point source and DAC that could bring large reductions in costs. This can support greater uptake of CO_2 capture across a range of emitters and increase opportunities for CCU.

50 Meckling J, Biber E (2021) *A policy roadmap for negative emissions using direct air capture*. Nature Communications. https://doi.org/10.1038/s41467-021-22347-1

51 House K.Z et al. (2011) *Economic and energetic analysis of capturing CO2 from ambient air.* Proceedings of the National Academy of Sciences December 2011

52 Müller L.J et al. (2020) *A Guideline for Life Cycle Assessment of Carbon Capture and Utilization.* Frontiers in Energy Research

53 Deutz S & Bardow A (2021) *Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption.* Nature Energy

54 Evans S (2017) *The Swiss company hoping to capture 1% of global CO2 emissions by 2025*. Viewed 3 May 2021, https://www.carbonbrief.org/swiss-company-hoping-capture-1-global-co2-emissions-2025

Table 2: Emerging CO_2 capture technologies

TYPE	TECHNOLOGY	TRL[55]	DESCRIPTION
Point source	Calcium (carbonate) looping[56]	6	In calcium looping, a cycle of calcination and carbonation produces a pure stream of post-combustion CO_2, using a reversible reaction. The pure CO_2 stream is extracted for use or storage. An advantage of this technology is the relatively low cost of calcium carbonate compared to other sorbents, such as monoethanolamine (MEA).
	Chemical looping combustion[57]	6–7	Chemical looping combustion uses a reversible reaction of solid metal oxide to provide the oxygen for fuel combustion. The process is similar to oxyfuel combustion, where there is limited contact between air and fuel, providing a near pure CO_2 stream which can be utilised or stored. Input metals include Fe, Mn, Cu, Co and potentially others. Advantage of this method over alternatives (such as oxyfuel combustion) is improved energy efficiency of the oxygen input.
	Electrochemical separation	7	CO_2 is separated from flue gases via electrochemical reactions. This is commonly conducted via electrodialysis, using a liquid electrolyte as a medium to absorb and release the CO_2, or via direct separation with an electrochemical cell (e.g. in a polymer electrolyte membrane electrolyser).[58] This method allows for high selectivity and does not require large pressure gradients or high temperatures, potentially reducing energy costs.
	Cryogenic separation	6	In cryogenic distillation, flue gases are separated by a series of compression and cooling steps to produce liquid CO_2. Obtaining liquid CO_2 is potentially useful for storage and transport, or for use in specific applications such as enhanced oil recovery. However, the process is more energy intensive than other technologies, as it requires high CO_2 pressure input gas to be effective. [59] Modelling has shown this process can be more cost-effective than traditional amine systems.[60]
	Biological systems for capture	1–9	Biological capture systems may offer cheaper and simpler systems for specific point source options. Although various microbes capture CO_2, RD&D is needed to transform laboratory systems into scalable technologies. Overcoming barriers, such as catalysts that do not require costly cofactors and are able to operate at the higher temperature of flue gas streams, are important to commercialising biological capture systems.[61] Some biological capture systems could instead be used to capture CO_2 directly from the air
Direct Air Capture	Hydrogels	3–4	'Hydrogels' increase the contact surface area between CO_2 and the amine sorbent to speed up the rate of reaction, while using low cost readily available materials.[62]
	Solution-based absorption and electrodialysis (no heat)	5	CO_2 is absorbed by an aqueous hydroxide solution, such as sodium hydroxide (NaOH). In the case of NaOH, the CO_2 reacts to form sodium carbonate (Na_2CO_3) solution, which is then acidified using sulfuric acid (H_2SO_4) to release near-pure CO_2. The NaOH and H_2SO_4 are then regenerated through electrodialysis to be used again. Only electricity is required for the process.[63]
	Metal organic frameworks (MOFs)	3–4	CO_2 is adsorbed through the pores of a MOF. The MOF can then be regenerated at temperatures of approximately 80°C.[64] A key advantage of MOFs is their tunability to CO_2 uptake, selectivity and heat of adsorption.[65] The technology remains at small scale, with CSIRO's Airthena technology able to capture 2 tonnes of CO_2 per year.[66]
	Membrane-based DAC		As in membrane-based separation for point source CO_2 capture, membranes could be applied for direct CO_2 capture from air. Currently membranes are only suited to separate CO_2 from high concentration streams, such as post-combustion gases, and are unlikely to be considered for DAC at their current state of development. However, if membranes with higher gas permeance and selectivity were achieved, CO_2 capture could become efficient enough to render membranes suitable for direct air capture.[67]

55 Global CCS Institute (2021) *Technology Readiness and costs of CCS*
56 Bui M et al. (2018) *Carbon capture and storage (CCS): the way forward.* Energy & Environmental Science
57 Bui M et al. (2018) *Carbon capture and storage (CCS): the way forward.* Energy & Environmental Science
58 Muroyama A.P, Patru A & Gubler L (2020) *Review—CO2 Separation and Transport via Electrochemical Methods.* Journal of The Electrochemical Society
59 Songolzadeh M, Soleimani M, Ravanchi M.T & Songolzadeh R (2013) *Carbon Dioxide Separation from Flue Gases: A Technological Review Emphasizing Reduction in Greenhouse Gas Emissions.* The Scientific World Journal
60 Hoeger C, Burt S, Baxter L (2021) *Cryogenic Carbon Capture™ Technoeconomic Analysis*. 15th International Conference on Greenhouse Gas Control Technologies
61 Bhatia S.K et al. (2019) *Carbon dioxide capture and bioenergy production using biological system – A review*. Renewable and Sustainable Energy Reviews
62 Bruce S et al. (2020) *Opportunities for hydrogen in commercial aviation*. CSIRO
63 Viebahn P, Scholz A & Zelt O (2019) *The Potential Role of Direct Air Capture in the German Energy Research Program—Results of a Multi-Dimensional Analysis.* Energies
64 Sadiq M.M et al. (2020) *A Pilot-Scale Demonstration of Mobile Direct Air Capture Using Metal-Organic Frameworks*. Advanced Sustainable Systems
65 Bui M et al. (2018) *Carbon capture and storage (CCS): the way forward*. Energy Environ. Sci.
66 CSIRO (2021) *Airthena – CO2 from Air.* Viewed 9 June 2021, https://www.csiro.au/en/work-with-us/ip-commercialisation/marketplace/co2gen
67 Fujikawa S, Selyanchyn R & Kunitake T (2021) *A new strategy for membrane-based direct air capture.* Polymer Journal

2 Distribution of CO_2

At ambient pressure and temperatures above -78°C, CO_2 is a colourless, odourless, incombustible gas. As with all gases, CO_2 has a relatively low volumetric density compared to liquid chemicals, such as methanol or petroleum. To transport CO_2 economically, the gas must either be compressed or liquefied to achieve a reasonable density. The optimal conditions and state of the CO_2 depend on the transport method used.

The current technologies for transporting CO_2 are shown in Table 3.

When in a supercritical phase, CO_2 shares the properties of both a liquid and a gas, allowing it to be more efficiently transported due its higher density. To reach liquid phase, CO_2 must be pressurised substantially. If it is simply cooled, it will solidify directly from the gas into a solid state.

Table 3: CO_2 distribution technologies

TRANSPORT METHOD	INDICATIVE DISTANCES	DESCRIPTION AND USE
Truck	Short-medium	CO_2 is liquefied for transport in pressurised vessels aboard freight trucks.[68]
Rail	Medium-long	CO_2 is transported on freight trains in the same way as truck transport.
Pipeline	Medium-long	CO_2 is compressed until it reaches a supercritical or 'dense' phase.[69] Impurities of concern for pipeline transport include water, which leads to corrosion of pipe steels, non-condensable gases (such as N_2, O_2, H_2, Ar)[70] and other contaminants (such as H_2S, CH_4,).
Ship	Long	CO_2 is compressed and often refrigerated to reach a liquid state, where it is stored in pressurised vessels.

Trucks

In Australia, CO_2 is most commonly transported by truck, where small volumes are delivered to multiple users. Depending on the customer, the CO_2 can be transported in gaseous or liquid form.[71] Trucks are likely to continue to be required for low volume transport, including for intra-site transport in co-located facilities where pipeline infrastructure is not available. Should capture technologies be deployed at large volumes in the medium term, the role for trucks may diminish.[72]

Rail

Where pre-existing rail infrastructure is available, this can be a cheaper option compared to trucking, especially as distances increase.[73] Rail is one of the lowest emissions insensitive modalities, notwithstanding the likely requirement for railcars engineered to transport CO_2.[74]

Similar to trucks, at large volumes and over long distances, rail is unlikely to be cost competitive with pipeline and emerging shipping infrastructure.

Pipeline

Pipelines are currently the most common method of transporting large quantities of CO_2.[75] There are over 6500km of pipeline worldwide, most of which are associated with enhanced oil recovery (EOR) in the US.[76] Europe has the next largest network where there are roughly 1000km of CO_2 pipelines.[77]

In Australia, there are 8km of CO_2 pipeline in the Gorgon project, where the CO_2 is injected into a sandstone formation.[78] The CarbonNet project proposes to deliver CO_2 from a range of sources to an offshore storage site via a pipeline stretching over 130km.[79]

68 Linde Engineering (2021) *CO2 purification and liquefaction plants.* Viewed 3 May 2021, https://www.linde-engineering.com/en/process-plants/co2-plants/co2-purification-and-liquefaction/index.html

69 Bui M et al. (2018) *Carbon capture and storage (CCS): the way forward.* Energy & Environmental Science

70 Bui M et al. (2018) *Carbon capture and storage (CCS): the way forward.* Energy & Environmental Science

71 Coal 21 (n.d.) *Carbon Capture and Storage: Transport CO2*. Viewed 3 May 2021, https://coal21.com/wp-content/uploads/2018/05/Coal21Fund_Fact_Sheet_-_Carbon_Capture_and_storage_-_Transporting.pdf

72 Global CCS Institute (2015) *Transporting CO2.* Viewed 17 May 2021, https://www.globalccsinstitute.com/archive/hub/publications/191083/fact-sheet-transporting-co2.pdf

73 Seedah D, Owens T, Bhat C & Harrison R (2013) *Evaluating Truck and Rail Movements along Competitive Multimodal Corridors.* Texas Department of Transportation

74 Department of the Environment and Energy (2017) *Australia's emissions projections 2017.* Commonwealth of Australia.

75 Global CCS Institute (n.d.) *Fact Sheet: Transporting CO2*. Viewed 3 May 2021, https://www.globalccsinstitute.com/wp-content/uploads/2018/12/Global-CCS-Institute-Fact-Sheet_Transporting-CO2-1.pdf

76 Bui M et al. (2018) *Carbon capture and storage (CCS): the way forward.* Energy & Environmental Science

77 Sandalow D et al. (2017) *Carbon Dioxide Utilization (CO2U) ICEF Roadmap 2.0*. Innovation for Cool Earth Forum

78 International Energy Agency (IEA) (2014) *CO2 Pipeline Infrastructure.* IEA

79 Victorian Government Department of Jobs, Precincts and Regions (2021) *About the project.* Viewed 3 May 2021, https://earthresources.vic.gov.au/projects/carbonnet-project/about-the-project

The cost of pipeline transport varies depending on the length of the pipeline and the amount of CO_2 transported. As the distance increases, so does the added cost to the price of CO_2 delivered. As the amount of CO_2 transported per day increases, larger pipes can be used which reduces the overall unit cost of transportation.

Ship

The transport of CO_2 is discussed extensively in the Intergovernmental Panel on Climate Change's *Special Report on Carbon dioxide Capture and Storage*.[80] CO_2 transport via ships is currently in early deployment around the world, with a few small ships actively transporting liquefied food-grade CO_2 from capture points to consuming regions. CO_2 is then transported to consumers by tanker truck or in pressurised cylinders. LNG and liquefied petroleum gases are already transported in marine tankers at global scale. Because the properties of liquid CO_2 are relatively similar to those of liquid petroleum gases, the storage technology for marine tankers can be readily applied to larger-scale CO_2 vessels. Approximately 230 kilotonne of CO_2 could be carried by vessels of similar size to modern LNG carriers. In Norway and Japan, larger CO_2 ships, liquefaction processes and intermediate storage facilities are being designed. One example is the Longship project in Norway which plans to ship liquefied CO_2 from the capture site in Oslo to the country's west coast.[81]

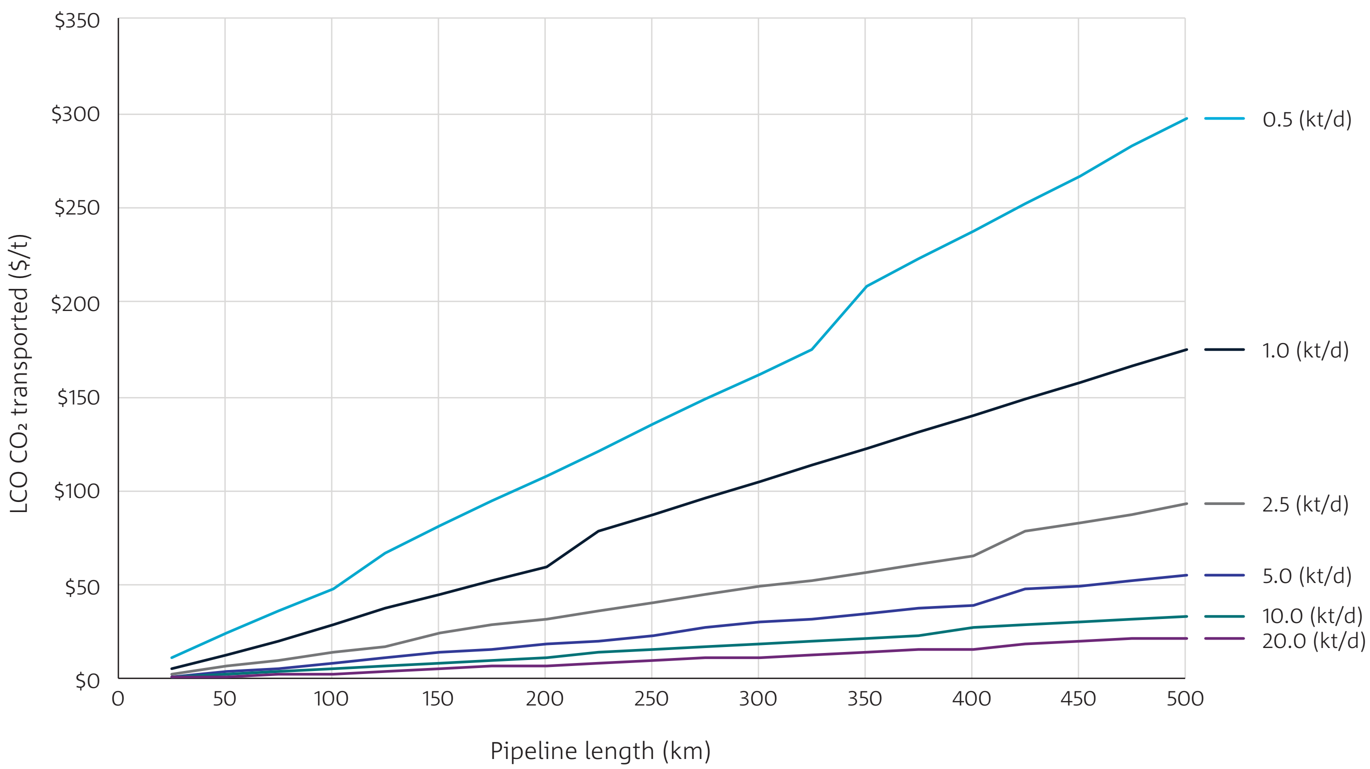


Figure 12: Levelised cost of CO_2 transported at different flowrates

This figure shows the costs associated with CO_2 pipeline transportation. For a given pipe diameter, as the length increases, so does the cost per tonne. Pipes with larger diameters provide a lower cost per tonne, so as the amount of CO_2 transported increases, the cheaper it becomes per tonne. These costs include the initial compression required to drive the CO_2 through the pipeline but not intermediate compression.

80 Doctor R et al. (2005) *Chapter 4: Transport of CO2. IPCC Special Report on Carbon dioxide Capture and Storage.* Intergovernmental Panel on Climate Change

81 Gassnova (2020) *Developing Longship: Key Lessons Learned.* Gassnova SF

2.1 Considerations

Commercial

Transport factors: For large volume CO_2 transport, it is likely that only pipelines and ship transport will be economical options for gaseous products,[82] and therefore truck and rail are unlikely to be used for the transport of large quantities.[83] One study focused on Europe found that over large distances (>1500km), it is expected that ship transport would be the most efficient option. At smaller scales, other transport options may be reasonable, such as for intra-hub transport.[84]

Infrastructure sharing: As part of scaling CCS operations around Australia, large CO_2 pipelines will be required to deliver CO_2 from industrial capture sources to storage reservoirs. These pipelines could also be used for delivering smaller quantities of CO_2 for utilisation, reducing overall capital costs. Further, multiple small emitters could share a pipeline with larger emitters to efficiently accumulate the CO_2 for utilisation at a centralised compression facility.

Policy and regulation

Permitting and approval: For CO_2 pipelines, permit and approval processes are a significant factor in project timelines and can take longer than the construction time itself.[85] Improved public awareness could aid in expediting approval processes, as it can reduce the risk of public distrust delaying regulatory approvals.

Environmental and social

CO_2 gas release risk: Whilst CO_2 does not present the same risk profile as natural gas, if CO_2 gases are accidentally released from pipelines or other transport modalities, this could present a risk to the project through loss of supply. Public concern over accidental release CO_2 will need to be addressed to maintain a social license and create further support for investment in auxiliary projects. Fugitive emissions during transport will need to be monitored as part of the overall emissions accounting.

RD&D

Pipeline integrity: The cast network of pipelines transporting CO_2 demonstrates the relative maturity of pipeline technology. Nevertheless, further research into how CO_2 pipelines are used in CCUS hubs, where there may be multiple streams both entering and leaving the system, is required. In particular, the effects of changes to pressure and CO_2 volume. In the event of a pipeline crack occurring, the pressurised CO_2 may expand rapidly, which can cause more damage and threaten pipeline integrity.[86]

82 Bui M et al. (2018) *Carbon capture and storage (CCS): the way forward.* Energy & Environmental Science

83 Global CCS Institute (n.d.) *Fact Sheet: Transporting CO2.* Viewed 3 May 2021, https://www.globalccsinstitute.com/wp-content/uploads/2018/12/Global-CCS-Institute-Fact-Sheet_Transporting-CO2-1.pdf

84 Bui M et al. (2018) *Carbon capture and storage (CCS): the way forward.* Energy & Environmental Science

85 International Energy Agency (IEA) (2014) *CO2 Pipeline Infrastructure.* IEA

86 Project Consulting Services (2020) *PCS Insights.* Viewed 3 May 2021, https://www.projectconsulting.com/pcs-insights/preventing-fracture-in-co2-transmission-system

Part II –

CCU applications

This report identified over 50 different use cases or products for CO_2 utilisation. These have been grouped into four broad areas: direct use of CO_2, mineral carbonation, conversion of CO_2 into chemicals and fuels, and biological conversion of CO_2.

Direct use

Established CO_2 demand from the food, beverage and agricultural industries could be leveraged as initial offtakers for the development of new point source capture plants and demonstration of DAC and purification technologies.

Chemicals and fuels

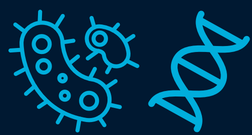
With Australia's emerging hydrogen industry and its history as an energy exporter, it is well positioned to support the long-term transition to lower-emissions chemicals and fuels, but high green premiums in the near-term may require a strategic investment.

Mineral carbonation

The cost competitiveness of mineral carbonation (i.e. the conversion of CO_2 into solid, carbonate based products) in the near-term can drive opportunities to utilise waste from heavy industry and mining, lock away CO_2 for the long term and lower the carbon intensity of the building industry.

Biological conversion

Australia's role as a global food exporter presents an opportunity to capitalise on emerging synthetic biological conversion pathways, including production of niche, high value products.



3 Direct use of CO_2

3.1 Key findings

Established CO_2 demand from the food, beverage and agricultural industries could be leveraged as initial offtakers for the development of new point source capture plants and demonstration of DAC and purification technologies.

Australian CO_2 demand is driven by the food, beverage and agricultural industries. These industries are currently reliant on limited capture sources and have experienced disruptions to supply due to capture facility downtime and issues in the CO_2 supply chain. CCU using new point sources, taking advantage of industrial hubs or deploying DAC in the longer term, may shore up supply for these industries.

The food, beverage and agricultural markets are projected to continue to grow, particularly for exports to neighbouring countries. Australia is well regarded as safe and sustainable food producer and has the potential to realise a premium for value-added products with low emissions profiles.

Scale-up considerations:

- **Initial application(s):** Demand for CO_2 from the food, beverage and agricultural industry is low compared to the potential of other applications (e.g. chemicals and fuels). However, these industries are established in their use of CO_2 and therefore can be used as offtakers for new CO_2 sources.
- **Deployment model:** Established CO_2 demand can be leveraged to demonstrate new, small-scale supply technologies. Co-location of plant greenhouses with capture facilities can support growing use of CO_2 and create new horticultural jobs as the industry grows to meet food demand. The scale up priorities to further develop direct users of CO_2 are set out in the table below.

ABATEMENT CONSIDERATIONS

Green premium[87]:

Although quantitative modelling for this application is beyond the scope of this report, it is likely that there will be a premium for emerging capture sources.

Cost of abatement:

Not analysed within the scope of this report.

Abatement potential:

Shifting to CO_2 sourced from DAC, as opposed to the current point source approach, coupled with renewables, could theoretically produce net zero emission food and beverage products.

Duration of CO_2 storage:

When used in greenhouses, CO_2 is stored in biomass until decomposed. It is released upon opening of carbonated beverages and food packaging.

Scale-up priorities:

IMMEDIATE (2020–2025)	SHORT-MEDIUM TERM (2025–2030)	LONG-TERM (2030–2040)
• Explore long-term contracts for point source CO_2 emitters • Identify point source/greenhouse co-location candidates • Demonstrate supply at offtaker sites	• Secure long-term contracts for medium partial pressure CO_2 • Demonstrate integrated point source/ greenhouse CO_2 flows and heat supply • Blend CO_2 sourced from new technologies into existing sources	• Establish commercial offerings for small scale CO_2 customers, e.g. pubs and restaurants • Demonstrate offerings for small greenhouses • Integrate CO_2 point sources at commercial scale

87 A green premium is the additional cost of choosing a product with a low emissions profile over one that emits a greater amount of greenhouse gases

3.2 Overview

Direct use of CO_2 is distinguished from other applications as CO_2 is not chemically converted into a new product prior to use. Australia's direct use applications are projected to grow 1.4% annually to 2025, driven by growth in a diverse range of downstream markets.[88] With food processing and beverage carbonation accounting for over 65% of the Australian CO_2 market, short term growth in demand will likely be driven by this industry.[89] It is important to note that while the food and beverage industry accounts for the majority of direct use applications in Australia, this is not reflective of the global context due to wider spread deployment of enhanced oil recovery (EOR).

Enhanced Oil Recovery (EOR)

EOR is the process of injecting CO_2 into subsurface oil reservoirs to increase overall pressure forcing oil towards production wells.[90] EOR is the largest direct use application globally, however this technology is not deployed in Australia. It has been used widely deployed in the US, where the three largest companies (75% of overall EOR production) also hold substantial CO_2 resources.[91] EOR faces high capital costs, significant transport costs for remote oil fields, is limited to suitable geology for injection and permanent storage, and has some risk of leaking CO_2 back into the atmosphere.[92] Although there is some interest in following the lead of the US in the Cooper and Eromanga Basins in South Australia,[93] the future of widespread deployment of EOR technologies in Australia is unclear. EOR is out of scope for this report, but further information on the Australian potential for EOR can be found in an upcoming report by NERA and the CO_2CRC.[94]

3.3 Food, beverage and agricultural industries

The food industry uses CO_2 for a range of preservation methods, including as an additive, for packaging, as a refrigerant and to decaffeinate coffee. CO_2 is also used in food packaging, where it can be used in conjunction with nitrogen to exclude oxygen from the atmosphere surrounding the food, improving shelf life and freshness.[95] While multi-national corporations control much of the carbonated beverage market, manufacturing of these beverages, and in turn sourcing of CO_2, is often localised to countries or regions.[96] This demonstrates potential for local sourcing of CO_2, as well as a potential to export to surrounding countries and regions.

In the agricultural industry, greenhouse horticulture plays a vital role in the production of high-value products as it offers greater control of environmental conditions required for plant growth. Greenhouses are sealed off from the atmosphere and therefore require additional CO_2 to maintain ambient air conditions while photosynthesis is occurring, thus optimising growth conditions. As a result, CO_2 is injected into greenhouses to stabilise CO_2 levels throughout the day and night.[97]

The CO_2 concentration required for optimum growth is above that of ambient air. CO_2 for this use is typically sourced from industrial waste streams (as discussed above) or on-site burning of LPG with integrated heat recovery for use in the greenhouse. Due to growing demand for fresh produce and reliance on greenhouses to grow produce in less arable environments, the CO_2 demand from this application is projected to grow. Further, changing conditions due to climate change is likely to increase the reliance on greenhouses to optimise yields and as a tool to reduce irrigation requirements.[98]

88 Richardson A (2019) *Carbon Dioxide Production in Australia*. IBISWorld

89 International Energy Agency (IEA) (2019) *Putting CO2 to Use*. IEA

90 McGlade C (2019) *Can CO2-EOR really provide carbon-negative oil?* Viewed 15 April 2021, https://www.iea.org/commentaries/can-co2-eor-really-provide-carbon-negative-oil

91 International Energy Agency (IEA) (2018) *World Energy Outlook 2018.* IEA

92 International Energy Agency (IEA) (2019) *Putting CO2 to Use*. IEA

93 Rendoulis N (2018) *Potential for Carbon Dioxide EOR in the Copper and Eromanga Basins.* Department for Energy and Mining

94 NERA (2020) *New project to reduce emissions and unlock Australia's energy potential through long-term carbon capture, utilisation and storage solution.* Viewed 21 April 2021, https://www.nera.org.au/News/CO2-EOR-project

95 Sun Lee D (2016) *Carbon dioxide absorbers for food packaging applications.* Trends in Food Science & Technology

96 Hardcastle J.L (2016) *Closed-Loop System Captures CO2 for Use in Beverage Industry.* Viewed 4 April 2021, https://www.environmentalleader.com/2016/05/closed-loop-system-captures-co2-for-use-in-beverage-industry/

97 Bao J, Lu W, Zhao J & Bi X.T (2018) *Greenhouses for CO2 sequestration from atmosphere.* Carbon Resources Conversion

98 Strickler J (2020) *High-Tech Greenhouses Could Be The Future Of Agriculture.* Viewed 3 May 2021, https://www.forbes.com/sites/jordanstrickler/2020/08/28/high-tech-greenhouses-could-be-the-future-of-agriculture/?sh=22750e47380f

3.3.1 The opportunity for Australia

The Australian food and agribusiness industry is projected to be worth $250 billion in 2030 (2.4% growth per annum), should the industry continue on the same growth trajectory.[99] While CO_2 is a valuable input into processes, it faces a number of supply constraints.

In Australia, current supply of CO_2 is closely linked to ammonia and ethanol production, where CO_2 is produced as a by-product.[100] As ammonia production is primarily used for explosives in the mining sector and production of fertiliser, CO_2 for direct use applications can face seasonable variability when sourced from fertiliser plants. While fertiliser manufacturing is largely carried out in preparation for spring planting and supply is highest in autumn/winter, the food and beverage industry often has highest demand in summer when most fresh produce has been picked.[101] This misalignment of supply and demand can lead to price hikes. On occasion, these challenges have also led to the import of CO_2 into Australia. Further, plant maintenance, decreasing demand for ammonia products and plant shutdowns can have significant consequences for downstream CO_2 users.[102] These plants can also be located long distances from the site of use, creating supply line risk.

Use of CO_2 capture from new point sources, with a longer term view to integrate DAC sourced CO_2, can support Australia's food, beverage and agricultural industries.

3.4 Considerations

Commercial

Supply chain security: CO_2 suppliers often have a direct relationship with offtakers, therefore there is significant variability in price and supply security across regions. In the near term, existing and new point sources can be fitted with capture technologies at a larger variety of locations and emission sources to help strengthen supply chains and cater to food, beverage and agricultural industry growth. This provides emitters with an early customer as other CCU applications begin to scale. In planning for long term CO_2 needs global beverage producers, such as Coca-Cola HBC Switzerland, are leading the implementation of direct air capture sources and associated purification technologies to reduce both costs and CO_2 emissions.

Case Study: Coca-Cola HBC Switzerland and Climeworks[103]

In 2018, Coca-Cola HBC Switzerland partnered with Swiss company, Climeworks, to use DAC sourced CO_2 in their beverage carbonation. As the largest bottler of non-alcoholic beverages in Switzerland, sourcing CO_2 for Coca-Cola HBC Switzerland from ambient air can demonstrate continued industrial scale deployment of Climeworks' DAC technology. Currently, it costs ~$780 per tonne of CO_2 for beverage carbonation and Climeworks' hoping to reduce this to ~$130 by 2030. Pentair Union Engineering is partnering with Climeworks on the project to purify the captured CO_2 to appropriate levels for consumption.

Cost of CO_2 treatment: Most direct use applications require specific CO_2 purity and pressure, and therefore there is a significant push by industry to find cost effective models of achieving this.[104] The variation in purity and pressure are shown in Table 4. Further, an increase in concentration of CO_2 in greenhouses can have adverse effects on human health and therefore enrichment of plant greenhouses can present a safety risk if not managed correctly.[105]

99 CSIRO Futures (2019) *Growth opportunities for Australian food and agribusiness: Economic analysis and market sizing.* CSIRO

100 Burnett C (2020) *Australia's brewers protected from CO2 shortages.* Viewed 1 May 2021, https://www.brewsnews.com.au/2020/05/22/australias-brewers-protected-from-co2-shortages/

101 International Energy Agency (IEA) (2019) *Putting CO2 to Use*. IEA

102 Sahli M (2018) *Gas shortages to affect brewers.* Viewed 10 April 2021, https://www.brewsnews.com.au/2018/10/26/gas-shortages-to-affect-brewers/

103 Jais A (2018) *Climeworks pioneering air-captured CO2 for drinks carbonation.* Viewed 11 April 2021, https://www.thechemicalengineer.com/news/climeworks-pioneering-air-captured-co2-for-drinks-carbonation/

104 Shell Global (n.d.) *Carbon Dioxide Purification Catalyst.* Viewed 4 April 2021, https://www.shell.com/business-customers/catalysts-technologies/catalysts/environmental-catalysts/carbon-dioxide-purification.html

105 Health and Safety Executive (n.d.) *General hazards of Carbon Dioxide.* Viewed 6 April 2021, https://www.hse.gov.uk/carboncapture/carbondioxide.htm

Table 4: CO_2 purity and pressure for food and beverage direct use applications[106]

APPLICATION	PURITY (%)	PRESSURE (BAR)
Carbonated beverage	99.9	2
Refrigerant	99	70–100
Decaffeination agent	99	300

The cost of CO_2 treatment is dependent on source purity, available transport options and the specifications required for end use.[107] Importantly, treatment adds cost and therefore the supply chain is likely to be tailored to the requirements of the end user.

Integration into emerging and existing hubs: Hubs that capture CO_2 and produce waste heat would make good candidate sites for the integration of established direct use applications, such as greenhouses, and emitters. The sites would provide low cost CO_2 and heat, while providing emitters with a mature offtaker. Co-location of emitters and offtakers in the food, beverage and agricultural industries may create opportunities to share infrastructure, particularly related to treatment.

DAC green premium and carbon neutral products: DAC coupled with CO_2 purification is unlikely to compete with the established supply chain in the short term, meaning a green premium will likely be present. While the spot price of the existing supply chain is likely to be lower, this does not take into consideration supply insecurity costs, particularly where these supply costs create risks that impact downstream production and revenue. Integration of DAC could reduce the emissions profile of the end user and if renewable energy is used throughout, products could be classified as carbon neutral. This classification can support passing the premium onto consumers, absorbing the green premium to an extent.

Policy and regulation

Carbon footprint labels on food and beverages: Amid growing awareness of environmental impacts, there is increasing consumer pressure to label the carbon footprint of food and beverages.[108] Some food and beverage companies, such as Oatly,[109] have independently begun labelling the carbon footprint of their products. Implementation of mandated labelling and associated tracking and accountability could significantly impact the social license of large CO_2 users.

Environmental and social

Public awareness: Coupling direct use applications and capture technologies is seen a short term opportunity to decarbonise existing CO_2 use cases. However, there is a lack of public awareness on the potential pathways to reduce the carbon emissions of established industries where CO_2 is a key input. As such, a public education campaign on where CO_2 for food, beverage and agricultural processing is currently sourced from and the potential alternatives, can be a key enabler to furthering discussions of CO_2 sourcing in these industries. Further, education will be needed to assure the public that emerging CO_2 sources are purified and safe for consumption.

RD&D

Small scale modular capture, DAC and purification plants: Development of modular or small scale capture technologies could provide an option for small to medium emitters to retrofit capture technologies to their plant's point sources, allowing these emitters to capture and sell their CO_2 into the existing market. This can assist smaller firms to manage their emissions, as well as further diversifying the supply chain for direct users. In addition, development of small-scale DAC systems that can be co-located with end users (e.g. CCU hubs) could reduce CO_2 transport costs.[110] There is significant industry interest in development of modular purification technologies, including by Linde Engineering (UK) and Delta Cleantech (US).[111, 112]

106 Ho H, Iizuka A & Shibata E (2019) *Carbon Capture and Utilization Technology without Carbon Dioxide Purification and Pressurization: A Review on Its Necessity and Available Technologies.* Industrial & Engineering Chemistry Research

107 Ho H, Iizuka A & Shibata E (2019) *Carbon Capture and Utilization Technology without Carbon Dioxide Purification and Pressurization: A Review on Its Necessity and Available Technologies*. Industrial & Engineering Chemistry Research

108 Kateman B (2020) *Carbon Labels Are Finally Coming To The Food And Beverage Industry*. Viewed 3 May 2021, https://www.forbes.com/sites/briankateman/2020/07/20/carbon-labels-are-finally-coming-to-the-food-and-beverage-industry/?sh=54f981057c03

109 Oatly (2020) *Sustainability Report 2019.* Oatly

110 The Linde Group (TLG) (2017) *CO2 purification and liquefaction: Adding value through standardization and modularization.* TLG

111 Linde Engineering (2021) *Modular CO2 purification and liquefaction plants.* Viewed 10 April 2021, https://www.linde-engineering.com/en/process-plants/co2-plants/co2-purification-and-liquefaction/modular-co2-plants/index.html

112 Delta CleanTech (n.d.) *CO2 customized design gas purification systems*. Viewed 3 May 2021, https://deltacleantech.ca/purpose-built-co2-capture-plants/

4 Mineral carbonation

4.1 Key findings

The cost competitiveness of mineral carbonation (i.e. the conversion of CO_2 into solid, carbonate based products) in the near-term can drive opportunities to utilise waste from heavy industry and mining, lock away CO_2 for the long term and lower the carbon intensity of the building industry.

Carbonation is a process that occurs naturally as part of weathering, where CO_2 binds to minerals in the earth's crust to form carbonates. This process can be accelerated using thermal and chemical engineering to produce carbonates.

The modelling shows that carbonate products from CCU can be cost competitive, creating an opportunity to economically scale up existing projects in the near term. The production of carbonates utilises industrial waste or minerals, such as serpentinite, and can assist in mitigating challenges with sustainably managing waste. Additionally, the process does not require hydrogen, meaning it can scale-up independently of the hydrogen industry.

The concrete sector can also benefit from carbonation by incorporating CO_2 in concrete production. Carbonation during production can increase concrete strength, reducing the volume of cement required, thus reducing carbon intensity and feedstock costs. Australian demand for concrete is projected to grow and as CO_2 is stored permanently in these products, it presents a near-term opportunity to reduce emissions.

Scale-up considerations:

- **Initial application(s):** Carbonate production can be integrated into mine tailings and industrial waste management to reduce financial liabilities. CO_2-derived concrete products are likely to import IP from overseas.
- **Deployment model:** Given Australia's resources sector is a global exporter, large quantities of mine tailings and other waste material are generated, which could act as feedstock for carbonation. This may be a key opportunity to sequester significant volumes of CO_2. Concrete facilities can adopt CO_2-derived aggregates to create local carbonate demand. The scale-up priorities to develop mineral carbonation are set out in the table below.

ABATEMENT CONSIDERATIONS

Green premium:

Unlike other in-scope applications, mineral carbonation products can be cost competitive with existing processes.

Cost of abatement:

Cost of abatement varies by sale price of product, with negative cost of abatement indicating a profit.

Abatement potential:

Only limited by feedstock availability. Use of DAC in carbonate and concrete products can produce negative emissions as CO_2 is locked away for the long term.

Duration of CO_2 storage:

CO_2-derived carbonate and concrete products lock away emissions permanently in most use cases.

Scale-up priorities:

IMMEDIATE (2020–2025)	SHORT-MEDIUM TERM (2025–2030)	LONG-TERM (2030–2040)
• Demonstrate small scale, technology driven mineral carbonation to inform economic use cases • Inform and establish customer base • Demonstrate CO_2-curing and aggregates in low risk non-reinforced concrete • Integrate CO_2-derived aggregates into concrete mixes at one or more concrete plant • Examine scenarios and infrastructure requirements to match source of CO_2 and mineral location	• Establish commercial offerings of mineral carbonation for range of emitters and end users • Demonstrate CO_2 curing and aggregates in medium risk structural concrete (e.g. houses)	• Achieve larger scale adoption of carbonate products • Establish industry standard of mineral carbonate aggregates and cured concrete in wide range of mixes

4.2 Overview

Carbonation is a process that occurs naturally as part of weathering, where CO_2 binds to minerals in the earth's crust. CO_2 reacts with magnesium and calcium oxides to produce their respective carbonates. Because these oxides are co-products of silicate minerals, both carbonates and silica can be obtained from carbonation, increasing the value of the carbonation process. Carbonation can be enhanced to create a product with many industrial applications. In some cases, it can sequester CO_2 permanently. In other cases, such as where magnesium carbonate is used to produce magnesium oxide, CO_2 is re-released upon use.

4.3 Carbonate products

Carbonate products can be used as additives in rubber and plastic industries, paper mills, paints, ink, thermal insulation, fire retardants, water absorbing applications and food applications. It can also be used to treat waste material (e.g. mine tailings, kiln dust, steel/iron slag) to create new aggregates for use in building materials. Silica (SiO_2), another common product of the carbonation process, is the main feedstock for glass production, among other applications (see Table 5). Note that silica, while a valuable by-product of the carbonation process, does not contain or store carbon.

Methods to enhance CO_2 uptake by raw materials and conversion to carbonate solids include crushing and grinding to increase surface area, applying heat and pressure, and introducing different substances and catalysts to improve the speed and efficiency of carbonation.[113] The crushing, grinding and heating processes are highly energy intensive, and may result in additional process emissions that will need to be accounted for to measure overall emission benefits. Carbonation can today yield valuable products that serve identical functions to materials already in use, for various market applications. Table 5 provides a summary of mineral carbonate products and their applications.

A variety of feedstocks and CO_2 sources can be used to form mineral carbonates. Each combination comes with a set of considerations around quantity, location, and composition. Choice of feedstock and CO_2 source will be unique to each business case. Matching the location of feedstocks and CO_2 source is a major challenge for economic carbonation, with the transport of either the feedstock or the CO_2 adding to costs.

Table 5: Mineral carbonate products and their applications

OUTPUTS	APPLICATIONS	GLOBAL MARKET SIZE ($)
Magnesium carbonates[114]	Cement/concrete additive, fire retardant building material, food processing, cosmetics, insulation, fertiliser, whitener.	$258 million[115]
Calcium carbonates[116]	Steel manufacture, additive to asphalt in road paving, stabilise soils, producing mortar to bind bricks, use in chemicals (manufacture of paper, coatings for paints), waste treatment, food and nutrition (toothpaste, dietary supplement, animal feed).	$55,850 million[117]
Silica[118,119] (as a co-product of carbonation)	Cement/concrete additive, glass production, water filtration, ceramic production, paints and coatings, fertiliser, tyres.	$6,750 million[120]

113 Azadi M, Edraki M, Farhang F & Ahn J (2019) *Opportunities for Mineral Carbonation in Australia's Mining Industry*. Sustainability

114 European Chemicals Agency (ECHA) (n.d.) *Substance Infocard: Magnesium carbonate*. Viewed 3 May 2021, https://echa.europa.eu/substance-information/-/substanceinfo/100.008.106

115 Future Market Insights (2020) *Magnesium Carbonate Minerals Market*. Viewed 3 May 2021, https://www.futuremarketinsights.com/reports/magnesium-carbonate-minerals-market

116 Jimoh O.A, Ariffin K.S, Hussin H.B & Temitope A.E (2018) *Synthesis of precipitated calcium carbonate: a review*. Carbonates and Evaporites

117 Grand View Research (2020) *Calcium Carbonate Market Size, Share & Trends Analysis Report By Application (Paper, Plastics, Adhesives & Sealants), By Region (APAC, Europe, North America, Central & South America, MEA), And Segment Forecasts, 2020–2027*. Viewed 3 May 2021, https://www.grandviewresearch.com/industry-analysis/calcium-carbonate-market

118 Industrial Minerals Association – North America (n.d.) *What is industrial sand?* Viewed 3 May 2021, https://www.ima-na.org/page/what_is_ind_sand

119 Agripower Australia (2021) *Silicon Science*. Viewed 7 June 2021, https://agripower.com.au/silicon-science/

120 Grand View Research (2019) *Silica Market Size, Share & Trends Analysis Report By Application (Construction, Oral Care, Agrochemicals, Rubber, Food & Feed), By Region, Competitive Landscape, And Segment Forecasts, 2019–2026*. Viewed 3 May 2021, https://www.grandviewresearch.com/industry-analysis/silica-market

Feedstocks

Industrial waste (steel slag, alkaline ash)
+ Free waste
+ No grinding required
+ Neutralises waste
+ Appeals to decarb. plans
– Limited sources
– Site dependent
– Separation required

Mine tailings
+ No grinding required
+ Neutralises waste
+ Appeals to decarb. plans
– Would require transport from remote sites
– Chemical makeup is site-specific
– Often in remote locations

Mined ore
+ Prevalent and plentiful
– Requires crushing
– Requires transports

+

CO_2 source

Flue gas
- Purification not required
- Potentially limited source

Pure from point source
- Location dependent or transport costs required
- Cheaper than DAC

Pure from DAC
- Location independent
- Higher CO_2 cost
- Can lead to carbon negative product

→

Outputs

Calcium carbonates

Products/customers:
- Filler
- Whitening agent
- Building material aggregate

Magnesium carbonates

Products/customers:
- Flooring
- Fire proofing
- Fire extinguisher
- Cosmetics
- Building material aggregate

Silica

Products/customers:
- Glass
- Concrete additive
- Fertiliser
- Ceramic and paint additive

Figure 13: Summary of mineral carbonation processes

A mineral feedstock is combined with a chosen CO_2 source to form carbonate products. CO_2 sources can include flue gas (an industrial waste stream containing CO_2), high-concentration point source CO_2 emissions from industrial processes, or CO_2 from DAC. The products obtainable are determined by the presence of minerals (containing calcium, magnesium, silica) within the feedstock. Note that silica (SiO_2) is not a carbonate, however it can provide an additional revenue stream as a valuable product.

Formation of mineral carbonates in mine tailings happens naturally through extended weathering of the tailings. In particular, the high proportion of reactive surface area found in crushed tailings is ideal for reacting with CO_2. Mine tailings containing calcium, magnesium and sodium are potentially suitable for mineral carbonation.[121] The carbonation process can be sped up by spreading tailings into thin sheets or regularly stirring to prompt exposure to CO_2, accelerating the CO_2 utilisation process. Looping methods can be used to reduce costs, through calcining (heating pure CO_2) and recycling metal oxides in the process.[122]

Beyond CO_2 utilisation, forming mineral carbonates from tailings can help to sustainably manage waste by reducing acid mine drainage, immobilising environmentally hazardous metals for the long term, and providing a secondary opportunity for ore recovery.[123]

4.3.1 The opportunity for Australia

Australian industry generates waste streams (such as steel slag and fly ash) that carbonation could help to remediate while providing an economic benefit. Australia's significant bauxite endowment and alumina industry has created significant by-product quantities, which are highly caustic and are subject to waste management and remediation costs. In the case of the Australian and global mining industry, ongoing growth in metals and minerals demand continues to increase the scale of the challenge related to sustainably managing waste, particularly tailings.

In addition to environmental risks related to acid mine drainage, large financial liabilities exist associated with management, closure and remediation of tailings storage facilities. For mine operations, mineral carbonation can reduce waste management costs and, in some circumstances, produce value-added products that can improve the economics of CO_2 capture.[124]

Considering the financial liability related to mine closures, CO_2 utilisation could mitigate some of the emissions from the mining industry and improve mining waste management and land rehabilitation. It presents a near term opportunity to sequester large volumes of CO_2 with a relatively cheap and abundant feedstock (e.g. tailings). Moreover, Australian mining operations are often co-located with high solar irradiance regions. Integration of concentrated solar thermal heat into the mineral carbonation process could help to avoid further CO_2 emissions and optimise tailings processing via renewable technologies. Importantly, and unlike most other CO_2 opportunities, economic feasibility is not linked to scale-up of the hydrogen industry and therefore is not reliant on technology developments in this adjacent industry.

121 Azadi M, Edraki M, Farhang F & Ahn J (2019) *Opportunities for Mineral Carbonation in Australia's Mining Industry*. Sustainability

122 Kelemen P.B et al. (2020) *Engineered carbon mineralization in ultramafic rocks for CO2 removal from air: Review and new insights*. Chemical Geology

123 Azadi M, Edraki M, Farhang F & Ahn J (2019) *Opportunities for Mineral Carbonation in Australia's Mining Industry*. Sustainability

124 Yadav V.S et al. (2010) *Sequestration of carbon dioxide (CO2) using red mud*. Hazardous Materials

4.3.2 Levelised cost of production, modelling results

Modelling was used to analyse the production of two products from the mineral carbonation process, magnesium carbonate ($MgCO_3$) and silica (SiO_2). Analysis of the levelised cost of production for carbonate products considers two separate cases to account for the broad range of deployment scenarios that could be employed. In both cases, the raw mineral is mined for use in the carbonation process.

The first case considers mined raw serpentinite being transported by rail to a steel or cement plant for carbonation using operational flue gas. In this scenario the flue gas does not require treatment or purification, reducing capture costs. This case is shown in Figure 14. The costs of mining the serpentinite are included in the levelised cost.

The second case considers mined raw serpentine carbonated on site, using CO_2 capture from a high partial pressure point source, with the resultant product transported away from this site. CO_2 from a high partial pressure source is chosen as it is the cheapest form of CO_2 capture for this scenario. The effect of different CO_2 sources is shown in Figure 15. The costs of mining the serpentinite are included in the levelised cost.

Analysis of levelised cost for both use cases demonstrates that mineral carbonation can be profitable in the near-term when compared to the mass market prices. This is in addition to other benefits including permanent storage of CO_2. It is important to note that both silica and magnesium carbonate can be sold for higher prices in premium and speciality markets, however further processing may be required depending on the market. The cost competitiveness of mineral carbonation is subject to location of CO_2 and feedstock minerals and would differ under other scenarios.

As capture scale increases, an increased supply of $MgCO_3$ and SiO_2 can result in a risk of oversupply. This creates potential for lower prices for carbonate products which can affect profitability and costs. However, new supply of low-cost carbonates could lead to the development of new markets.

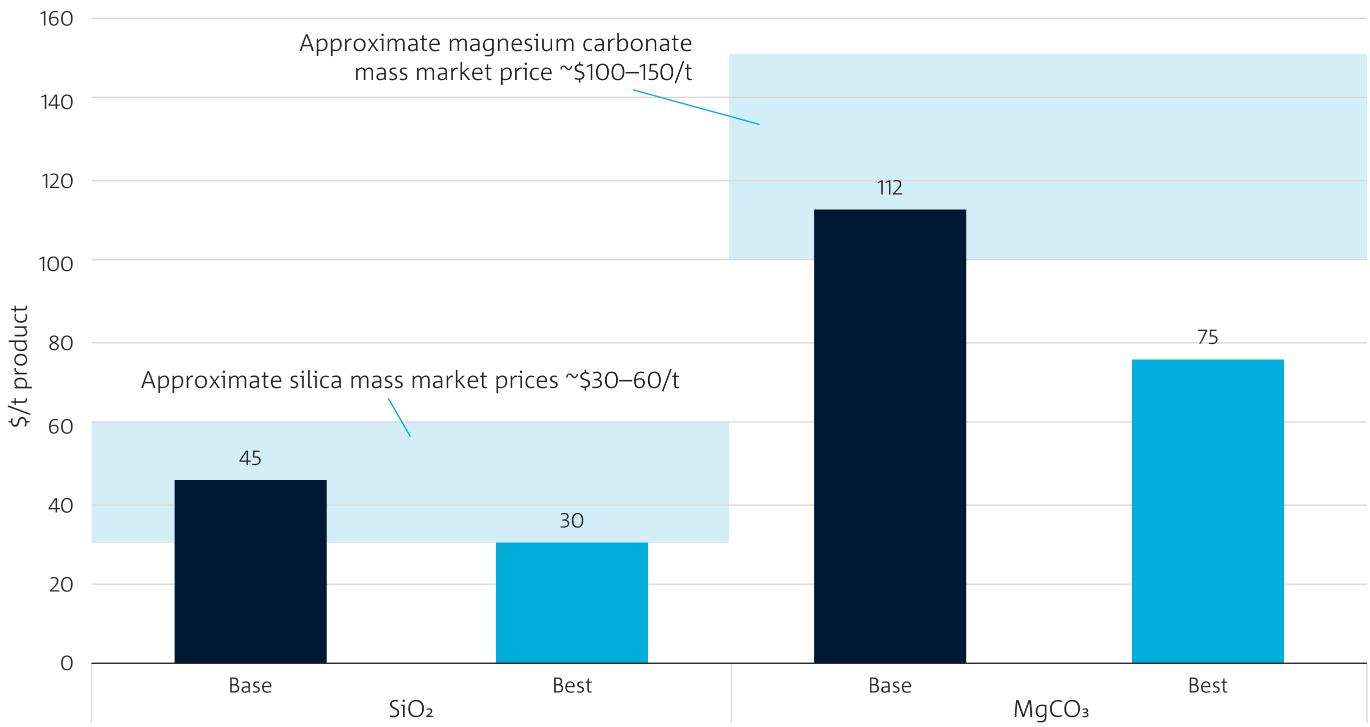


Figure 14: Case 1 – levelised cost of production for carbonate products using mined raw serpentine and flue gases from a steel or cement plant

Levelised cost of products calculated on a value allocation to account for the two products (SiO_2, $MgCO_3$). Base case assumes 1,000 t/day of CO_2. Best case assumes 5,000 t/day of CO_2. See Appendix C for modelling assumptions.

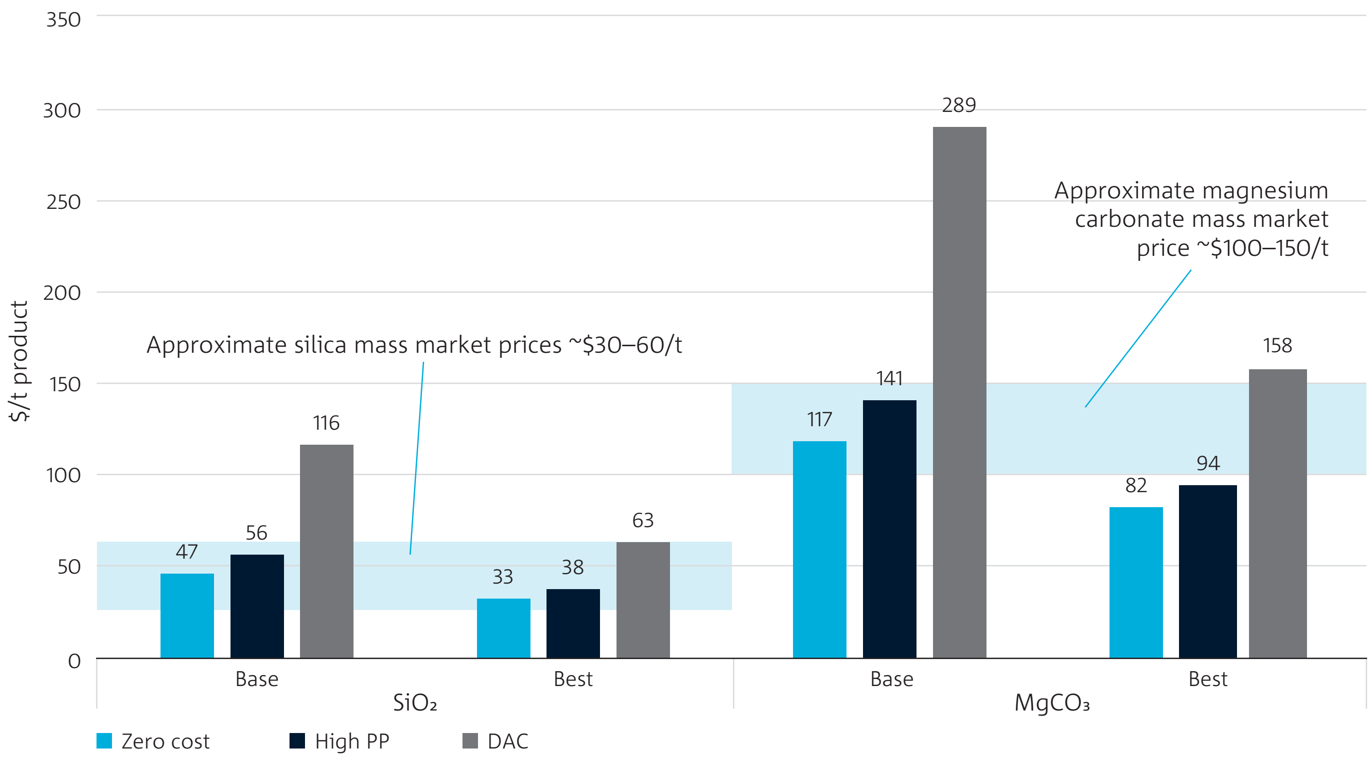


Figure 15: Case 2 – levelised cost of production for carbonate products using mined raw serpentine carbonated on site, with product transported away

Levelised cost of products calculated on a value allocation to account for the two products (SiO_2, $MgCO_3$). Base case assumes 1,000 t/day of CO_2. Best case assumes 5,000 t/day of CO_2. See Appendix C for modelling assumptions.

4.3.3 Abatement potential

For mineral carbonation, analysis of the cost of abatement calculates how much each tonne of CO_2 costs to avoid. However, changes in commodity prices will have a direct effect on the abatement cost (see Figure 16). In most commodity cost scenarios, the CO_2 abatement cost is negative due to the revenue generated from selling the carbonates and silica being higher than the costs associated with producing them, indicating a profit can be made. If the $MgCO_3$ cannot be sold, CO_2 abatement is still achieved. In that scenario, the associated cost of that abatement is indicated by the $0/t $MgCO_3$ cost line. The cost of abatement decreases as the selling price for SiO_2 goes up.

The cost of abatement does not consider other co-benefits that may be realised at different sites, such as waste neutralisation.

Considerations for carbonate products are discussed in Section 4.5.

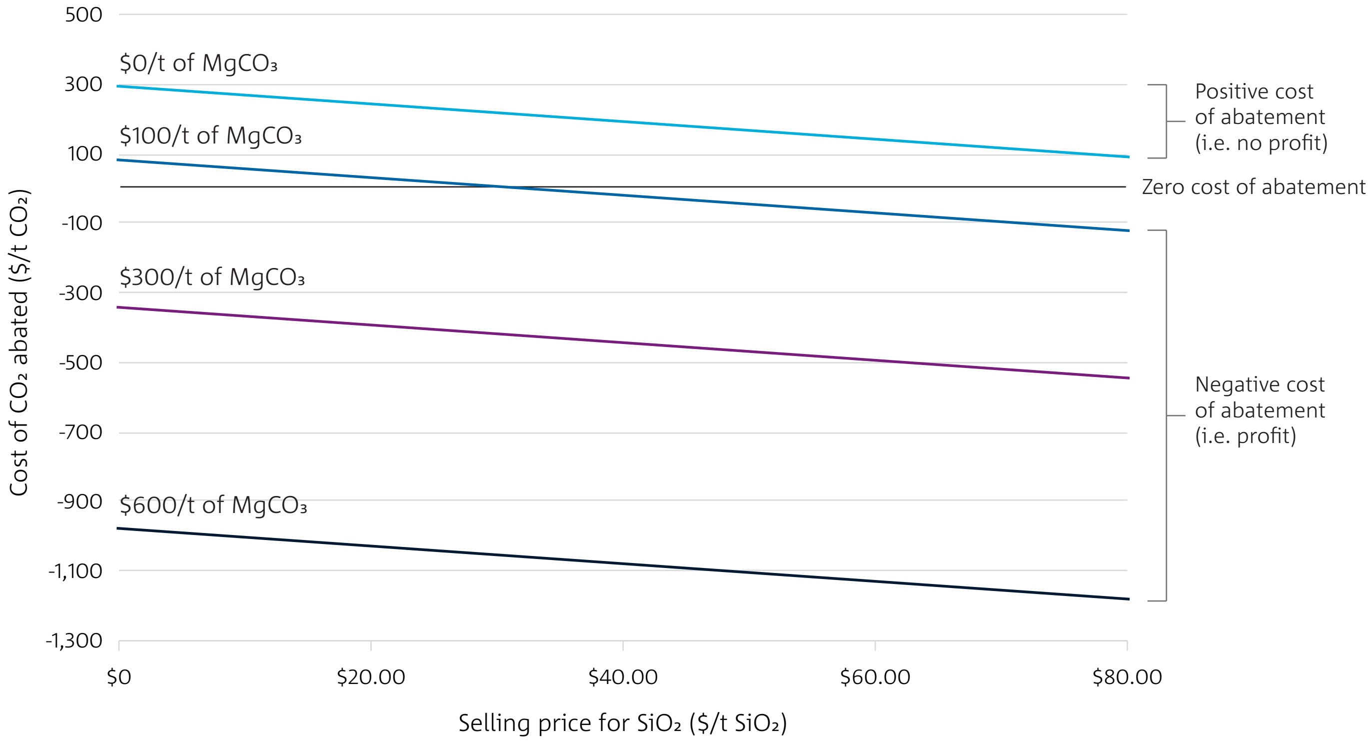


Figure 16: Change to cost of abatement for carbonate products with different commodity prices

Cost of abatement considers the effect of different SiO_2 and $MgCO_3$ sales prices, using the best case results from Case 2 assumptions (mined raw serpentine carbonated on site, with product transported away using CO_2 capture from a high partial pressure point source). See Appendix C for modelling assumptions.

4.4 Concrete

The concrete industry in Australia is predicted to grow by 1.7% through to 2026,[125] hence there is a significant opportunity to both reduce the emissions associated with concrete production and to produce low emissions construction products.

Concrete is typically made using three key components: cement, an aggregate, and water. $CaCO_3$, in the form of limestone, is a key ingredient of cement which acts as a binding and hardening material. Aggregates are granular filling materials such as sand, ground rock and gravel that make up 60–80% of a concrete's volume.[126]

CO_2 can be utilised in concrete in the following ways: to form carbonated aggregates, addition of CO_2 to concrete mixes (during mixing at the fresh stage) and concrete curing with CO_2. Because concrete has a long lifetime, CO_2 sequestered within the concrete can be considered permanent storage.

A significant portion of emissions from concrete are produced during cement production. Up to 60% of emissions from cement production are due to process emissions associated with converting limestone to clinker, one of the key components of cement. In 2018–19, the average emissions intensity of cement produced from clinker was 0.77 tonnes CO_2-e per tonne of cement.[127] Given this process is inherent in the production of cement, it will be extremely difficult to abate the associated emissions entirely. The Cement Industry Federation has suggested cement production emissions can be reduced by utilising alternative fuels and raw materials, substitution of cement clinker with higher ratios of alternative aggregates, improving energy efficiency and capture of plant emissions.[128]

125 Kelly A (2020) *Concrete Product Manufacturing in Australia*. IBISWorld

126 National Academies of Sciences, Engineering, and Medicine (2019*) Gaseous Carbon Waste Streams Utilisation Status and Research Needs*. The National Academies Press

127 Cement Industry Federation (2020) *Australian Cement Report*. Cement Industry Federation

128 Cement Industry Federation (2020) *Australian Cement Report*. Cement Industry Federation

Carbonated aggregates

Aggregates are filling materials such as sand, ground rock and gravel that are used to construct roads and fill concrete.[129] The addition of greater volumes of aggregates to concrete means carbon intensive components like cement can be reduced, decreasing the overall carbon intensity of concrete products. As aggregates have competing uses across the construction industry and this sector is expected to continue to grow, there is potential for difficulty in matching supply with demand.[130]

CO_2 can be used to treat waste material (e.g. mine tailings, kiln dust, steel/iron slag), reacting to form new mineral carbonate aggregates (carbonated aggregates) for use in concrete or other building materials. The technology maturity for waste-based aggregates varies substantially from research to commercial stage (TRL 4–8), based on the composition of the waste input used. Where waste materials are used as feedstocks, carbonated aggregates offer the additional benefit of remediating a waste stream which may otherwise require additional costs for management and treatment. Carbonated aggregates can reduce the demand for natural aggregates, mitigating the carbon emissions associated with conventional aggregate mining and transportation.

CO_2 as an additive during mixing

CO_2 can be added to cement, aggregates and water during the mixing stage, resulting in the formation of microscopic $CaCO_3$ mineral particles. These mineral particles serve to increase the compressive strength of the concrete when hardened, allowing reduced cement content, while maintaining similar compressive strength to traditional concrete mixtures.

Case study – CarbonCure (US)

CarbonCure's system attaches to existing concrete plants, capturing CO_2 from existing sources and injecting it back into the concrete during mixing. This technology can be licensed to existing concrete producers to facilitate more efficient rollout of the technology across dispersed plant locations. CarbonCure claims their process can increase the concrete's compressive strength, allowing less cement to be used to achieve the same strength. The process is also claimed to reduce solid waste disposal and freshwater required. To date, over 1 million truckloads of CarbonCure concrete have been delivered for use.[131] Australian company CE Construction Solutions has also announced that it will be applying CarbonCure's technology to their concrete products.[132]

Concrete curing

Traditional concrete curing allows formation of hydration products, including calcium silicate hydrates (the binder gel) and calcium hydroxide, by reaction of cement with water. The binder gel is responsible for setting and hardening of cementitious mixtures.

This process can be sped up by injecting CO_2 during the mixing and hardening stage, to produce solid calcium carbonate through a carbonation reaction, which contributes to the concrete's material properties. Introduction at the early stage of mixing enables substantial diffusion of CO_2 into the material, leading to increased carbonation and accelerated gain in strength.[133] This increases CO_2 uptake significantly.[134]

Mature concrete continues to naturally absorb CO_2 from the air over the course of decades. However, this natural carbonation is limited to the top layer of the concrete due to lower diffusion through the dense material.

129 National Academies of Sciences, Engineering, and Medicine (2019*) Gaseous Carbon Waste Streams Utilisation Status and Research Needs*. The National Academies Press

130 Cement Concrete & Aggregates Australia (2013) *Sustainable Use of Aggregates.* Concrete: The Responsible Choice.

131 Carbon Cure (2021) *Carbon Cure Technologies*. Viewed 3 May 2021, https://www.carboncure.com/

132 Carbon Cure (2020) *CE Construction Solutions to introduce CarbonCure's carbon removal technology for concrete to Australian market*. Viewed 3 May 2021, https://www.carboncure.com/news/ce-construction-solutions-to-introduce-carboncures-carbon-removal-technology-for-concrete-to-australian-market/

133 Rostami V, Shao Y & Boyd A.J (2012) *Carbonation Curing versus Steam Curing for Precast Concrete Production*. Materials in Civil Engineering

134 Alberici S et al. (2017) *Assessing the potential of CO2 utilisation in the UK*. Imperial College London & ECOFYS

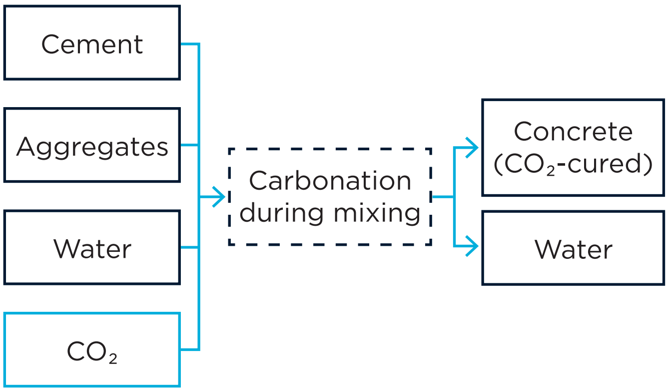


Figure 17: Process diagram of concrete curing using CO_2 feedstock

CO_2-cured concrete provides additional benefits beyond carbon sequestration. CO_2-cured concrete can today deliver lower costs and improved performance compared to conventionally-cured concrete.[135] US company, Solidia aims to produce high performance, cheaper and rapidly formation concrete, while reducing water cost.[136] This technology seeks to store 30% of the overall product weight in CO_2 and reduce the overall carbon footprint by up to 60%.[137]

Applicability of CO_2 curing to reinforced concrete may be limited, due to potential corrosion of the steel reinforcement bars as it reduces the alkalinity of the water in the concrete's pores. Additionally, curing is currently only applicable to pre-cast concrete and may not be applicable to standard pumpable bulk cement, which makes up the majority of concrete used today.

4.4.1 The opportunity for Australia

Australia produces significant quantities of cement and concrete and demand is expected to continue to grow. Cement production was 10.4 million tonnes in 2018–19, up 9% on previous year.[138] Following a dip in 2020–21 due to COVID-19, industry revenue is forecast to grow at 2.0% annual through 2025–26.[139] The five integrated cement facilities operating in Australia served approximately 90% of local demand in 2018–19. During this period, total greenhouse emissions from the production of clinker and cement were approximately 5.1Mt CO_2-e,[140] which is equivalent to 1.2% of Australia's greenhouse emissions in the same year.[141]

Scale up and deployment of low emissions concrete provides a new pathway to shore up domestic supply of construction materials. Utilisation of waste streams for aggregate supply reduce the potential for scarcity of natural resources and responds to sustainability concerns in their use. [142]

4.4.2 Abatement potential

Abatement potential for concrete applications was not modelled for this report due to a lack of data, and literature availability and industry consensus. Abatement potential of these technologies requires more analysis. The amount of CO_2 utilised and abated for concrete applications varies widely.

- **CO_2 as an additive during mixing:** CarbonCure claims the mineralisation of approximately 1kg of CO_2 per cubic metre of concrete. However, the technology is claimed to abate 17kg of CO_2 for every cubic metre of concrete produced.[143] This abatement is largely due to the reduction of cement used, thus avoiding associated emissions from cement production.

135 International Energy Agency (IEA) (2019) *Putting CO2 to Use*. IEA

136 Solidia (n.d.) *Impact*. Viewed 3 May 2021, https://www.solidiatech.com/impact.html

137 LafarageHolcim (n.d.) *Solidia Cement: Reducing Significantly the Carbon Footprint of Precast Concrete*. Viewed 3 May 2021, https://www.lafargeholcim.com/sites/lafargeholcim.com/files/atoms/files/low-carbon_construction_solidia_co2_curing.pdf

138 Cement Industry Federation (2020) *Australian Cement Production*. Viewed 3 May 2021, https://cement.org.au/australias-cement-industry/about-cement/australias-cement-industry/

139 Kelly A (2020) *Cement and Lime Manufacturing in Australia*. IBISWorld

140 Cement Industry Federation (2020) *Australian Cement Report*. Cement Industry Federation

141 Australian Government Clean Energy Regulator (2020) *2018–19 published data highlights.* Viewed 3 May 2021, http://www.cleanenergyregulator.gov.au/NGER/National%20greenhouse%20and%20energy%20reporting%20data/Data-highlights/2018-19-published-data-highlights

142 Cement Industry Federation (2020) *Australian Cement Report*. Cement Industry Federation

143 Carbon Cure (2020) *CE Construction Solutions to introduce CarbonCure's carbon removal technology for concrete to Australian market*. Viewed 3 May 2021, https://www.carboncure.com/news/ce-construction-solutions-to-introduce-carboncures-carbon-removal-technology-for-concrete-to-australian-market/

- **Concrete curing:** Solidia claims a reduction of up to 30% in CO_2 emissions during the production of Solidia cement, and an overall carbon footprint production of up to 60% compared to ordinary Portland cement (OPC).[144] The capacity for CO_2-curing to provide a carbon sequestration benefit relies on ensuring the compressive strength is maintained above the level where more OPC is required in the concrete mixture. If a CO_2-curing method results in weaker concrete, more cement may be required. If so, the overall net emissions could be minimal or even increase as a result, outweighing the CO_2-curing benefits.[145]

4.5 Considerations

Commercial

Start with low-risk applications. There are many different concrete mixtures that have been developed to meet the material characteristics required of various bulk or specialised applications, ranging from footpaths to skyscraper platforms. To initially prove the functionality and value of concrete CO_2 applications, manufacturers could begin with implementing the technologies for low-risk classes of concrete. This includes footpaths, curbs, drain channels, secondary roofs, non-load bearing residential walls and many other non-structural applications. The construction sector is more likely deploy new materials in lower risk contexts, where the materials can be demonstrated to increase industry and public confidence. Approval and certification of the use of these concretes in low-risk applications could also be more easily achieved, promoting their uptake. The Japanese Ministry of Economy, Trade and Industry expects CO_2-based road curb blocks to be similar in price to existing products by 2030.[146]

Co-location of feedstocks and carbonation facilities: Production costs are strongly influenced by the price of feedstocks. Distribution of these feedstocks can add to operating costs significantly. By pursuing co-location use cases where mineral feedstock and CO_2 capture are co-located, added costs can be avoided.

Policy and regulation

Concrete standards: Utilising CO_2 in building materials often results in compositions that differ from conventional mixtures, however there is currently no direct regulation for CO_2 content in concrete. Composition-based standards, which are defined by the presence and ratio of components, can be a significant hurdle in introducing new products. Shifting from composition-based to performance-based standards, or introducing new standards, could enable faster approval and uptake of CO_2 mineralised building materials. [147]

Carbon intensity ratings: To promote demand for CO_2-based products, carbon intensity ratings systems for new buildings could be established. This may incentivise the use of CO_2 as an input into building materials. Gradually ramping up carbon intensity standards could provide industry time to develop capability to supply these CO_2-based products for future construction and transport projects.

Case Study: Honolulu resolution to consider CO_2 mineralisation[148]

In 2019, the municipality of Honolulu passed a resolution which requests the city administration to consider CO_2 mineralised concrete in all future infrastructure projects, where the utilisation of CO_2 does not significantly increase cost or delay a project. Additionally, the resolution required consideration of an incentive system to encourage the use of CO_2 mineralisation in concrete in all city and city-contracted projects. Effectively, these resolutions serve to encourage the use of CO_2 mineralisation in city infrastructure projects where favourable. The US conference of mayors passed a similar resolution shortly after.

144 LafarageHolcim (n.d.) *Solidia Cement: Reducing Significantly the Carbon Footprint of Precast Concrete*. Viewed 3 May 2021, https://www.lafargeholcim.com/sites/lafargeholcim.com/files/atoms/files/low-carbon_construction_solidia_co2_curing.pdf

145 Ravikumar D et al. (2021) *Carbon dioxide utilization in concrete curing or mixing might not produce a net climate benefit.* Nature Communications

146 Ministry of Economy, Trade and Industry (METI) (2019) Roadmap for Carbon Recycling Technologies. METI

147 International Energy Agency (IEA) (2019) *Putting CO2 to Use*. IEA

148 Honolulu City Council (2018) *Resolution: Requesting the city administration to consider using carbon dioxide mineralization concrete for all future city infrastructure projects utilizing concrete*. Viewed 3 May 2021, https://honolulu.granicus.com/MetaViewer.php?view_id=&event_id=461&meta_id=85271

Environmental and social

Public and industry acceptance of new building materials: Demonstrating the viability of building materials made using CO_2 and communicating the potential carbon sequestration benefits to the public could support widespread uptake. As described above, low risk concrete types could be demonstrated first to build acceptance of the new materials.

CO_2 source and net emissions: Concrete mineralisation and carbonate products present the opportunity to sequester CO_2 permanently in some cases. However, the initial source of the CO_2 is important in determining the overall carbon benefit. CO_2 sourced from DAC provides a greater overall carbon reduction than CO_2 sourced from industrial waste streams, but currently at a greater cost. Robust and verifiable measurements and lifecycle analyses should be conducted to ensure an overall emission reduction has been achieved.

RD&D

Early trials to test novel materials: The building sector has historically been conservative in adoption of new materials. Conducting trials to demonstrate the long-term durability of new products and providing rapid and low-cost certification processes for low-carbon concrete could accelerate approval and industry uptake.[149]

CO_2 curing process and material improvements: Maximising compressive strength, decreasing electricity usage and a reduction in process emissions are large factors in the potential CO_2 benefit from CO_2 curing.[150] Further testing of CO_2 curing in reinforced steel may be required to understand and manage corrosion risk.

Thermal activation of mineral feedstocks: Some mineral feedstocks require grinding and/or heating in order to maximise their reactivity with CO_2 to form mineral carbonates. This step requires temperatures up to 600-700°C, which is a key component of the process cost and could contribute to further emissions. While natural gas combustion coupled with CO_2 capture could provide the necessary heat, alternative heat sources such as concentrated thermal power could be utilised.

Case Study: NRG COSIA Carbon XPrize[151]

The NRG COSIA Carbon XPrize was launched in 2015 and has awarded $26 million to companies converting CO_2 into valuable products. Prizes were awarded to technologies that convert the most CO_2 emissions into the highest value products, with consideration for usage of other such as energy, water and land use. In April 2021, the two prize winners were announced: CarbonCure Technologies and UCLA CarbonBuilt. CarbonCure's technology is discussed above. UCLA CarbonBuilt produces concrete products by directly injecting CO_2 from flue gas streams into a concrete mixture. This reduces the carbon footprint and raw material costs of concrete, while maintaining material reliability.

149 Alberici S et al. (2017) *Assessing the potential of CO2 utilisation in the UK*. Imperial College London & ECOFYS

150 Ravikumar D et al. (2021) *Carbon dioxide utilization in concrete curing or mixing might not produce a net climate benefit.* Nature Communications

151 XPRIZE (2021) *XPRIZE announces the two winners of $20m NRG COSIA Carbon XPRIZE, with each team creating valuable products out of CO2 emissions*. Viewed 3 May 2021, https://www.xprize.org/prizes/carbon/articles/xprize-announces-the-two-winners-of-20m-nrg-cosia-carbon-xprize-with-each-team-creating-valuable-products-out-of-co2-emissions

5 Conversion of CO_2 into chemicals and fuels

5.1 Key findings

With Australia's emerging hydrogen industry and its history as an energy exporter, it is well positioned to support the long-term transition to lower-emissions chemicals and fuels, but high green premiums in the near-term may require a strategic investment.

Demand for carbon based chemicals and fuels is expected to continue growing. Therefore, chemicals and fuels from CCU present a growth opportunity for Australia, especially when considering the export markets and alignment with the Australian Government's National Hydrogen Strategy and proposed hydrogen and CCS hubs. However, due to high green premiums, near-term investments in Australia will likely be driven by strategic or political motivations, such as providing fuel security or supporting the domestic plastics and chemicals industry.

Currently, the source of carbon for these products is derived from fossil fuels. While carbon offsets could be considered to support long-term net zero targets for these industries, CCU provides a pathway that could support the transition to low-emissions alternatives.

Scale-up considerations:

- **Initial application(s):** Methanol is a standalone growth market and a platform chemical which can be used as a feedstock chemical for synthesis of other chemicals and fuels. Aligning methanol scale-up with the hydrogen industry development can create a hydrogen off taker and potential carrier (alongside ammonia).
- **Deployment model:** Co-location in hubs with existing infrastructure and feedstocks will help match supply and demand and is vital for cost reduction. In the near-term hybrid models that start with natural gas and increasingly blend renewable hydrogen, could be considered as hydrogen cost and availability are established. The scale up priorities to develop fuel and chemical facilities are set out in the table below.

ABATEMENT CONSIDERATIONS

Green premium:

Even with advancements in technology and large-scale production, assuming today's prices, green premiums will be attached to synthetic fuels and chemicals.

Cost of abatement:

Cost of abatement varies by sale price of product. Plastics (olefins) can have a negative cost of abatement (profit) with high sale price.

Abatement potential:

Dependent on domestic hydrogen production. When using DAC, potential for low net emissions but point source CO_2 can only theoretically avoid further emissions by 50%.

Duration of CO_2 storage:

Released on use for some downstream applications (e.g. fuels) or locked away for the life of the product (e.g. polymers for years to decades depending on the use-case).

Scale-up priorities:

IMMEDIATE (2020–2025)	SHORT-MEDIUM TERM (2025–2030)	LONG-TERM (2030–2040)
• Demonstrate hybrid methanol facility using combination of fossil fuels and renewable H_2 • Conduct feasibility studies for electrofuel production site selection • Conduct feasibility studies for Methanol-to-olefin (MTO) synthesis plants • Establish potential synthetic olefin customers • Demonstrate distributed SNG plants	• Establish methanol base case scale facility in industrial hub • Set up methanol feeds into new offtakers • Demonstrate blending of electrofuels from fuel plant into fossil fuel supply • Demonstrate base case MTO plant • Demonstrate integration of CO_2-based polymer feedstocks into existing polymer production plants • Establish SNG base case plant to blend into existing supply	• Achieve operation of best case scale methanol facility • Secure large synthetic offtakers • Explore potential for methanol export • Establish best case electrofuel scale facilities to serve airports • Establish best case scale MTO facilities • Explore potential for synthetic olefin export • Establish best case SNG plant

5.2 Overview

This chapter explores chemicals and fuels that are achieved via conversion of CO_2 through thermochemical processes.

Chemicals and fuels can be produced through a range of conversion pathways as seen in Figure 18. Direct hydrogenation is a newer commercial process that can avoid extra process steps and enables the production of shorter hydrocarbons for more targeted fuel production.[152] The direct hydrogenation route was selected for modelling for these reasons. These fuels and chemicals can also be produced with CO_2 as a feedstock by utilising microorganisms to facilitate the conversion. Biological conversion is explored in Chapter 6.

The versatility of methanol allows it to act as a building block for a variety of products, particularly those that are difficult to decarbonise with the implementation of renewable energy technologies alone. As such, renewable methanol, created using H_2 and CO_2, is discussed in this report in detail and plays a role in subsequent opportunities – namely synthetic jet fuel (electrofuels), olefins (used to create polymers/plastics) and other chemicals.

Biomass conversion

This report focuses on the conversion of CO_2 into chemicals and fuels through thermochemical processes and via biological organisms. Alternatively, there is also a 'biomass conversion' pathway, in which CO_2 is naturally absorbed via photosynthesis in algae, trees and other plants to produce biomass. The biomass is then processed thermochemically or biologically to generate power or a range of products. In these processes, CO_2 is generated. The CO_2 could then be captured for utilisation. For example, biomass can be burnt to produce power for electricity, releasing CO_2 in the process which is then captured and utilised; or biomass sugars can be fermented in a biorefinery, producing CO_2 as a by-product which is then captured and utilised. This model is similar to bioenergy with carbon capture and storage (BECCS), with the key difference being the utilisation of CO_2 for a secondary purpose, rather than storage.[153]
The key barriers that biomass conversion faces are: competition between crops grown for biomass use, and those used primarily for food generation; and scalability challenges associated with the complexity and early-stage nature of biorefineries.

152 Bruce S et al. (2020) *Opportunities for hydrogen in commercial aviation*. CSIRO

153 Gabrielli P, Gazzani M, Mazzotti M (2020) *The Role of Carbon Capture and Utilization, Carbon Capture and Storage, and Biomass to Enable a Net-Zero-CO2 Emissions Chemical Industry*. Industrial & Engineering Chemistry Research.

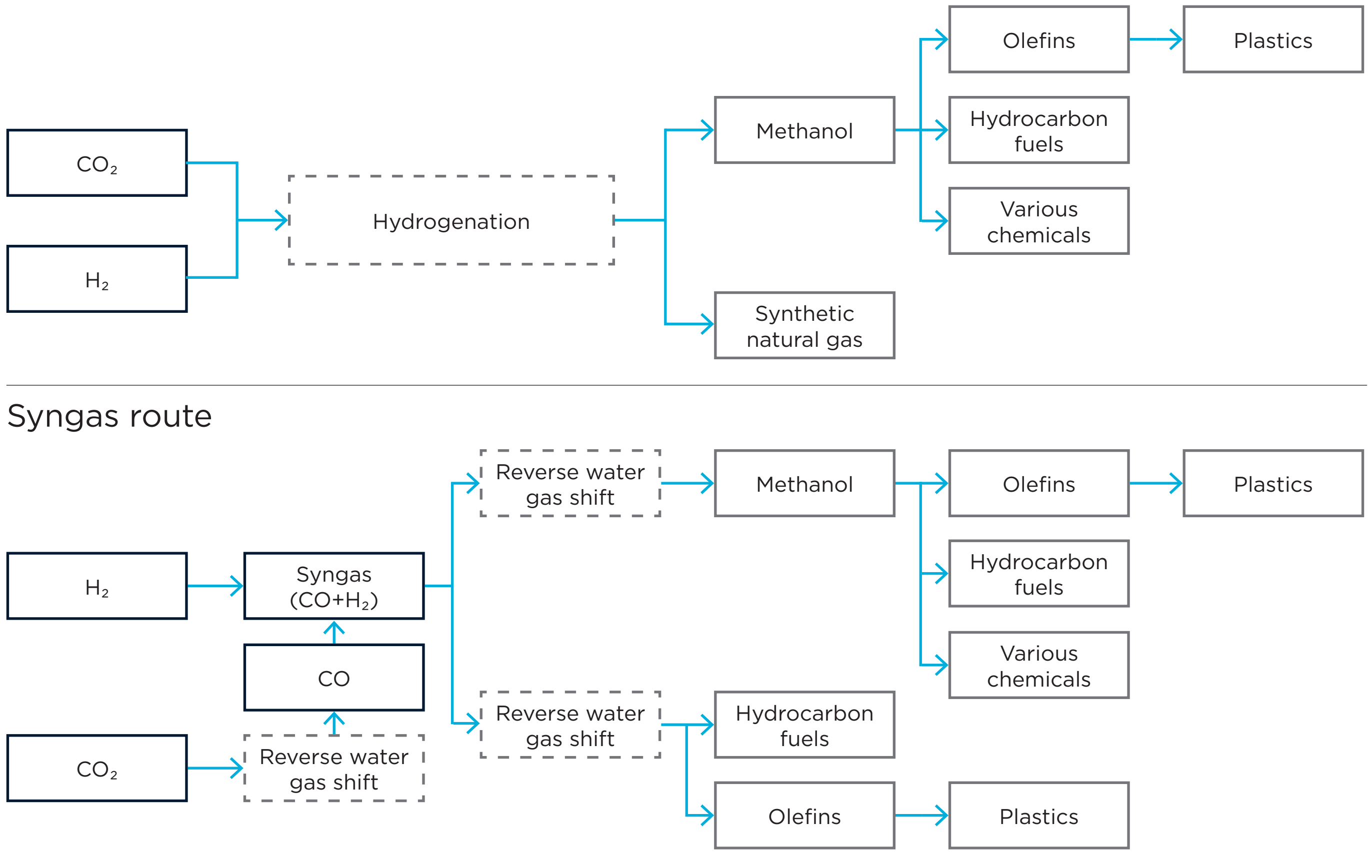


Figure 18: Conversion of CO_2 into chemicals and fuels via different pathways

5.3 Methanol

Methanol is a valuable product used for the production of thousands of everyday items, including a broad range of plastics, plywood, sealants, medical equipment, insulation and paints. It is also sometimes used as a fuel or an additive to other fuels, providing an alternative to conventional transport fuels.

Global methanol production in 2020 was just over 100 million tonnes per annum.[154] Global analysis published by the International Renewable Energy Agency (IRENA) and the Methanol Institute has predicted that global methanol production could grow to 500Mt by 2050. [155] Methanol is conventionally synthesised from synthesis gas (or syngas) derived through steam reforming (SMR) of natural gas or steam gasification of coal. As such, IRENA calculated that if future growth was solely sourced from fossil fuels it would result in the release of 1.5Gt CO_2 per annum. [156]

The expected growth and associated emissions of the industry are focusing greater attention on the renewable methanol production from biomass/biogas/waste or through the utilisation of CO_2 (specifically direct hydrogenation of CO_2). Both pathways are technically mature, however renewable methanol currently has a price premium when compared to the conventional production using fossil fuels. This report focuses on the utilisation of CO_2, particularly from point source capture and DAC. Although valuable, it does not consider bio-methanol from biomass feedstocks.

154 Methanol Market Services Asia (2020) *Methanol price and supply/demand*. Viewed 3 May 2021, https://www.methanol.org/methanol-price-supply-demand/

155 IRENA & Methanol Institute (2021) *Innovation Outlook: Renewable Methanol*. IRENA

156 IRENA & Methanol Institute (2021) *Innovation Outlook: Renewable Methanol*. IRENA

5.3.1 The opportunity for Australia

Australia does not currently produce methanol, with the only production facility, operated by Coogee in Victoria, placed into care and maintenance mode in 2016.[157] This was the result of high east coast gas prices and lack of long-term gas supply, despite electrifying components of the synthesis process. During plant operation, approximately 72,000 tonnes of methanol was produced per year which serviced 80% of local demand.[158] Options to restart the plant are currently being assessed. However, there are other projects being evaluated, some of which could transition to renewable methanol alongside further scale-up of renewable hydrogen and CO_2 capture. For example:

- Wesfarmers, Coogee Chemicals and Mitsubishi's 2018 announcement of a pre-feasibility study into a large scale methanol plant in Burrup Peninsula, Western Australia.[159] The plant is targeting a world-scale methanol plant, producing 1.8 million tonnes of methanol per annum, with a goal of bringing the plant online by the mid-2020s, if the companies decide to proceed.[160]
- Coogee Chemicals' 2019 announcement of plans to conduct a feasibility study for a $500 million, 350,000 t/per year methanol plant in Darwin.[161]
- ABEL Energy's announcement in 2020 to explore development of Australia's first renewable methanol plant located in Bell Bay, Tasmania. The plant targets 60,000 tonnes of methanol per year with first production planned for 2023.[162]

With a lack of operating methanol plants in Australia, there remains a risk in accessing the appropriate capabilities needed to develop and operate new chemical and fuels synthesis plants. In addition to being a large-scale hydrogen offtaker should domestic methanol production come online, methanol can also be used as a hydrogen carrier. Given that the demand for methanol is predicted to grow, the opportunity exists for Australia to both meet its own domestic needs and potentially develop an export market for low emissions methanol.

5.3.2 Levelised cost of production, modelling results

Figure 19 explores the levelised cost of producing renewable methanol with different CO_2 feedstocks, compared to the production of methanol derived from fossil fuels. It also includes a zero capture cost sensitivity, where the overall cost of CO_2 capture is considered zero, to indicate the influence of capture on production. These levelised costs sit within the range of recent analyses on e-methanol.[163]

To standardise analysis across CCU applications, methanol plant scale is a function of the scale of CO_2 capture that is explored in Chapter 1.

Analysis indicates that renewable hydrogen production is a major cost driver, accounting for approximately 60% of the total levelised cost of methanol production. Sensitivity analysis indicates that a premium would exist even if Australia was to achieve or exceed its long-term stretch hydrogen production target of $2/kg hydrogen, as seen in Figure 20.

157 Coogee (2021) *Methanol Plant in North Laverton, Melbourne*. Viewed 3 May 2021, https://www.coogee.com.au/Our-Businesses/Chemicals-Manufacturing/Manufacturing-Facilities/Methanol-plant-in-North-Laverton,-VIC

158 Richardson A (2020) *Basic Organic Chemical Manufacturing in Australia*. IBISWorld

159 Milne P (2018) *Wesfarmers and Perdaman advance WA petrochemical plans for Burrup Peninsula*. Viewed 3 May 2021, https://thewest.com.au/business/energy/wesfarmers-and-perdaman-advance-wa-petrochemical-plans-for-burrup-peninsula-ng-b881021412z

160 Richardson A (2020) *Basic Organic Chemical Manufacturing in Australia*. IBISWorld

161 Northern Territory Government of Australia (2019) *Start of Gas Manufacturing Industry in NT: 1000 Jobs in Construction through Methanol Project Planned for NT*. Viewed 3 May 2021, https://newsroom.nt.gov.au/mediaRelease/31427

162 ABEL Energy (2020) *Our projects*. Viewed 3 May 2021, https://www.abelenergy.com.au/our-projects

163 IRENA & Methanol Institute (2021) *Innovation Outlook: Renewable Methanol*. IRENA

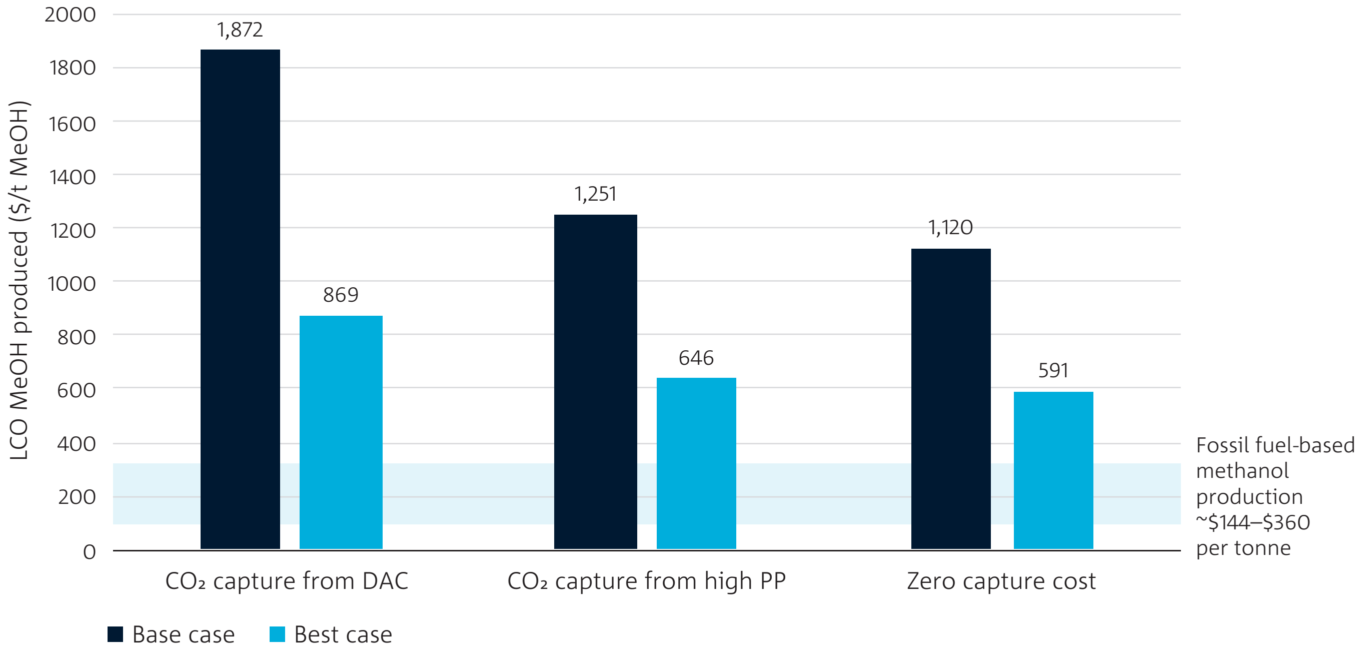


Figure 19: Levelised cost of methanol production with different CO_2 feedstocks[164]

Renewable methanol production assumes the use of renewable hydrogen. CO_2 feedstocks include CO_2 capture from high temperature DAC, high partial pressure point source and a zero dollar capture cost. Base case considers utilisation of 1,000t/d of CO_2 and a production scale of 636t/day MeOH. Best case assumes utilisation of 5,000t/d CO_2 and a production scale of 3,182t/day MeOH. The production scale for the base and best case both exceed current Australia annual demand. See Appendix C for modelling assumptions. In terms of hydrogen requirements, the base case requires 132t/d of H_2 from a 330MW electrolyser and the best case requires 660t/day H_2 from a 1,376MW electrolyser. The production scale for the best and base case exceed current Australia annual demand.

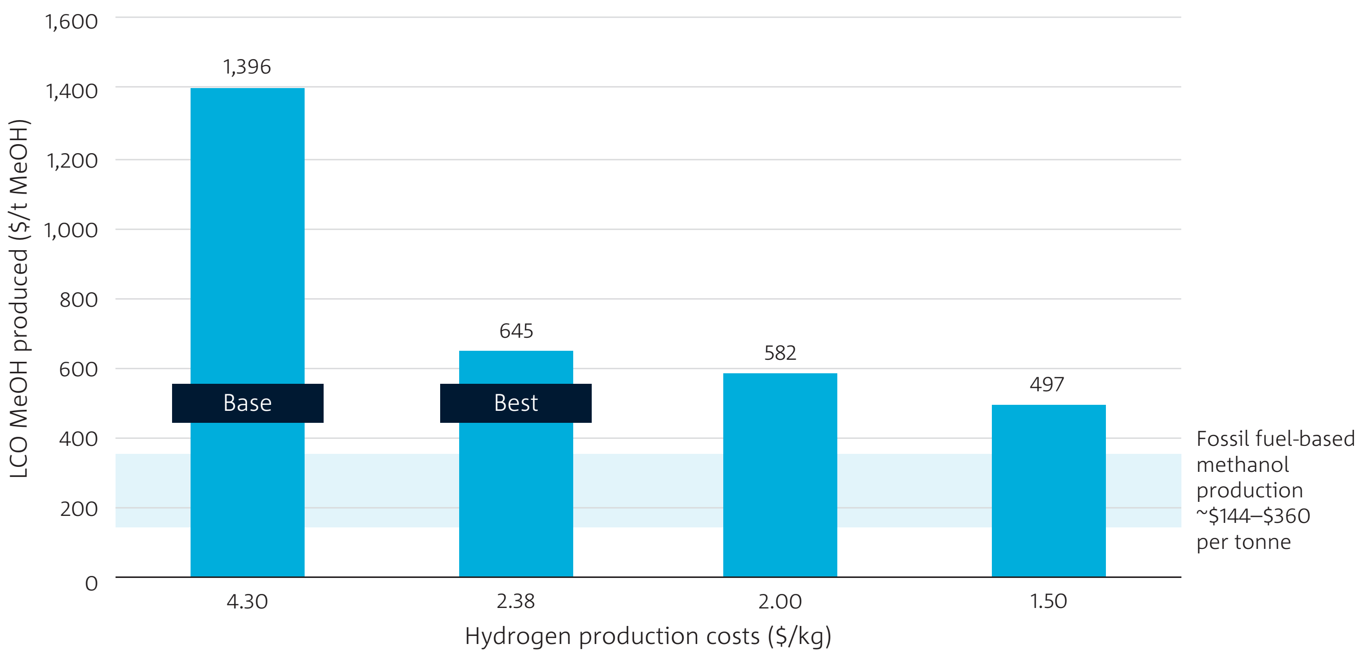


Figure 20: Influence of hydrogen production costs on levelised cost of methanol production

This sensitivity analysis shows the effect that hydrogen production costs have on the final product, with stretch goals of $2/kg and $1.50/kg. These figures assume that CO_2 is sourced from a high partial pressure point source.

164 Fossil fuel-based methanol production prices sourced from: IRENA & Methanol Institute (2021) *Innovation Outlook: Renewable Methanol*. IRENA

5.3.3 Abatement potential and costs

Assessment of abatement potential using production as a boundary condition shows that for every 1 tonne of renewable methanol produced via CO_2 hydrogenation, 1.911 tonnes of CO_2 are abated, assuming the CO_2 is sourced from DAC. If CO_2 was from a point source, the abatement potential would be 1.126 tonnes of CO_2 for every tonne of renewable methanol produced. See Appendix D for abatement potential approach.

This analysis excludes lifecycle emissions which would change the net abatement potential. For example, the analysis assumes renewable energy is used in the hydrogenation production process, including renewables to create hydrogen. The abatement potential does not consider end use, which would also vary in the case of methanol as it could be used directly as a fuel and the CO_2 would be released on use or the methanol could be used to create plastics which would lock away a portion of the CO_2 for a longer period.

As an illustration, Figure 21 assumes an annual consumption of 100,000t of methanol per annum, which is approximately Australia's present-day consumption. During initial uptake, it is assumed that renewable methanol will be scaled up progressively, displacing a certain percentage of the fossil fuel-derived supply which can be seen on the figure. If Australia develops its methanol industry with a view towards export the abatement potential can be far larger.

The cost of abatement (\$/t CO_2) would vary depending on the sale price of the methanol (see Figure 22), which since the mid-1990s has had an average contract price that has fluctuated between approximately \$290 to \$580 per tonne.[165]

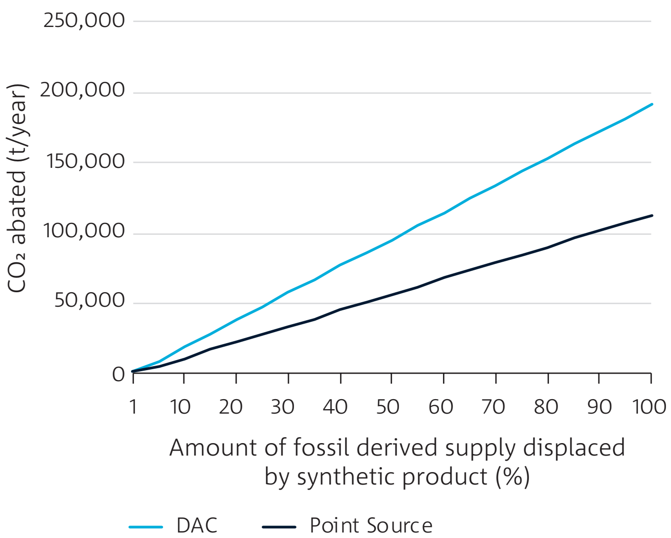


Figure 21: CO_2 abatement in methanol production using different CO_2 sources

CO_2 abatement potential uses production as a boundary condition and does not consider full lifecycle emissions. The figure demonstrates abatement potential using an illustrative case of 100,000t of methanol per annum with best case assumptions, considering the effect of renewable methanol displacing a certain percentage of the fossil fuel-derived supply. Best case used in figure assumes utilisation of 5,000t/d CO_2 and a production scale of 3,182t/day MeOH, including CO_2 capture from high temperature DAC and a high partial pressure point source. See Appendix D for abatement potential approach. This figure illustrates how CO_2 abatement increases as more synthetic product is introduced into the Australian market, with DAC providing the most abatement potential given the closed loop use of CO_2.

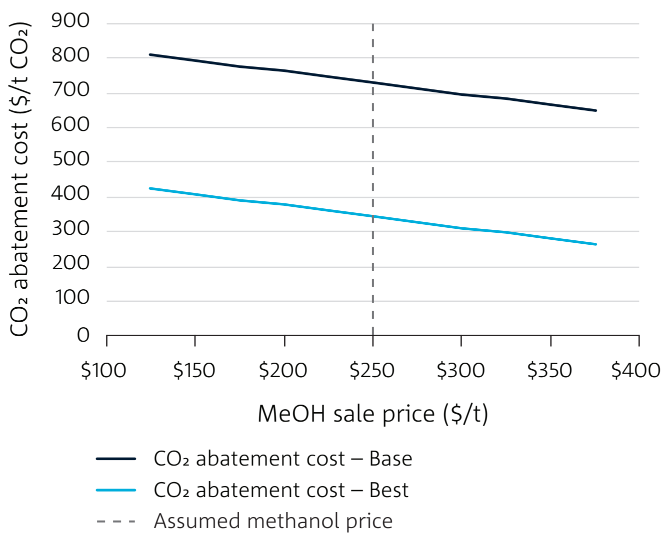


Figure 22: Effect of MeOH sale price on cost of abatement

Effect of different MeOH sales prices on cost of abatement using high partial pressure capture with base and best case assumptions. Base case considers utilisation of 1,000t/d of CO_2 and a production scale of 636t/day MeOH. Best case assumes utilisation of 5,000t/d CO_2 and a production scale of 3,182t/day MeOH. See Appendix C for modelling assumptions. This figure illustrates how an increase in the sale price of the synthetic product reduces the cost of CO_2 abatement.

165 Average contract price in Europe sourced from: IRENA & Methanol Institute (2021) *Innovation Outlook: Renewable Methanol.* IRENA. Converted to AUD from USD using an exchange rate of 0.69

5.4 Jet fuel

Conventional jet fuel consists of several different crude oil-based compounds which are combusted to power aircraft engines. The extraction, distribution, and hydrotreatment of oil to produce jet fuel, as well as the combustion of the final product, all contribute to CO_2 emissions. Conventional jet fuel is defined by its performance specification, as opposed to the molecules it is comprised of, making the substitution of low emissions fuels simpler to achieve certification.

The International Air Transport Association (IATA) has set major decarbonisation goals over the coming decades, aiming for a reduction in net aviation CO_2 emissions of 50% by 2050, relative to 2005 levels, which will require the production of low emission jet fuel.[166] However, few alternatives for decarbonisation in long distance aviation transport exist. For the distances required, electrification is not technologically feasible in the short to medium term. The introduction of unconventional fuels would require extensive new refuelling infrastructure and potentially new engine designs. The existing aircraft fleet assets have long life spans, of the order of 30 years, which will prolong the demand for jet fuel beyond 2050.

Synthetic electrofuels are one of a class of sustainable aviation fuels, synthesised from hydrogen sourced from electrolysers and captured CO_2. Electrofuels have the advantage of being considered a “drop-in” fuel, ie. no or minimal engine modifications are required. Electrofuels can also burn more efficiently and with fewer contaminants than traditional fuels.[167] Biofuels are likely to also play a role in decarbonising the aviation sector, but given the size of the challenge, other sustainable jet fuels like electrofuels will be required.

Electrofuels can be synthesised from CO_2 and hydrogen via two processes, methanol upgrading and through the Fischer-Tropsch process. Previous modelling[168] has shown the methanol pathway is more economical and thus will be the focus of this chapter.

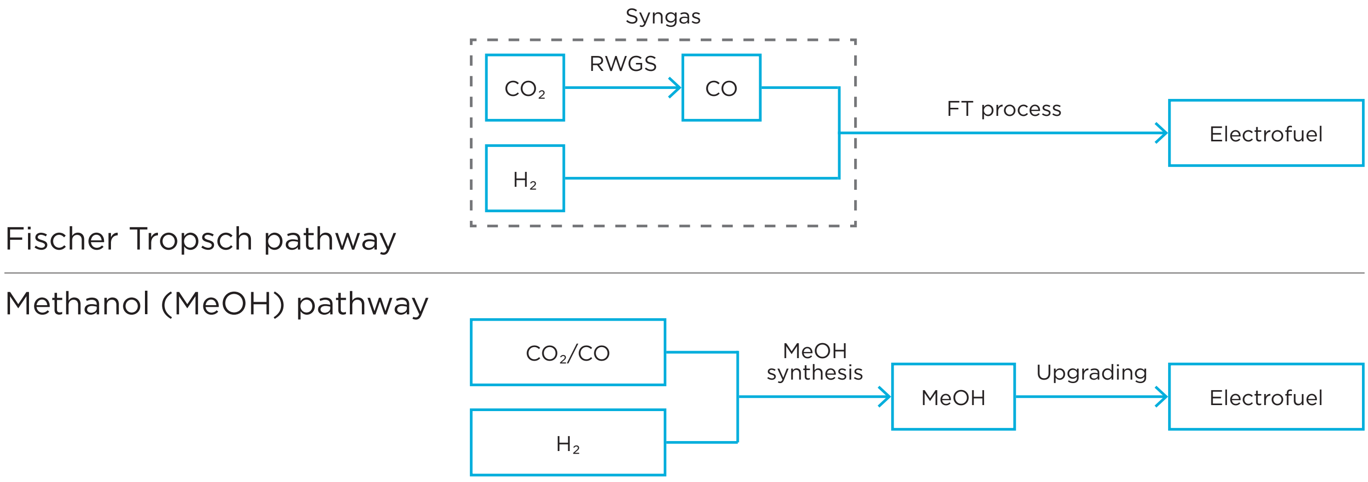


Figure 23: Synthesis pathways for electrofuels

This diagram shows two methods of converting hydrogen and CO_2 into electrofuel. The hydrogen is produced by electrolysers that are powered by electricity. RWGS refers to reverse water gas shift reaction which is required to convert carbon dioxide to carbon monoxide.

166 International Aviation Transport Association (IATA) *Working towards ambition targets.* Viewed 20 June 2021, https://www.iata.org/en/programs/environment/climate-change/

167 Argonne National Labs (2012) *Life Cycle Analysis of Alternative Aviation Fuels in GREET*. US DOE

168 Bruce S et al. (2020) *Opportunities for hydrogen in commercial aviation*. CSIRO

5.4.1 The opportunity for Australia

Australia imports 40% of its jet fuel and obtains the remaining 60% from refining its crude oil reserves. Reliance on imported jet fuel is projected to grow, with the continued rapid decline in domestic oil production and refining capacity; and growth in required jet fuel volumes.[169]

Significant historical demand, projected growth and the quantity of CO_2 required for synthesis combine to make the CCU potential of electrofuels considerable. There is significant demand for jet fuel in Australia and abroad, meaning there will be offtakers and the market will be hard to flood. Pre-COVID aviation fuel sales for Australian domestic and international use was approximately 170,000 barrels per day (bbl/day).[170] Following a sharp fall in 2020, passenger numbers in Australia are expected to return to 2019 levels in 2023 at the earliest.[171]

Although electrofuels face a green premium, there may be strategic or political motivations to pursuing domestic production. Importantly, it would assist in securing fuel supply by reducing reliance on imports of crude oil and refined products. While this is important across commercial use cases, it is a particularly important consideration for defence applications, where increased supply chain risks can have flow on effects for national security. The Australian Government Department of Defence spent approximately $423 million on fuel in 2016–17, with the majority of this used by the Air Force. However, the Australian National Audit Office has 'consistently identified weaknesses in Defence's fuel supply chain management'.[172] Therefore, CO_2-derived jet fuel can support the transition to lower-emissions products while also offering fuel security for Australia.

5.4.2 Levelised cost of production, modelling results

Figure 24 explores the levelised cost of producing electrofuels with different CO_2 feedstocks compared to the production of jet fuels derived from fossil fuels. It also includes a zero capture cost sensitivity, where the overall cost of CO_2 capture is considered zero, to indicate the influence of capture on production. It shows that even with technology improvements and scale-up, there remains a significant premium compared to today's fossil fuel derived jet fuel price.

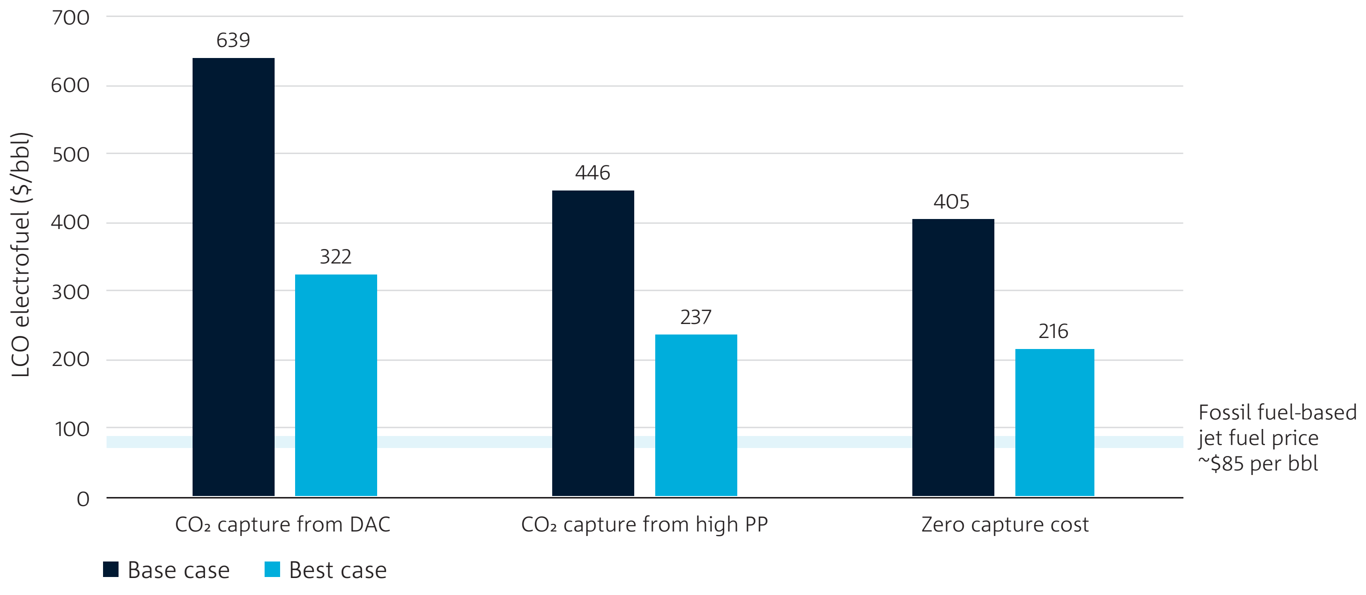


Figure 24: Levelised cost of electrofuels production with different CO_2 feedstocks

Production of electrofuels assumes the use of renewable hydrogen. CO_2 feedstocks include CO_2 capture from high temperature DAC, high partial pressure point source and a zero dollar capture cost. Base case considers utilisation of 1,000t/d of CO_2 and a production scale of 1,179bbl/day (263t/d). Best case assumes utilisation of 5,000t/d CO_2 and a production scale of 5,897bbl/d (1,317t/d). The production scale for the best case accounts for the majority of annual Australian demand currently. See Appendix C for modelling assumptions. In terms of hydrogen requirements, the base case requires 132t/d of H_2 from a 330MW electrolyser and the best case requires 660 t/day H_2 from a 1,376MW electrolyser.

169 ACIL Tasman (2009) *Petroleum import infrastructure in Australia*. ACIL Tasman

170 Australian Government Department of Industry, Science, Energy and Resources (DISER) (2020) *Australian Petroleum Statistics*. DISER

171 International Air Transport Association (2020) *IATA Response on Future of Australia's Aviation Sector*. Viewed 3 May 2021, https://www.infrastructure.gov.au/aviation/future/files/future_aviation_39_IATA_2020.pdf

As per methanol in the previous section, the major cost driver and focus for cost reduction is hydrogen production. Sensitivity analysis indicates that a premium would exist even if Australia was to achieve or exceed its long-term stretch hydrogen production target of $2/kg hydrogen, as seen in Figure 25.

5.4.3 Abatement potential and costs

Assessment of abatement potential using production as a boundary condition shows that for every 1 tonne of electrofuels produced via methanol, 3.213 tonnes are abated, assuming the CO_2 is sourced from DAC. If CO_2 was from a point source the abatement potential would be 2.486 tonnes of CO_2 for every tonne of electrofuels produced. See Appendix D for abatement potential approach.

This analysis excludes lifecycle emissions such as the source of the energy required to produce the electrofuels, as well as the energy required for the methanol used in this process. The abatement potential does not consider end use, which in this case would result in the burning of the fuel and the release of CO_2. This stresses the importance of DAC to create a carbon neutral fuel, however if the fuel is created using point source emissions the overall carbon intensity of those emitting industries is still reduced.

As an illustration of abatement potential, Figure 26 assumes an annual consumption of 10,000,000t of jet fuel per annum, which is approximately Australia's annual consumption, pre COVID-19. During initial uptake, it is likely that electrofuels will be scaled up progressively, displacing a certain percentage of the fossil fuel-derived supply which can be seen in the figure.

The cost of abatement ($/t CO_2) would vary depending on the sale price of the electrofuel (see Figure 27). The past decade has seen relatively low jet fuel prices, which fell further during 2020 as a result of the COVID-19 pandemic and its impact on global travel.

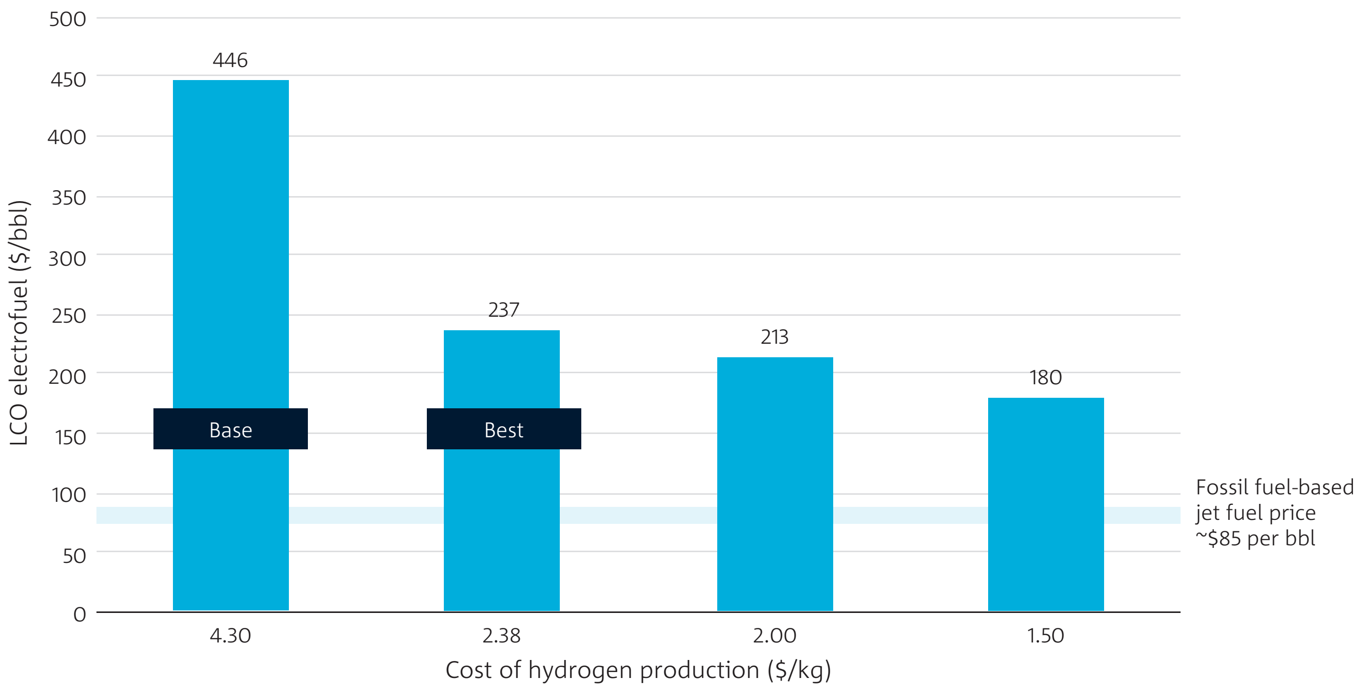


Figure 25: Influence of hydrogen production costs on levelised cost of electrofuel production

This sensitivity analysis shows the effect that hydrogen production costs have on the final product, with stretch goals of $2/kg and $1.50/kg. These figures assume that CO_2 is sourced from a high partial pressure point source.

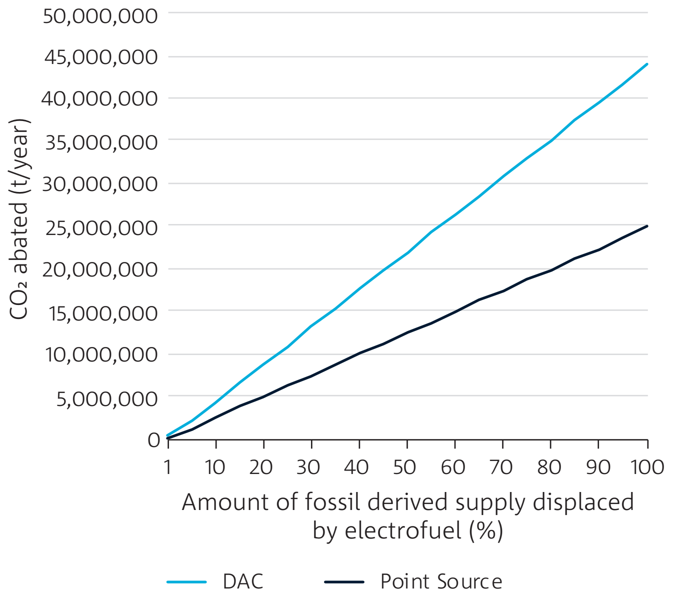


Figure 26: CO_2 abatement in electrofuels production using different CO_2 sources

CO_2 abatement potential uses production as a boundary condition and does not consider full lifecycle emissions. The figure demonstrates abatement potential using an illustrative case of 10,000,000t of jet fuel per annum with best case assumptions, considering the effect of electrofuel displacing a certain percentage of the fossil fuel-derived supply. Best case assumes utilisation of 5,000t/d CO_2 and a production scale of 5,897bbl/d (1,317t/d), including CO_2 capture from high temperature DAC and a high partial pressure point source. See Appendix D for abatement potential approach. This figure illustrates how CO_2 abatement increases as more synthetic product is introduced into the Australian market, with DAC providing the most abatement potential given the closed loop use of CO_2.

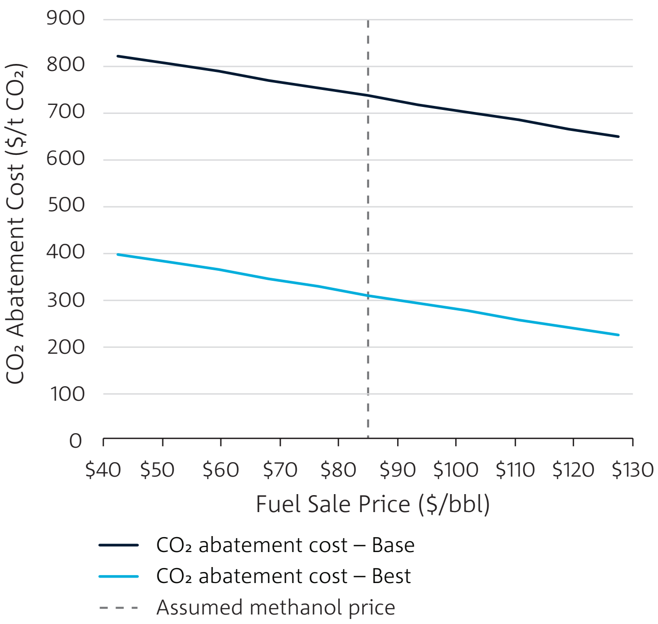


Figure 27: Effect of fuel sale price on cost of abatement

Effect of different electrofuel sales prices on cost of abatement using high partial pressure capture with base and best case assumptions. Base case considers utilisation of 1,000t/d of CO_2 and a production scale of 1,179bbl/day (263t/d). Best case assumes utilisation of 5,000t/d CO_2 and a production scale of 5,897bbl/day (1,317t/d). See Appendix C for modelling assumptions. This figure illustrates how an increase in the sale price of the synthetic product reduces the cost of CO_2 abatement.

5.5 Polymers

Plastics are ubiquitous in our households, workplaces and industries, finding use in clothing, coatings and adhesives, elastomers, electrical and automotive parts, consumer products, and construction materials. They are also at the core of recent developments in biomaterials, medical devices and therapeutics, electronics, semiconductors and nanotechnology. Plastics are polymers largely composed of carbon, hydrogen, oxygen, and smaller amounts of other elements. The global plastics industry currently relies mainly on petroleum (fossil fuels) as the source for the building blocks (or monomers) used to make polymers.

Global plastics production, which was 311 million tonnes in 2014, is expected to double by 2036 and almost quadruple by 2050.[173] Additionally, the use of oil by the plastics industry is expected to increase alongside plastics production, growing by 3.5–3.8% each year.[174] 3.5 million tonnes of plastics were used in Australia in 2018 to 2019, of which around 60% was imported.[175]

Improving the sustainability of the plastics industry will require significant steps to increase plastic recycling, reuse, and biodegradability (noting some of these measures are mutually exclusive). However, demand for new plastic feedstocks is still expected to continue to increase despite these measures. If global recycling rates rose from today's 14% to more than 55%, requirements for new plastic feedstock would still double by 2050.[176]

Additionally, while recycling, avoidance and sustainable alternative materials may mitigate some plastic applications significantly, there are many long-term applications of plastic (such as construction and electronics) that will be difficult or undesirable to substitute, and that are therefore likely to require new plastic material in future. Figure 28 demonstrates that while the building and construction market used 19% of plastic produced in 2015, it only generated 5% of total plastic waste.

Polymers can be divided into several groups that have different properties and different production processes but can be derived from a common chemical. Table 6 describes the most common polymer groups, their uses, and global share of polymer resin production. Figure 28 compares the production and waste generation of plastic uses by market sector, highlighting the application areas where products are more likely to have longer lifespans.

CCU presents an opportunity to create new plastics which make use of existing CO_2 in the atmosphere or waste streams, helping to transition the industry towards lower-emissions products. The synthesis routes for polymers broadly follow the same pathways as previously described for methanol in Chapter 5.3. Hence, the same opportunities for substitution of fossil fuels for low-emission CO_2 and renewable hydrogen exist (see Figure 29).

172 Australian National Audit Office (ANAO) (2018) *Defence's Procurement of Fuels, Petroleum, Oils, Lubricants, and Card Services*. ANAO
173 World Economic Forum (2016) *The New Plastics Economy: Rethinking the future of plastics*. World Economic Forum
174 World Economic Forum (2016) *The New Plastics Economy: Rethinking the future of plastics*. World Economic Forum
175 Australian Government Department of Agriculture, Water and the Environment (DAWE) (2021) *National Plastics Plan 2021*. DAWE
176 World Economic Forum (2016) *The New Plastics Economy: Rethinking the future of plastics*. World Economic Forum
177 Geyer R et al. (2017) *Production, use, and fate of all plastics ever made*. Science Advances

Table 6: Common polymers and their uses

POLYMER GROUP	EXAMPLE APPLICATIONS	GLOBAL SHARE OF RESIN PRODUCTION, BY MASS[177]
Polyethylene	Packaging (including milk bottles and shopping bags), cable insulation, and many other products.	36%
Polypropylene	Packaging (e.g. margarine containers, microwavable containers, sterilisable containers), chemical tanks, automotive interiors, appliance casings, light switches.	21%
Polyvinyl chloride (PVC)	Rigid pipes, construction (window frames, cladding).	8%
Polyethylene terephthalate (PET)	Packaging (e.g. beverage containers, barrier films), electronics.	12%
Polystyrene	Packaging insulation.	10%
Polyurethane	Insulation foam, cushioning, shoe soles, coatings, adhesives.	8%
Polycarbonates	Electronics, construction materials, DVDs.	<5%

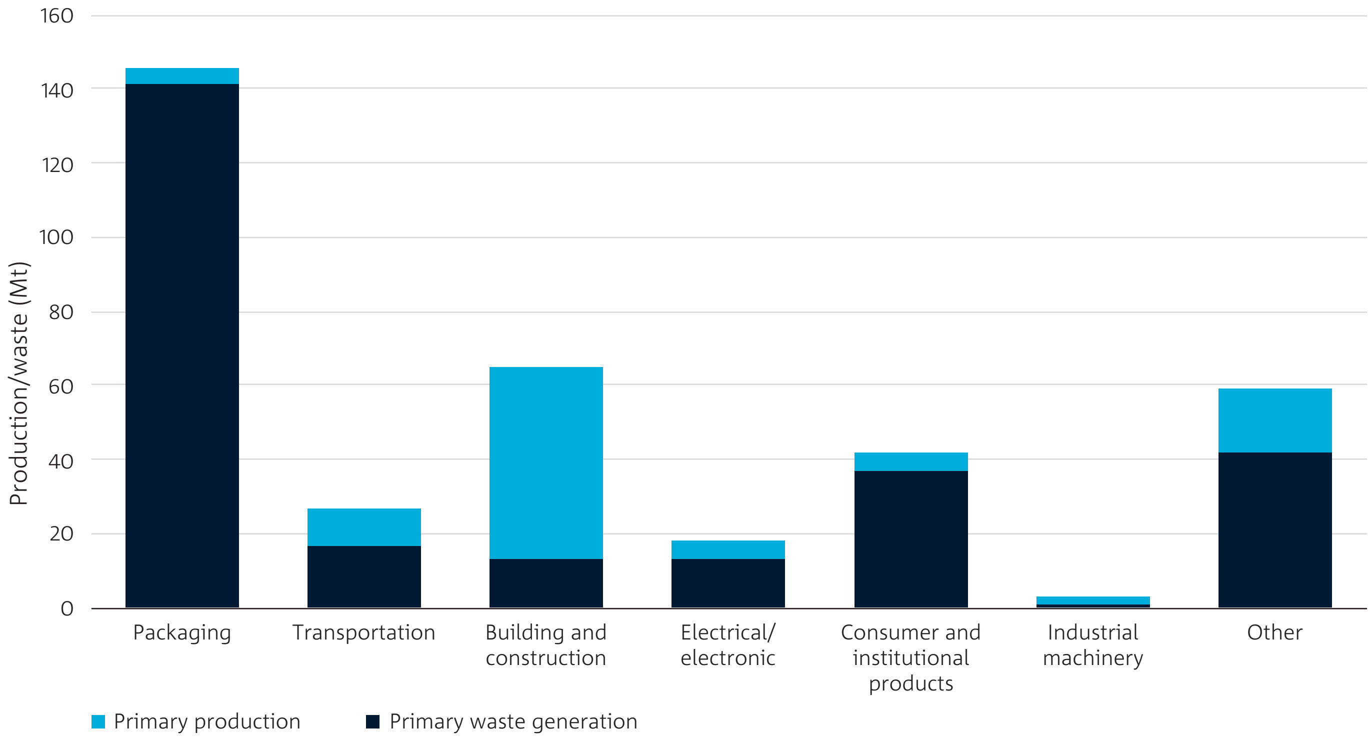


Figure 28: Global non-fibre plastics production and waste generation, by market[178]

178 Geyer R et al. (2017) *Production, use, and fate of all plastics ever made*. Science Advances

Typically, polymers are largely derived via cracking of hydrocarbon feedstocks such as ethane from natural gas.[179,180,181] Polymers are commonly made from ethylene or propylene (also known as olefins), and various other chemicals depending on the polymer being produced. CO_2 can also be utilised to make polymers via the following described pathways.

Ethylene and propylene synthesis from CO_2. CO_2 and hydrogen are converted into methanol, when is then converted into ethylene and propylene. Figure 29 demonstrates these steps as part of a polymer production chain.

Note that this diagram shows only the olefin-based routes to the chemicals shown and is not a complete picture of polymer synthesis. Further, new approaches such as direct electrochemical synthesis of olefins and other chemicals may skip some synthesis steps entirely. The other chemicals required along with propylene and ethylene to synthesise the polymers listed are not shown in this diagram. These chemicals often make up a substantial portion of the overall mass of the polymers. These other chemicals are also typically derived from petrochemical feedstocks; in some cases they could be sourced from CO_2-based feedstocks.

Aromatics (benzene, xylene and toluene) synthesis from CO_2. Among their many other uses, these chemicals can be used as feedstocks for various polymers. For example, benzene is a major input to make polystyrene, and xylene is an important precursor for PET plastic.

Addition of CO_2 in the synthesis of polyols and polycarbonates. CO_2 is combined with an epoxide to produce polycarbonates or polyols, depending on the catalyst and reaction conditions applied. Polyols are key building blocks for polyurethane.

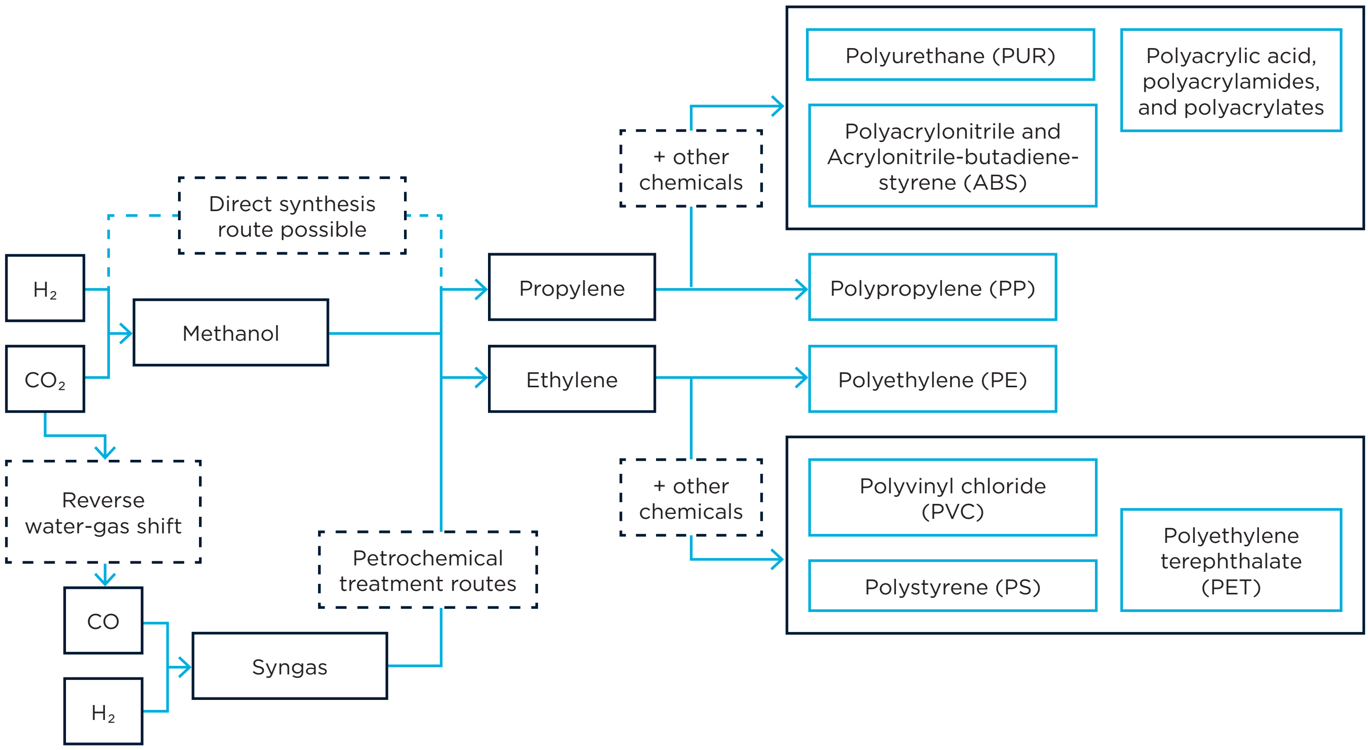


Figure 29: Process diagram for olefin and polymer production

179 Zhang B et al. (2020) *Highly Electrocatalytic Ethylene Production from CO2 on Nanodefective Cu Nanosheets*. American Chemical Society

180 Linde Gas (2021) *Industrial Gases: Propylene*. Viewed 3 May 2021, https://www.linde-gas.com/en/products_and_supply/gases_fuel/propylene.html

181 Encyclopedia Britannica (2018) *Petroleum Refining: Petrochemicals*. Viewed 3 May 2021, https://www.britannica.com/technology/petroleum-refining/Petrochemicals

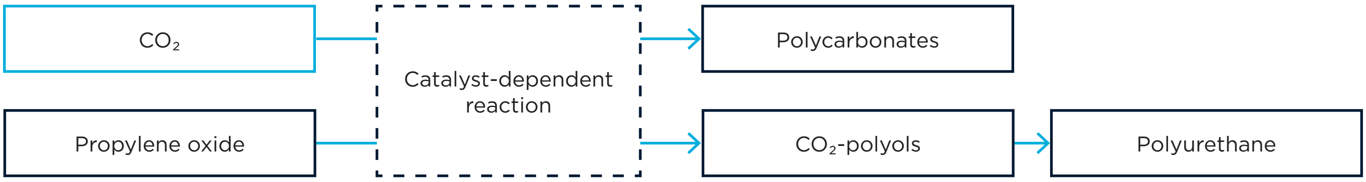


Figure 30: Process diagram for the addition of CO_2 into polyols and polycarbonates production

It is important to note that the olefins ethylene and propylene, and the aromatics benzene, xylene and toluene have a wide variety of other applications beyond use as polymer feedstocks. These other applications are described in Chapter 5.7.

5.5.1 The opportunity for Australia

Plastics are expected to continue to be important materials in Australia in the long term. The total estimated demand in Australia for plastics and plastic-based products is $8 billion.[182] The Australian synthetic resin and rubber manufacturing industry revenue was $2.3 billion in 2021.[183] Australia has an annual ethylene production capacity of 500,000 tonnes.[184] However, Australian domestic manufacturing and exports are facing increasing global competition, particularly from lower cost jurisdictions. Further, stricter emission and pollution regulations are expected to place downward pressure on profit margins over the next five years.[185] Importantly, high value polymers that face supply risks (such as plastics for medical use) do not face the same downward cost pressure due to their strategic value.

Australian industries can capitalise on small-scale domestic manufacturing capabilities to produce high value polymers which reduce the use of petrochemical feedstocks. Polymers with a higher market value may also allow a proportionally lower green premium compared with cheaper polymer products. Targeting polymers with longer lifespans that are able to lock away CO_2 for decades is an important measure in reducing emissions from a lifecycle perspective.

The Australian government recognised the opportunity in polymer production through the 2021 Recycling and Clean Energy National Manufacturing Priority Roadmap, which states that 'Manufactured products that use recycled materials or clean energy as inputs', such as 'green' plastics are a future growth opportunity.[186] There is also growing shareholder pressure for public plastic companies to decarbonise their processes, while maintaining their market share.[187] CO_2-derived plastics provides an opportunity for producers of single use plastics to maintain their market share in the short to medium term, while also responding to pressure to act on climate change and transition to lower-emissions products.

5.5.2 Levelised cost of production, modelling results

Figure 31 explores the levelised cost of utilising CO_2 to make the olefins ethylene and propylene from methanol. These olefins can subsequently be used as inputs to produce a range of plastic products. The figure also includes a zero capture cost sensitivity, where the overall cost of CO_2 capture is considered zero, to indicate the influence of capture on production. It shows that there remains a premium compared to today's fossil fuel derived olefins.

The major cost driver and focus for cost reduction is hydrogen production. Sensitivity analysis indicates that a premium would exist even if Australia was to achieve or exceed its long-term stretch hydrogen production target of $2/kg hydrogen, as seen in Figure 32.

182 International Trade Administration (2017) *Australia Plastics Industry*. Viewed 3 May 2021, https://www.trade.gov/market-intelligence/australia-plastics-industry

183 Allday A (2020) *Synthetic Resin and Synthetic Rubber Manufacturing in Australia*. IBISWorld

184 Richardson A (2020) *Basic Organic Chemical Manufacturing in Australia*. IBISWorld

185 Allday A (2020) *Synthetic Resin and Synthetic Rubber Manufacturing in Australia*. IBISWorld

186 Australian Government Department of Industry, Science, Energy and Resources (DISER) (2021) *Recycling and Clean Energy National Manufacturing Priority road map*. Australian Government DISER

187 The Minderoo Foundation (2021) *The Plastic Waste Makers Index: Revealing the source of the single-use plastics crisis.* The Minderoo Foundation

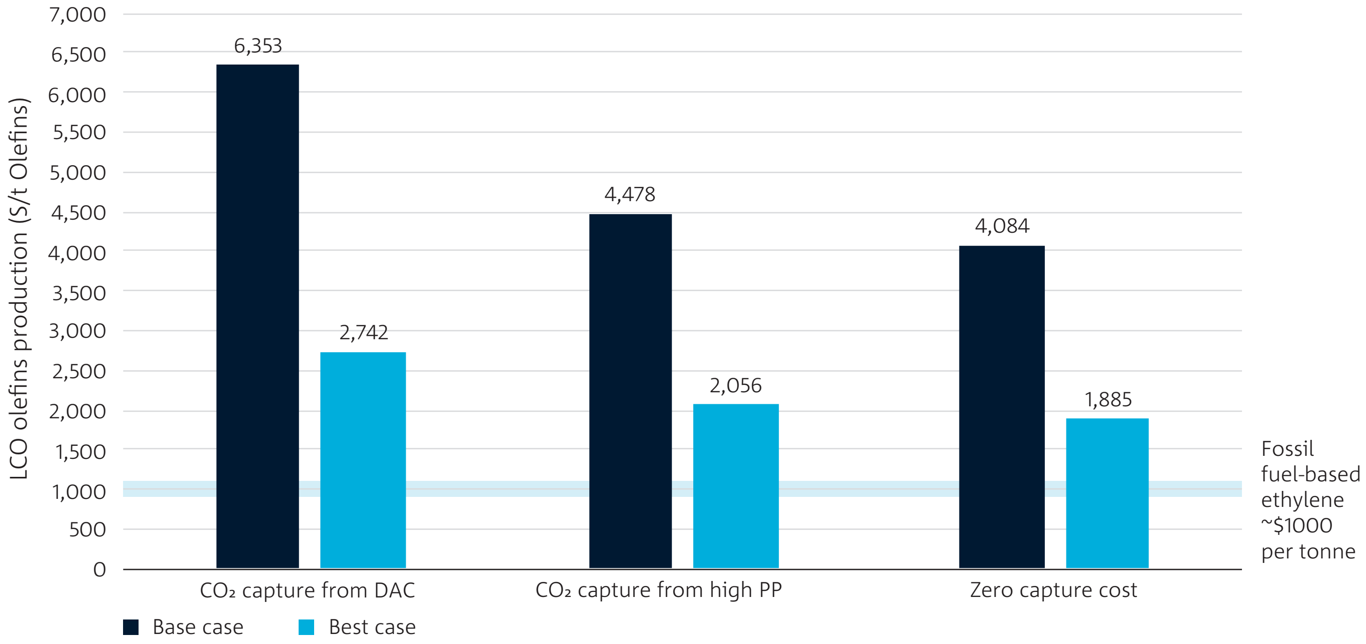


Figure 31: Levelised cost of synthetic olefin production with different CO_2 feedstocks[188]

Production of synthetic olefins assumes the use of renewable hydrogen. CO_2 feedstocks include CO_2 capture from high temperature DAC, high partial pressure point source and a zero dollar capture cost. Base case considers utilisation of 1,000t/d of CO_2 and a production scale of 211t/d olefins. Best case assumes utilisation of 5,000t/d CO_2 and a production scale of 1,264t/d olefins. See Appendix C for modelling assumptions. In terms of hydrogen requirements, the base case requires 132t/d of H_2 from a 330MW electrolyser and the best case requires 660t/day H_2 from a 1,376MW electrolyser.

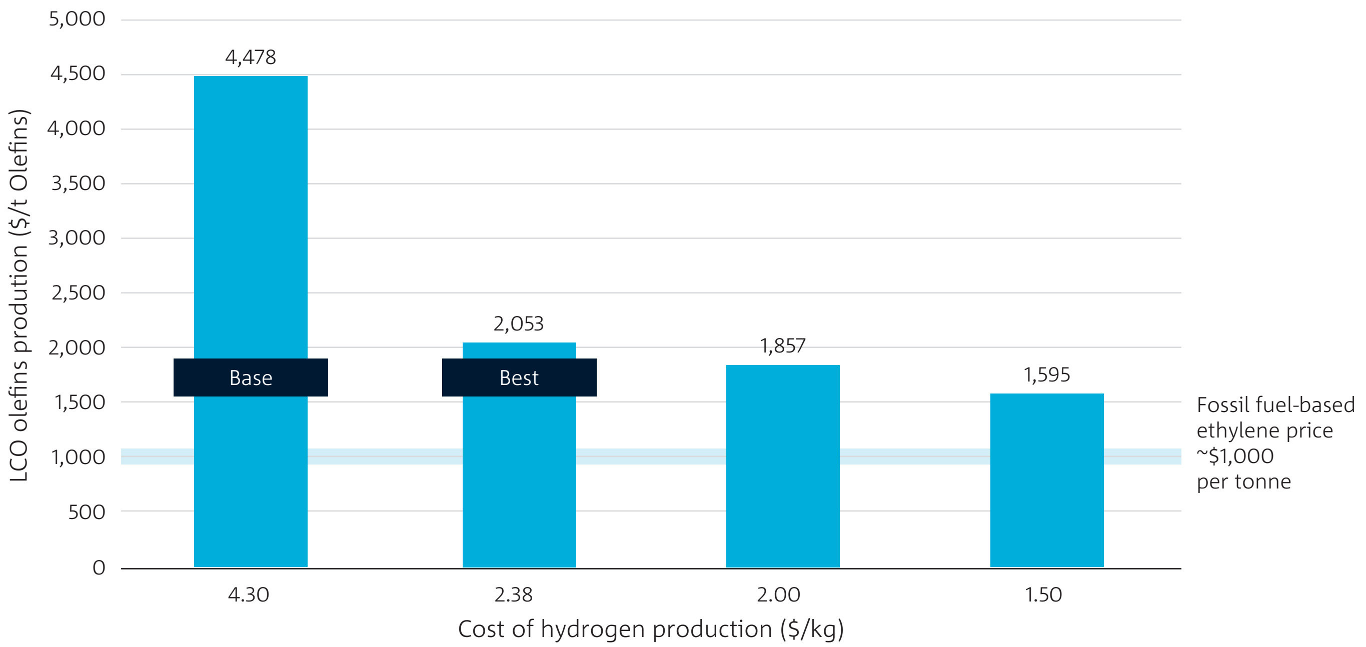


Figure 32: Influence of hydrogen production costs on levelised cost of olefin production

This sensitivity analysis shows the effect that hydrogen production costs have on the final product, with stretch goals of $2/kg and $1.50/kg. These figures assume that CO_2 is sourced from a high partial pressure point source.

188 Average ethylene and propylene prices sourced from: Statista (2021) Price of ethylene worldwide from 2017 to 2021. Viewed 5 May 2021, https://www.statista.com/statistics/1170573/price-ethylene-forecast-globally and Statista (2021) Price of propylene worldwide from 2017 to 2021. Viewed 5 May 2021, https://www.statista.com/statistics/1170576/price-propylene-forecast-globally/. Exchange rate of 1 USD to 1.3 AUD used.

5.5.3 Abatement potential and costs

Assessment of abatement potential using production as a boundary condition shows that for every 1 tonne of synthetic olefins produced via methanol, 5.364 tonnes are abated, assuming the CO_2 is sourced from DAC. If CO_2 was from a point source the abatement potential would be 2.994 tonnes of CO_2 for every tonne of synthetic olefins produced. See Appendix D for abatement potential approach.

It is important to note that this abatement potential is only the case for polyethylene and polypropylene, where it is assumed that all of the polymer is derived from CO_2 and H_2. For more complex polymers, CO_2 may only make up 50% or less of the polymer by mass, with remaining petrochemical inputs. In regards to lifecycle emissions, CO_2 is typically locked away until the product is oxidised via incineration (ranging from years to decades depending on the use-case of the plastic).

As an illustration, Figure 33 assumes an annual consumption of 500,000t of olefins per annum, which is approximately Australia's consumption. During initial uptake, it is likely that synthetic olefins will be scaled up progressively, displacing a certain percentage of the fossil fuel-derived supply which can be seen on the figure.

The cost of abatement ($/t CO_2) would vary depending on the sale price of the synthetic olefins (see Figure 34). Using ethylene as an example, the price per tonne varies by market and in 2019 ranged from approximately $550/t in North America to between $1300-$1400/t in Asia and Europe.[189]

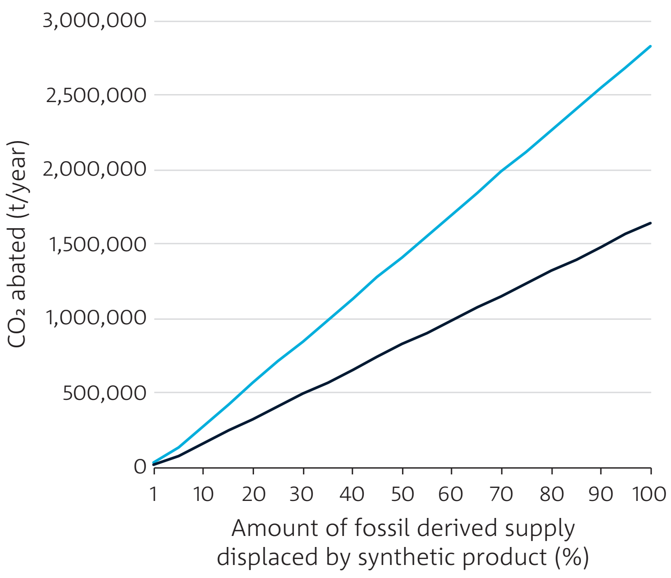


Figure 33: CO_2 abatement in synthetic olefin production using different CO_2 sources

CO_2 abatement potential uses production as a boundary condition and does not consider full lifecycle emissions. The figure demonstrates abatement potential using an illustrative case of 500,000t of olefins per annum with best case assumptions, considering the effect of synthetic olefins displacing a certain percentage of the fossil fuel-derived supply. Best case assumes utilisation of 5,000t/d CO_2 and a production scale of 1,264t/d olefins, including CO_2 capture from high temperature DAC and a high partial pressure point source. See Appendix D for abatement potential approach. This figure illustrates how CO_2 abatement increases as more synthetic product is introduced into the Australian market, with DAC providing the most abatement potential given the closed loop use of CO_2.

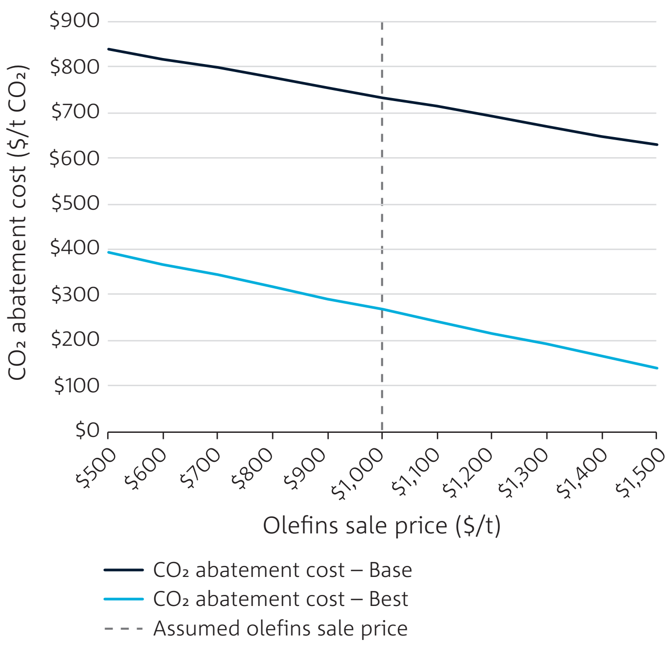


Figure 34: Effect of olefin sale price on cost of abatement

Effect of different olefin sales prices on cost of abatement using high partial pressure capture with base and best case assumptions. Olefin sales price considers ethylene as an example. Base case considers utilisation of 1,000t/d of CO_2 and a production scale of 211t/d olefins. Best case assumes utilisation of 5,000t/d CO_2 and a production scale of 1,264t/d olefins. See Appendix C for modelling assumptions. This figure illustrates how an increase in the sale price of the synthetic product reduces the cost of CO_2 abatement.

189 Annual ethylene capacity/demand growth and regional price developments, 2015–2020 – Charts – Data & Statistics – IEA. USD to AUD exchange of 0.69.

5.6 Synthetic Natural Gas (SNG)

Natural gas is a naturally occurring combination of hydrocarbon gases, consisting mostly of methane, that are found in underground accumulations. Natural gas is used as a heat source in Australian households and throughout industry. It is also used as a feedstock for a variety of chemical processes and is one of Australia's largest exports. Australia's domestic natural gas consumption in 2018–19 was 1,592 PJ.

Natural gas is cooled and liquified for export in the form of liquid natural gas (LNG). Australia is the largest global exporter of LNG, with 78 million tonnes exported in 2018–19.[190] A projected 80.9 million tonnes will be exported 2020–21.[191] Together, the industry's 10 LNG projects have an annual nameplate capacity of 88 million tonnes per year.[192] Natural gas has been used in Australia for decades, as such, its market, distribution and users are well established in Australia.

Using a nickel catalyst, methane can be produced from hydrogen and CO_2 at elevated temperatures. This process is well established and is referred to as the Sabatier process. By using captured CO_2 and renewable hydrogen with zero-emission energy, a low net carbon synthetic natural gas can be synthesised for use domestically. As with the other synthetic fuels previously discussed, the entrained CO_2 is released to the atmosphere during combustion and the net emissions is dependent on the source of the CO_2, the hydrogen and the energy required for the process.

5.6.1 The opportunity for Australia

Domestic and industrial equipment across Australia uses natural gas, including in appliances, industrial boilers and chemical processes, with industrial consumption of gas for direct usage forecasted to remain stable over the next 20 years.[193] To decarbonise the sector and transition to lower-emissions fuels, the gas industry has identified a range of natural gas alternatives to adopt, including biogas, hydrogen and SNG, the latter of which is considered expensive.[194] The modelling in this chapter contributes to this narrative, by showing a significant premium for SNG.

Given the cost and current plans of the gas sector, large scale production of synthetic natural gas is unlikely and therefore the scope for SNG production will be focused on certain use cases. For example, SNG could be produced in distributed systems for small scale users in remote areas. These customers may have equipment with long asset lives or a lack of alternatives and will therefore require natural gas for many years to come. SNG may be the best option for early decarbonisation. This could also apply to larger industrial users where equipment could have decades of asset life remaining and thus will require carbon neutral synthetic natural gas for processes or heat.

5.6.2 Levelised cost of production, modelling results

Figure 35 explores the levelised cost of utilising CO_2 to make SNG. The figure also includes a zero capture cost sensitivity, where the overall cost of CO_2 capture is considered zero, to indicate the influence of capture on production. It shows that there remains a significant premium compared to today's natural gas prices and the other CO_2-derived chemicals and fuels analysed.

The major cost driver and focus for cost reduction is hydrogen production. Sensitivity analysis indicates that a premium would exist even if Australia was to achieve or exceed its long-term stretch hydrogen production target of $2/kg hydrogen, as seen in Figure 36.

190 EnergyQuest (2021) *Another LNG export record in 2020*. Viewed 3 May 2021, https://www.energyquest.com.au/another-australian-lng-export-record-in-2020/

191 Thomson J (2020) *Liquefied Natural Gas Production in Australia*. IBISWorld

192 Thomson J (2020) *Liquefied Natural Gas Production in Australia*. IBISWorld

193 Australian Energy Market Operator (AEMO) (2021) *Gas Statement of Opportunities: For eastern and south-eastern Australia*. AEMO

194 Energy Networks Australia (2020) *Gas Vision 2050; Delivering a Clean Energy Future.*

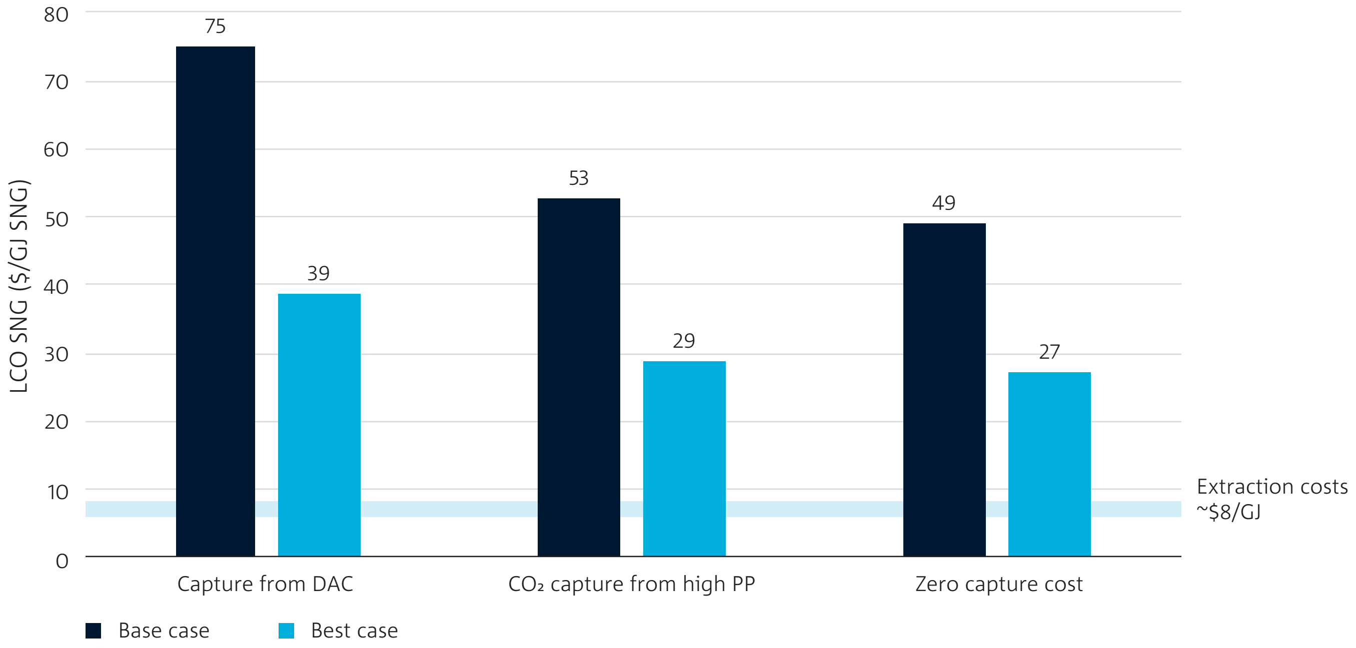


Figure 35: Levelised cost of synthetic natural gas production with different CO_2 feedstocks

Production of synthetic natural gas assumes the use of renewable hydrogen. CO_2 feedstocks include CO_2 capture from high temperature DAC, high partial pressure point source and a zero dollar capture cost. Base case considers utilisation of 1,000t/d of CO_2 and a production scale of ~18,000GJ/d (360t/d), approximately equivalent to the daily gas consumption of 200,000 Australian homes.[195] Best case assumes utilisation of 5,000t/d CO_2 and a production scale of ~90,000GJ/d (1,800t/d), approximately equivalent to the daily gas consumption of 995,000 Australian homes). See Appendix C for modelling assumptions. In terms of hydrogen requirements, the base case requires 183t/d of H_2 from a 458MW electrolyser and the best case requires 916 t/day H_2 from a 1,901MW electrolyser.

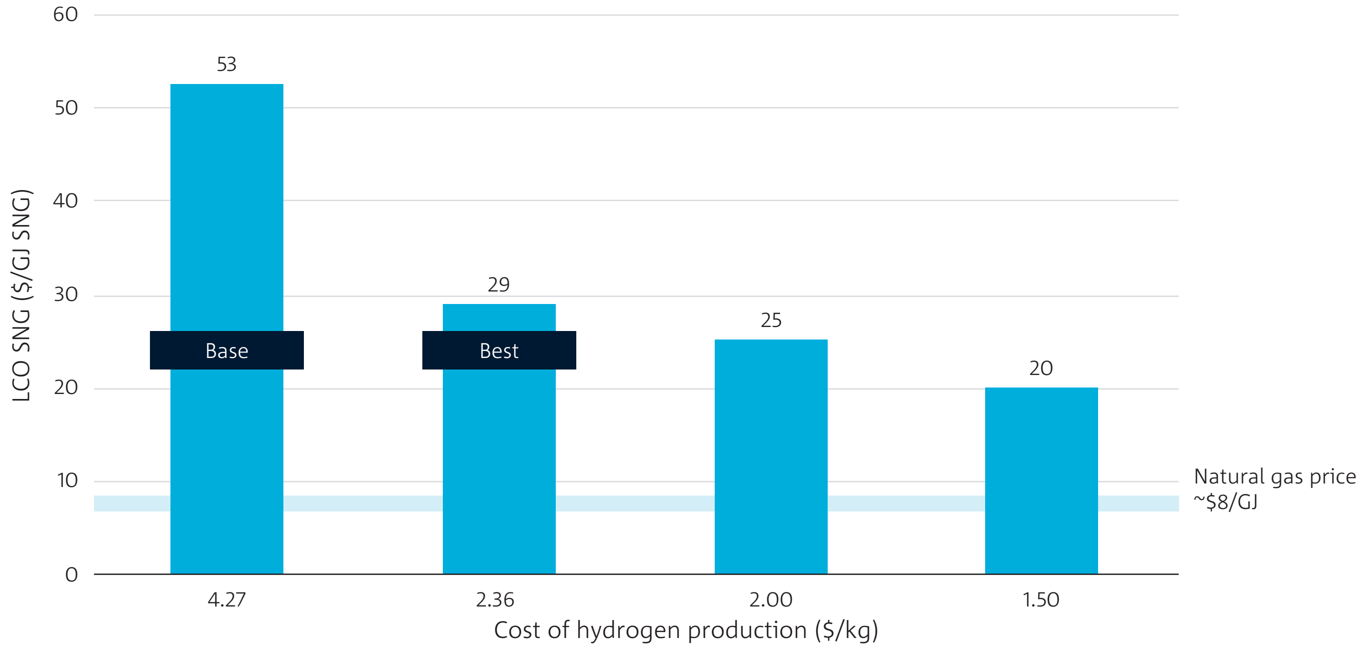


Figure 36: Influence of hydrogen production costs on levelised cost of SNG production

This sensitivity analysis shows the effect that hydrogen production costs have on the final product, with stretch goals of $2/kg and $1.50/kg. These figures assume that CO_2 is sourced from a high partial pressure point source.

195 Energy Networks Australia (2017) *Reliable and clean gas for Australian homes*. Energy Networks Australia

5.6.3 Abatement potential and costs

Assessment of abatement potential using production as a boundary condition shows that for every 1 tonne of synthetic natural gas produced, 3.213 tonnes are abated, assuming the CO_2 is sourced from direct air capture. If CO_2 was from a point source the abatement potential would be 1.838 tonnes of CO_2 for every tonne of synthetic natural gas produced. See Appendix D for abatement potential approach.

As an illustration of abatement potential, Figure 37 assumes an annual consumption of 10,000,000t of natural gas per annum, which is approximately 35% of Australia's domestic consumption annually.[196] During initial uptake, it is assumed that synthetic natural gas will be scaled up progressively, displacing a certain percentage of the fossil fuel-derived supply which can be seen in the figure.

This analysis excludes lifecycle emissions, which have similar considerations to electrofuels given the CO_2 would be released on use of the natural gas. The analysis also excludes fugitive emissions from synthetic natural gas.

The cost of abatement ($/t CO_2) would vary depending on the sale price of natural gas (see Figure 38). In Australia, it is also important to consider the differences in gas markets on the east and west coast of the country.

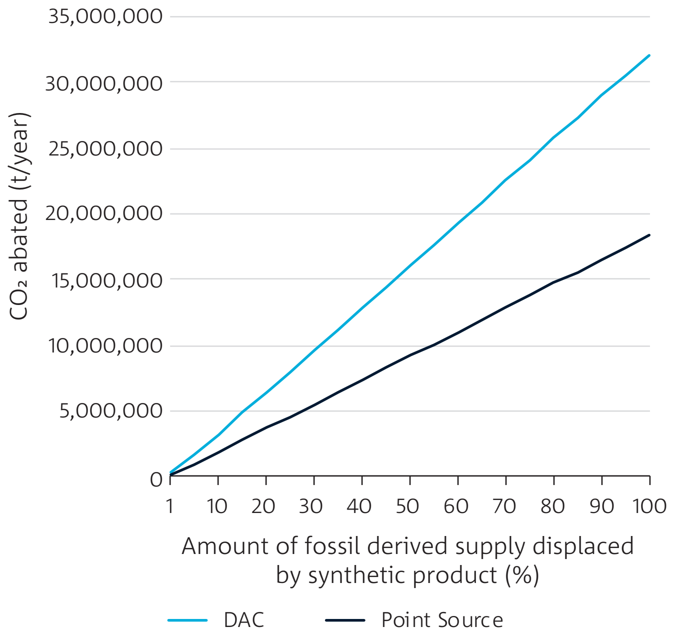


Figure 37: CO_2 abatement in synthetic natural gas production using different CO_2 sources

CO_2 abatement potential uses production as a boundary condition and does not consider full lifecycle emissions. The figure demonstrates abatement potential using an illustrative case of 10,000,000t of natural gas per annum with best case assumptions, considering the effect of synthetic natural gas displacing a certain percentage of the fossil fuel-derived supply. Best case assumes utilisation of 5,000t/d CO_2 and a production scale of ~90,000GJ/d (1,800t/d), including CO_2 capture from high temperature DAC and a high partial pressure point source. See Appendix D for abatement potential approach. This figure illustrates how CO_2 abatement increases as more synthetic product is introduced into the Australian market, with DAC providing the most abatement potential given the closed loop use of CO_2.

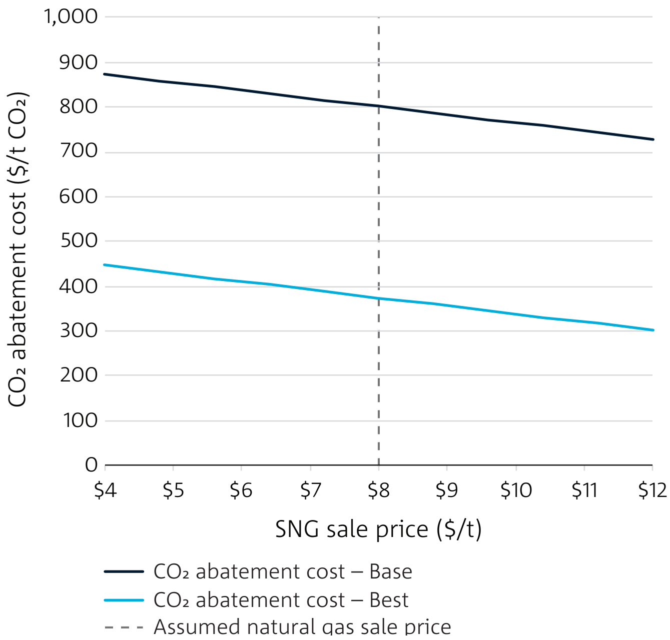


Figure 38: Effect of synthetic natural gas sale price on cost of abatement

Effect of different synthetic natural gas sales prices on cost of abatement using high partial pressure capture with base and best case assumptions. Olefin sales price considers ethylene as an example. Base case considers utilisation of 1,000t/d of CO_2 and a production scale of 18,000GJ/d (360t/d). Best case assumes utilisation of 5,000t/d CO_2 and a production scale of 90,000GJ/d (1,800t/d). See Appendix C for modelling assumptions. This figure illustrates how an increase in the sale price of the synthetic product reduces the cost of CO_2 abatement.

196 Australian Government Department of Industry, Science, Energy and Resources (2020) *Australian Energy Update 2020*. Australian Energy Statistics

5.7 Other chemicals

There are a great number of chemicals beyond those discussed in the previous chapter that can be derived from CO_2, and many which could be derived from methanol. These are set out in Figure 39 below and discussed further in Table 7. Generally, there is little local production of these chemicals, with the exception of urea.

Although urea production uses large quantities of CO_2, it is not expected to be a large offtaker moving forward, as the CO_2 used is recycled from earlier in its own production during the initial step of reforming methane. The CO_2 from the SMR step is used for combination with the ammonia at the end to produce urea, making it almost a closed loop. This means that urea production is already supplied with CO_2 and it is not seen as a growing offtaker in the medium term. This may change in the longer-term as renewable ammonia reaches scale.

There are a number of projects under development to scale-up renewable ammonia production, which will require a new source of CO_2 to reach commercialisation. One such project is being undertaken by Yara Pilbara Fertilisers in partnership with ENGIE Services Australia and with support from the Australian Renewable Energy Agency (ARENA). This collaboration is completing feasibility studies for the production of renewable hydrogen via electrolysis to blend with existing fossil fuel derived supply. Yara Pilbara Fertilisers uses up to 30,000 tonnes per year of ammonia from hydrogen, which this feasibility project hopes to displace with blended hydrogen.[197]

Chemical manufacturing in Australia is in a long-term decline as products can be sourced more economically in international markets. As such, while there are opportunities to utilise CO_2 to produce a broad range of chemicals, any further investment would also need to consider the existing manufacturing base and how it could be strengthened.

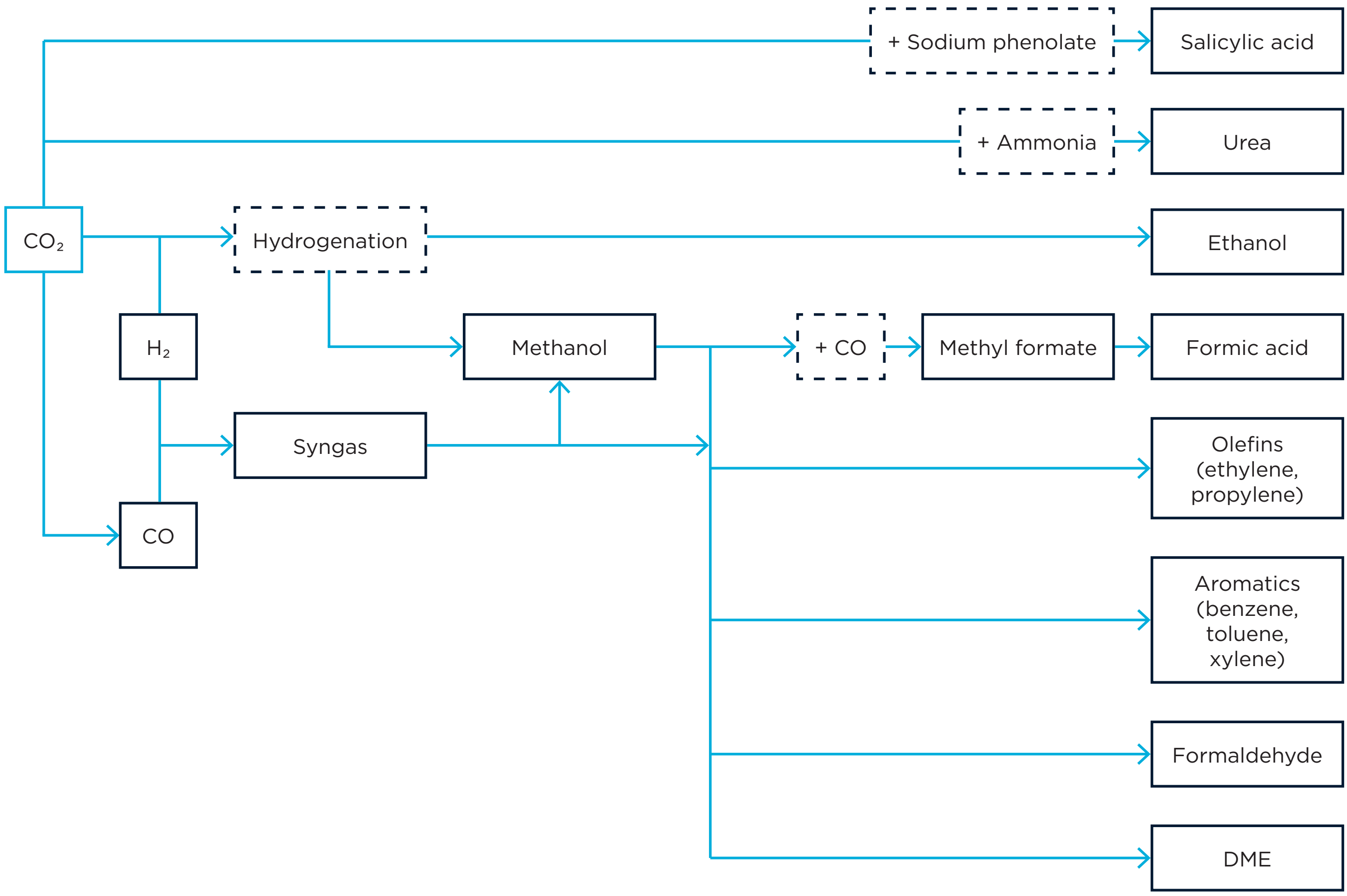


Figure 39: Process diagram of potential products synthesised from CO_2

197 ARENA (2021) *Yara Pilbara Renewable Ammonia Feasibility Study*. Viewed 17 May 2021, https://arena.gov.au/projects/yara-pilbara-renewable-ammonia-feasibility-study/.

An overview of applications and the status of current domestic production is set out in Table 7.

Table 7: CO_2-derived chemicals, applications and domestic production

CHEMICAL	APPLICATIONS	DOMESTIC PRODUCTION
Salicylic acid	Used as a precursor to aspirin and widely in other pharmaceuticals and cosmetic products.	Produced domestically by pharmaceutical companies.
Urea	Used primarily in fertiliser production.	An established industry in Australia that continues to grow, with new companies entering the market in recent years (e.g. Strike Energy and Perdaman Industries).[198,199] Potential for growing demand from new sources as renewable ammonia production scales up.
Ethanol	Used widely to produce transport fuels. Other uses include pharmaceuticals, plastics, polishes and cosmetics. Ethanol is currently produced from biomass feedstocks.	Australia's production capacity of ethanol is approximately 450 million litres (250 million litres pre-COVID). Manildra Milling Pty Ltd (NSW) is the leading manufacturer.
Formic acid	Used by the agriculture, leather, textiles and food manufacturing industries.	Australian production is not scaled to a significant capacity.
Olefins: Ethylene, propylene	Used as precursors to polymers and other chemicals, as well by the agriculture, medical and LNG industries.[200]	See Chapter 5.5 for discussion.
Aromatics: Benzene, toluene xylene.	Used as a feedstock to produce plastics, clothes, paints, adhesives and IT equipment. Aromatic production is from crude oil. Production from methanol is an emerging technology.	Production in Australia is as a by-product of coking coal in steel manufacturing.
Formaldehyde	Used in car manufacture, resins, medical products, food preservation, fertiliser production and resins.	There are four plants operating in Australia: Orica (VIC), Borden Australia (VIC and QLD), and Dyno (WA).
Dimethyl ether (DME)	Used in pesticides, polishes, aerosol propellant, refrigerant and as an alternative to diesel fuels.	Australian production is not scaled to a significant capacity.

198 Landgrafft T.D (2021) Strike Energy plan fertiliser plant capable of supplying bulk of Australia's urea needs. Viewed 3 May 2021, https://www.abc.net.au/news/rural/2021-01-12/strike-energy-plans-urea-fertiliser-plant-burrup-peninsula/13051000

199 Perdaman (2021) *$4.5bn Karratha urea project agrees EPC terms*. Viewed 3 May 2021, https://perdaman.com.au/2020/07/01/4-5bn-karratha-urea-project-agrees-epc-terms/

200 Linde Gas (2021) *Industrial Gases: Ethylene*. Viewed 3 May 2021, https://www.linde-gas.com/en/products_and_supply/packaged_chemicals/product_range/ethylene.html

5.8 Considerations

This chapter sets out the policy and investment priorities required to achieve or exceed the best case for the technologies described, while considering the Australian context. It does this by synthesising literature, consultation insights and modelling results and assumptions to understand commercial, regulatory, environmental and social considerations that could assist in absorbing the cost premium and scaling production.

Commercial

Alignment to hydrogen economy: Due to the large hydrogen requirements of synthetic chemicals and fuels, production scale will be closely tied to the rollout of Australia's hydrogen economy. This includes the location of hydrogen production and the size and speed at which it scales.

The base case for methanol production calls for a ~330MW electrolyser, whilst the best case would require ~1,400MWs of electrolyser. The procurement and establishment of this amount of hydrogen production aligns with the 2025 and 2030 progress indicators identified in the Australian Government's National Hydrogen Strategy.[201]

Synthetic fuel and chemicals can create a sizable hydrogen offtake that boosts domestic demand for hydrogen and encourages further hydrogen supply cost reductions through improvements in efficiency and economies of scale.

Plant scale: Higher plant capacities are likely to result in large production cost reductions. Scale up of plant from base to best case, as shown in Figure 40, reduces capital costs by 42%. The scale up benefit for methanol production has flow on effects to the production costs of electrofuels and polymers.

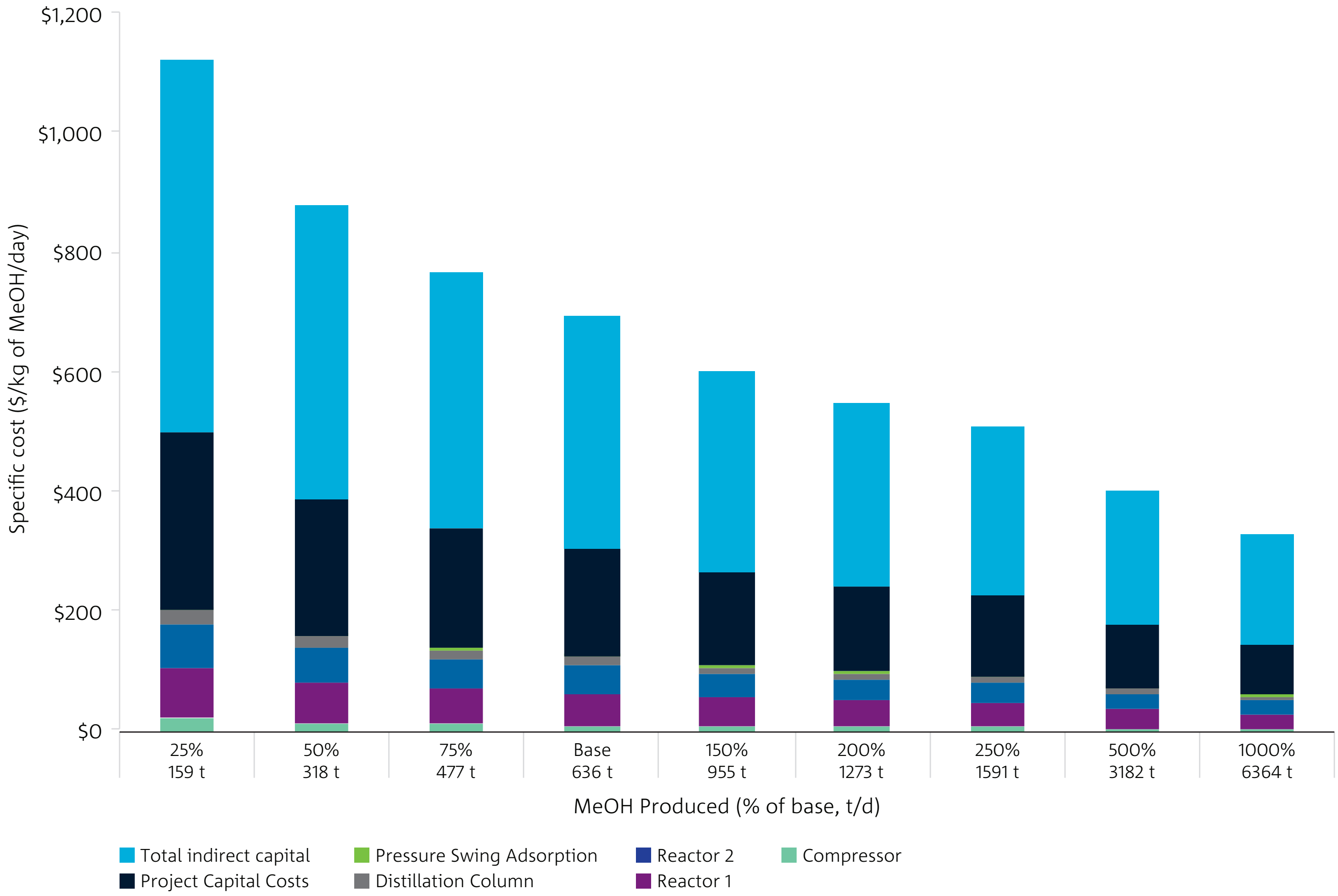


Figure 40: Effect of plant scale on Methanol synthesis capital costs

201 COAG Energy Council Hydrogen Working Group (2019) *Australia's National Hydrogen Strategy.* COAG Energy Council

Methanol as a platform chemical: Scaling Australian renewable methanol production will be key to supporting the conversion of CO_2 into a variety of chemicals and fuels. Although present domestic demand may be low, development of synthetic chemical and fuel production could drive demand for methanol by orders of magnitude. In the near-term, hybrid models that start with natural gas and increasingly blend renewable hydrogen could be considered as hydrogen cost and availability becomes established.

Co-location of feedstocks and production facilities: Production costs are strongly influenced by the price of feedstocks. Distribution of these feedstocks can add to operating costs significantly. By pursuing hub models where production of hydrogen and CO_2 capture are co-located, added costs can be avoided. Hydrogen and CCS hubs are beginning to be mapped out across Australia and these locations should be examined for demonstration plants and scale-up facilities.

Green premiums: Even with advancements in technology and large-scale production, assuming today's prices, green premiums will be attached to synthetic fuels and chemicals derived from renewable or low-emissions sources. The green premium, and customer willingness to pay, varies across the products and will change over time.

Countries with fuel standard goals or more aggressive decarbonisation strategies may be more willing to pay premiums or have access to funding/tax schemes to bridge the premium gap, in which case export may be the more economic offtake.

In the long-term, fossil fuel-derived products will face price volatility, which can reduce green premiums. For example, through the introduction of carbon taxes or border tax prices; or increases in electrification and fuel switching, which could impact petrochemical refinery margins and costs. Business models that encourage the uptake of the synthetic fuels despite their price will be key to creating demand. For example, the commercial aviation industry could consider awarding frequent flyer points to those who opt for sustainable fuels or targeting corporate customers seeking to lower their carbon footprint.

Progressive scale-up: Given the drop-in nature of synthetic fuels and chemicals, their production can be progressively scaled up and introduced to existing supply chains. This can reduce the risk of investment, as existing markets are able to integrate the product immediately. Progressively scaling renewable production through hybrid plants can also help manage risks. By co-feeding renewable feedstocks like captured CO_2 and renewable hydrogen into existing plants, a lower carbon intensity product can be made. This allows the gradual scale up of electrolysers and CO_2 capture by acting as an offtaker.[202]

Products with low hydrogen ratio: Given hydrogen is a key cost, the higher the hydrogen ratio in the final product, likely the greater the green premium will be. Initially targeting chemicals and fuels with low ratios can help reduce costs.

Capability requirements: Although Australia has experience and capability in the production and export of some chemicals and fuels, such as ammonia and some refining, scale up of new chemical and fuel synthesis facilities may require additional capability to be developed.

Environmental and social

Abatement potential of different products: Each product will lock away CO_2 for different periods of time. Fuels will release CO_2 into the atmosphere on use, unless otherwise captured. Whereas plastics will lock away carbon until they have been destroyed or recycled, which could range from years to decades. The length of time that CO_2 is locked away could influence decisions on investment.

Life cycle assessments: LCAs are vital to ensuring there are net reductions in CO_2 emissions**.** Analysis of CO_2 abatement and sequestration potential will need to be supported by greater lifecycle assessments. LCAs will need to include considerations such as the feedstocks required, which will have their own land and environmental considerations. They will also need to consider the various potential end-uses of the product, for example the use of methanol as a feedstock or a fuel. Life cycle assessments are also discussed in the RD&D section below.

202 IRENA & Methanol Institute (2021) *Innovation Outlook: Renewable Methanol.* IRENA

Support long-term scale up of capture technologies: While there are options to electrify much of the transport sector, heavy duty transport such as long-haul aviation and shipping remains difficult to decarbonise without the use of synthetic fuels. The utilisation of CO_2 from point sources provides opportunities for CO_2 avoidance and can reduce the carbon intensity of these fuels. However, the full emissions reduction potential for synthetic fuels can only be achieved when DAC technologies become deployed at scale.

Ensure public acceptance: The production of synthetic fuels could be perceived as an attempt to prolong their use and prevent the necessity of exploring alternative pathways. The public needs to be informed of the carbon intensity of fuel alternatives to demonstrate the case for synthetic fuels in the medium term. Another key risk is hesitation in the market for products derived from CO_2 rather than fossil fuels, including by companies that require and purchase polymers.[203]

Land use and rights: Land use, land rights and area requirements need to be considered for CCU production facilities and supporting infrastructure. This is particularly important for large scale centralised facilities, which could require vast renewable resources on land over which Indigenous traditional owners have rights and interests. Engaging with all stakeholders, including Traditional Owners will be critical to understand and drive long-term opportunities for the community and region.

There are also ecological implications to large scale land use such as soil structure degradation, interruption of natural water cycles, or impacts on flora and fauna species. Therefore, in addition to considering the end-use application, land rights, ecological implications and area requirements need to be considered for any infrastructure related to the CCU facilities, including renewables and hydrogen production facilities.

Policy and regulation

Guarantees of origin: Given the role of low emission fuels and chemicals in enabling decarbonisation, a guarantee of origin scheme could be considered that verifies and rewards the production of low-emission intensive fuels. An example of this is the Low Carbon Fuel Standard in California. Policies could also include eco-labelling of bio-and e-based chemicals and products, information campaigns and subsidies for producers of materials, that would be progressively phased out as technology matures and production costs decrease. [204]

Case Study: The Californian Low Carbon Fuel Standard[205]

The LCFS is designed to reduce carbon emissions from California's transport sector through the use and production of low-carbon and renewable fuels. California's Environmental Protection Agency provides a carbon intensity score for each fuel type, which is used to track progress of fuel providers against a declining carbon intensity benchmark each year. The carbon intensity score for each fuel is calculated based on a life cycle assessment of greenhouse gas emissions used for production, distribution, and end use. The Pacific Coast Collaborative, comprised of California, Oregon, Washington and British Columbia, is seeking to build an integrated west coast market for these low-carbon fuels.

Fuel rebates: The United Kingdom introduced its Renewable Transport Fuel Obligation scheme in 2008. Fuels that are categorised as Renewable Fuels of Non-Biological Origin such as e-methanol, are incentivised by awarding double credits per litre or kilogram supplied. These credits are known as Renewable Transport Fuel Certificates and can be traded between suppliers of fossil transport fuels or eligible biofuels. In 2018, 57 million litres of bio-methanol were blended with gasoline in the United Kingdom.[206]

203 Alberici S et al. (2017) *Assessing the potential of CO2 utilisation in the UK*. Imperial College London & ECOFYS

204 IRENA & Methanol Institute (2021) *Innovation Outlook: Renewable Methanol.* IRENA

205 California Air resources Board (2021) *Low Carbon Fuel Standard: About*. Viewed 3 May 2021, https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard/about

206 IRENA & Methanol Institute (2021) *Innovation Outlook: Renewable Methanol.* IRENA

Carbon price mechanism: A carbon tax would drive up the cost of fossil fuels and traditional industrial products with high carbon intensity. This would have the effect of reducing the green premium for products made using CO_2 as inputs, supporting their entry into the market. Such a tax may also encourage capture and lead to low cost CO_2 feedstocks.

Standards development: Regulation addressing the approval of new synthetic fuels and chemicals may be required to allow their use. For example, current global regulations allow blending of synthetic fuels produced by the Fischer-Tropsch method up to 50% content, but those derived from methanol are yet to be approved. These processes and how they are progressing are laid out in the *Opportunities for hydrogen in commercial aviation* report.[207] Similar consideration could also be given to the potential of using synthetic fuels or methanol in shipping. Similar to aviation, the shipping industry is seeking alternatives to fossil fuels. As well as new production of these fuels, standards need to be developed to allow their uptake.[208]

Introduction of blending mandates or quotas: The implementation of blending mandates, where there is a requirement to blend a percentage of synthetic fuels, would also create demand for synthetic fuels that can increase in proportion as scale of production grows. These schemes have proved effective for alternative fuels such as ethanol, as shown by the Brazilian government who has mandated increasing requirements of ethanol blending to aid the scale up of production.[209]

International collaboration to manage scale-up: By securing export offtake agreements, similar to hydrogen, demand for low emission fuels and chemicals could be built which will help reduce investment risk into new plants.

RD&D

Continuous improvement, integration and optimisation: Continued research into new materials and catalysts for synthesis processes will be required to further reduce costs and better optimise systems that reduce feedstock inputs and energy intensity. Studying new processes, including new direct synthesis routes, that could bring about step changes in cost is also important and should be pursued by research bodies. Directly synthesising longer hydrocarbon chains could facilitate cost reductions and improve the overall efficiency of obtaining fuels from CO_2.

Energy efficiency evaluations: CCU for chemicals and fuels will require the conversion of large amounts of CO_2 and hydrogen and further processing to achieve the final low emissions product. As such, each process step requires energy and has inherent losses. Analysis to better understand energy usage and efficiency across each individual process steps and the value chain will be valuable as the industry develops to ensure the most appropriate allocation of resources.

Emerging point sources suitable for synthesis: As new industrial processes are developed, there is the potential for new flue gases compositions that are suitable for conversion to chemicals and fuels. Green steelmaking, where hydrogen replaces coking coal, is gaining more traction as net zero targets are pursued and early research is indicating that the flue gases from this process may be suitable for methanol production. Further research into how new industrial systems can be integrated with CCU could help to reduce costs of production and lower emissions.[210]

R&D breakthroughs could bring significant step changes in cost reductions: As described, hydrogen, methanol and syngas are key platform chemicals to produce a range of other chemicals and fuels. Reducing the cost of producing methanol would therefore offer significant benefit for many of its subsequent products. These costs could be further reduced by directly synthesising some chemicals, such as ethylene, as show in Table 8. A number of new synthesis routes and systems designs are emerging that could yield significant energy and cost savings. These routes and other emerging technologies are described in Table 8.

207 Bruce S et al. (2020) *Opportunities for hydrogen in aviation*. CSIRO

208 Maritime Knowledge Centre (MKC), TNO & TU Delft (2018) *Public final report – Methanol as an alternative fuel for vessels*. MKC, TNO & TU Delft

209 Morgera E, Kulovesi K & Gobena A (2009) *Case Studies on bioenergy policy and law: options for sustainability*. FAO

210 Wich-Konrad T, Luke W, Oles M, Deerberg G (2020) *Assessment of Industrial Greenhouse Gas Reduction Strategies Within Consistent System Boundaries*. Chemie Ingenieur Technik

Table 8: Emerging synthesis technologies[211]

TECHNOLOGY	TRL	DESCRIPTION
Methanol: Direct hydrogenation	6–7	CO_2 is reacted with hydrogen to produce methanol directly. This reduces system complexity by skipping the syngas production step.
Methanol: Photocatalysis	2–4	CO_2 and water are converted into methanol via photocatalysis. This makes use of sunlight as an energy source and reduces system complexity through direct synthesis.
Methanol: Solid oxide electrolysis	1	Methanol is synthesised directly from steam and carbon dioxide gas in a solid oxide electrolysis cell at elevated temperatures. Methanol can be synthesised directly from water and carbon dioxide, without requiring a precursory hydrogen production step. This reduces system complexity and could yield energy savings.
Combined methanol system synthesis	5–6	Hydrogen is produced via solid oxide electrolysis, then fed into a second reactor in which it is combined with carbon dioxide to produced methanol. The heat from the methanol production step is then fed back to the solid oxide electrolysis cell for further hydrogen production. This reduces the amount of input energy required for the solid oxide electrolysis step.
Hydrogen: Solid oxide electrolysis	7	Uses high temperatures (~700–800°C) and electricity to synthesise hydrogen from steam. CO_2 can be added to the input stream to produce syngas directly. In the case of Fischer-Tropsch production, this can lead to cost reductions by removing the reverse water gas shift step. When the heat is provided as waste heat, this process can reduce the cost of fuel production.
Syngas: Photo-electrochemical synthesis	2–3	Photoelectrochemical direct synthesis of syngas from aqueous CO_2 and water removes the need for electricity to drive the reaction, instead depending on sunlight and catalysts to drive the reaction. This could lower costs due to the direct route and free renewable energy inputs.
Syngas: Integrated absorption and electrolysis production[212]	2–3	CO_2 from a point source or air is captured by a liquid absorbent, forming acarbamate and/or (bi)carbonate. These CO_2-species are directly electrolysed and converted into syngas, without involving the energy-intensive CO_2 desorption step. The syngas can be naturally separated from liquid feedstock, circumventing the costly product separation.
Concentrating solar fuels	4	By directing mirrors at a single point, high temperatures are generated that can be used to drive thermochemical reactions (TRL 4). For example, with CO_2 and water as inputs, syngas can be produced in the high temperature conditions to be used as an input to fuel processes. By using the sun to power reactions, energy costs can be reduced and reliance on fossil fuels for high temperatures can be eliminated
Ethylene: Direct synthesis	2–3	Direct production of ethylene from CO_2 has been technically demonstrated;[213,214,215] though it is early-stage and may take many years to produce polyethylene made from directly synthesised ethylene at a commercially viable scale.[216] Direct synthesis of ethylene could enable simpler plant design and reduced energy and monetary costs, potentially offering a more competitive pathway to produce polymers. Additionally, if ethylene is synthesised from CO_2 and H_2O, the cost-intensive hydrogen production step can be sidestepped entirely. Direct ethylene synthesis via co-electrolysis of CO_2 and H_2O is at TRL 2–3.[217] Ethanol can be co-produced with ethylene via direct electrochemical reduction of CO_2 and H_2.[218]

211 Charnock S et al. (2019) *Hydrogen Research, Development and Demonstration: Technical Repository*. CSIRO

212 Lee G et al. (2020) *Electrochemical upgrade of CO2 from amine capture solution*. Nature Energy

213 University of California – Los Angeles (2020) *Effective pathway to convert CO2 into ethylene*. Viewed 3 May 2021, https://www.sciencedaily.com/releases/2020/09/200917084058.htm

214 Choi C et al. (2020) *Highly active and stable stepped Cu surface for enhanced electrochemical CO2 reduction to C2H4*. Nature Catalysis

215 Li F et al. (2019) *Molecular tuning of CO2-to-ethylene conversion*. Nature

216 Cormier Z (n.d.) Turning carbon emissions into plastic. Viewed 3 May 2021, https://www.bbcearth.com/blog/?article=turning-carbon-emissions-into-plastic

217 Roh K et al. (2020) *Early-stage evaluation of emerging CO2 utilization technologies at low technology readiness levels*. Green Chemistry

218 National Academies of Sciences, Engineering, and Medicine (2019) *Gaseous Carbon Waste Streams Utilisation Status and Research Needs*. The National Academies Press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6 Biological conversion of CO_2

6.1 Key findings

Australia's role as a global food exporter presents an opportunity to capitalise on emerging synthetic biological conversion pathways, including production of niche, high value products.

Biological conversion of CO_2 is the use of microorganisms to produce a range of products. In some cases, the emerging field of synthetic biology could enhance biological systems.

Although low volumes of CO_2 would be utilised, niche, high value products provide a cost-competitive route to further develop the biological conversion pathway in Australia. Given, many niche, high value products respond to challenges facing the food and agricultural sectors (e.g. alternative feed for livestock) there is potential for the biological conversion of CO_2 to focus on global food export opportunities initially.

In future, it is possible that biological systems could produce many bulk and high value chemicals on demand to meet changing supply needs. These products would need to compete with other CCU processes, such as thermochemical methanol production.

However, Australia has a strong synthetic biology research base, emerging start-ups and national and state-level biofoundry investments that could be leveraged for the development of longer term CO_2 conversion applications.

Scale-up considerations:

- **Initial application(s):** Given the advancements in production of chemical and fuels via alternate pathways and the relatively small scale of emerging biological processes, niche, high value products for the food and agricultural sectors present an initial opportunity.
- **Deployment model:** Focused on development and demonstration of niche, high value products which respond to growing consumer demand for sustainable products. Continue to invest in RD&D to improve bulk processes for large-scale low emissions sources of chemicals and fuels. The scale-up priorities to develop synthetic biological conversion facilities are set out in the table below.

ABATEMENT CONSIDERATIONS

Green premium:

Although quantitative modelling for this application is beyond the scope of the report, it is likely that there will be a premium for these products.

Cost of abatement:

Not analysed within the scope of this report

Abatement potential:

The abatement potential is linked to the end use case.

Duration of CO_2 storage:

Released on use for some downstream applications (e.g. fuels) or locked away for the life of the product (e.g. polymers may be years to decades depending on use case).

Scale-up priorities:

IMMEDIATE (2020–2025)	SHORT-MEDIUM TERM (2025–2030)	LONG-TERM (2030–2040)
• Conduct feasibility studies to understand most economic niche and bulk products • Demonstrate biological systems for converting small quantities of CO_2	• Integrate demonstrator bioreactors into existing plants or industrial hubs	• Establish commercial offerings of bioreactors for emitters • Scale applications based on market demand for products

6.2 Overview

Biological conversion of CO_2 is the use of microorganisms to produce a range of products. In some cases, the emerging field of synthetic biology could enhance biological systems.

In biological conversion of CO_2, microorganisms such as algae, cyanobacteria, acetogens and methanogens take up CO_2 and convert it into a range of useful chemicals. Some of these products could be bulk chemicals, such as ethylene and ethanol, produced at large scale. More niche high value chemicals can also be made, such as pharmaceuticals, nutrients, cosmetics and fragrances; while low volume, these products may provide a more cost-competitive pathway than conventional industrial synthesis routes. The operating conditions of different microorganisms vary, as do their scalability and applicability to different contexts. Biological systems can be linked directly to flue gas streams or capture CO_2 directly from the air. Compared to industrial chemical methods, modular biological systems can work economically at smaller scales and minimise generation of toxic waste materials such as spent catalysts.

In future, it is possible that biological systems could produce many bulk and high value chemicals on demand to meet changing supply needs. In the near-term, however, only a few products have reached or are nearing commercial demonstration. The planning for larger-scale operations to date are focused on bulk ethanol and ethylene production, whereas some high value chemicals such as edible proteins are beginning to emerge with early funding and planned demonstration projects. In future, organisms could be tailored with genetic engineering or synthetic biology to potentially enhance yields and produce higher value compounds. However, this technology is currently in its infancy for bulk commodity production, such as algal biofuels.[219]

6.3 Bulk chemicals and fuels

Ethylene: As discussed in Chapter 5.5, ethylene is an important precursor for various polymers, such as polyethylene, polystyrene, PVC and PET plastic. It can also be upgraded to higher order hydrocarbons such as synthetic jet fuel. Bioethylene is typically produced by processing bioethanol, which itself is sourced from crops like corn and sugarcane.[220] Alternatively, bio-ethylene can be synthesised directly using biological organisms. For example, US-based Cemvita has plans to construct a pilot plant that uses engineered microorganisms to convert CO_2 from flue gases into ethylene.

Bioethanol: As discussed in Chapter 5.7, ethanol is used in transport fuels, [221] and in the manufacture of various other chemicals such as ethylene, pharmaceuticals, plastics, polishes and cosmetics.[222] Bioethanol is currently sourced from fermentation of crop biomass. Lanzatech is a US-based company producing ethanol and other higher value fuels from waste gas and syngas streams.[223]

Bioplastics: Bioplastics are plastics derived in whole or in part from biological material. Bioplastics differ from biodegradable plastics, which are readily decomposed by microorganisms. For example, polyhydroxyalkoanates (PHAs), can be synthesized by microbes with the polymer accumulating in the microbes' cells during growth. PHAs are used for packaging, injection-moulded products (such as pens), automotive parts, fabrics and fibres. Their production is expected to grow from 48Mt in 2018 to 138Mt in 2023.[224]

219 Jagadevan S et al. (2018) *Recent developments in synthetic biology and metabolic engineering in microalgae towards biofuel production.* Biotechnology for Biofuels

220 IEA-ESTAP & IRENA (2013) *Production of Bio-ethylene Technology Brief*. IEA-ESTAP & IRENA

221 Richardson A (2020) *Basic Organic Chemical Manufacturing in Australia.* IBISWorld

222 Strohm B (2014) *Encyclopedia of Toxicology: Ethanol*. Biomedical Sciences

223 BASF (2021) *LanzaTech Inc.* Viewed 3 May 2021, https://www.basf.com/global/en/who-we-are/organization/group-companies/BASF_Venture-Capital/portfolio/LanzaTech-Inc.html

224 Chen J (2019) *Global Markets and Technologies for Bioplastics*. BCC Market Research.

Table 9: Summary of active biological CO_2 conversion companies

COMPANY	DESCRIPTION	COMMERCIAL STATUS
Cemvita Factory (US)	Engineering microorganisms to convert CO_2 from flue gases directly into ethylene. Cemvita have identified a range of other bulk and higher value compounds that could be synthesised using their microorganisms.	Demonstration project to produce bioethylene planned with Oxy (Occidental).[225]
Lanzatech (US)	Producing ethanol and other higher value fuels from waste gas and syngas streams.	Collectively the company has reached over 70,000 hours of operation at five industrial demonstration sites.[226] Subsidiary Lanzajet partnered with British Airways to provide SAFs from bioethanol for flights by 2022.[227]

6.4 Niche, high value products

Many high value chemicals can be made using biological systems, including proteins, pharmaceuticals, nutraceuticals, cosmetics, animal feed, agricultural chemicals, and flavours and fragrances. While currently low TRL, synthetic biology could enable the creation of new organisms that can manufacture a broad range of high-performance products.

6.5 The opportunity for Australia

While biological conversion of CO_2 is still an emerging area, the broader field of synthetic biology has been under development for decades with various food related commercial applications of microorganisms. Australia has a strong synthetic biology research base, emerging start-ups and national and state-level biofoundry investments that could be leveraged for the development of longer-term CO_2 conversion applications.

Many biological conversion products respond to population growth and pressures to respond to climate change facing the food and agriculture industries. Due to the limited abatement potential at small scales, it is likely that investment in biological CO_2 conversion will be driven by consumer demand for more sustainable products (e.g. alternative feed for livestock), as opposed to by industry efforts to reduce emissions. Industry's ability to overcome commercial and technical hurdles to scale up production will also be key to future widespread deployment, as investments are de-risked over time.

Australia's trusted regulatory environment supports the nation's reputation as a safe and sustainable jurisdiction for emerging genetically modified products, which can enhance investor confidence and encourage domestic project development. While technologies used for bulk chemical and fuel products are more mature, niche and high value products present an opportunity for Australia to engage with an emerging industry that has significant growth potential. This approach builds on growing capabilities in Australian companies, such as Provectus Algae and BondiBio.

225 Oxy Low Carbon Ventures (2021) *Oxy Low Carbon Ventures, Cemvita Factory announce plan to develop pilot plant for innovative CO2-to-bio-ethylene technology*. Viewed 3 May 2021, https://www.prnewswire.com/news-releases/oxy-low-carbon-ventures-cemvita-factory-announce-plan-to-develop-pilot-plant-for-innovative-co2-to-bio-ethylene-technology-301262535.html

226 BASF (2021) *LanzaTech Inc.* Viewed 3 May 2021, https://www.basf.com/global/en/who-we-are/organization/group-companies/BASF_Venture-Capital/portfolio/LanzaTech-Inc.html

227 LanzaTech (2021) *British Airways Fuels Its Future with Second Sustainable Aviation Fuel Partnership*. Viewed 3 May 2021, https://www.lanzatech.com/2021/02/09/british-airways-fuels-its-futures-with-second-sustainable-aviation-fuel-partnership/

Table 10: Summary of active biological CO_2 conversion companies

COMPANY	DESCRIPTION	COMMERCIAL STATUS
Provectus Algae (AU)	Optimisation of algae for production of high value compounds for use in a wide array of industries/applications, including nutraceuticals, pharmaceuticals, natural pigments, and food and feed supplements.[228]	Manufacturing facility funded. First commercial products expected to be food flavouring and agricultural products.[229]
BondiBio (AU)	Designing cyanobacteria able to produce targeted compounds for a broad range of markets, including nutraceuticals, pharmaceuticals, agriculture and aquaculture feed, cosmetics, flavours, fragrances, and other speciality chemicals.[230]	Early-stage funding achieved.
Deep Branch (UK)	Converts hydrogen and CO_2 via gas fermentation into single-cell proteins, which are used as aquaculture feed.[231]	Demonstration aquaculture feed project announced.
Air Protein (US)	Converts hydrogen and CO_2 into proteins, which are sold in the form of flour.[232]	Early-stage funding achieved.[233]
Solar Foods (FI)	Converts hydrogen, oxygen and CO_2 (consumed from the air by microorganisms) into an edible single-cell protein.[234]	Funding achieved for beginning commercial-scale production.[235]

6.6 Considerations

Commercial

Conditions of operation: Each group of microorganisms has unique optimal operating conditions and feedstocks required to function. For example, algae and cyanobacteria require sunlight and therefore maintaining productivity while achieving system scale-up relies on available surface area. Other microorganisms such as acetogens may require hydrogen gas as an energy input to function.

CO_2 input: Some biological systems can be connected directly to existing flue gas streams to extract and convert the CO_2 without the need for pre-treatment of the gas stream.[236] Others uptake CO_2 directly out of the air, bypassing the need for point source or direct air capture entirely. This could reduce capital cost requirements for capture and filtration systems.

Policy and regulation

Genetic engineering and synthetic biology regulation: Existing biosafety risk assessment frameworks have previously been determined likely to be sufficient to assess the risks of near-term synthetic biology applications. Additionally, the Third Review of the National Gene Technology Scheme recommended that a watching brief on synthetic biology be maintained to ensure appropriate regulation is applied to future applications. [237]

228 Provectus Algae (2020) Services. Viewed 3 May 2021, https://provectusalgae.com/services

229 Advanced Manufacturing Growth Centre Ltd (n.d.) *Manufacturing of high-value algae species.* Viewed 3 May 2021, https://www.amgc.org.au/project/manufacturing-of-high-value-algae-species/

230 BondiBio (n.d.) *Solar Biomanufacturing*. Viewed 3 May 2021, https://www.bondi.bio/

231 Deep Branch (2021) *Technology*. Viewed 3 May 2021, https://deepbranch.com/technology/

232 Air Protein (2019) *Science.* Viewed 3 May 2021, https://www.airprotein.com/science

233 Air Protein (2019) *Science.* Viewed 3 May 2021, https://www.airprotein.com/press

234 Solar Foods (2021) *What is Solein*. Viewed 12 July 2021, https://www.solein.com/what-is-solein

235 Solar Foods (2021) *Solar Foods accelerates production of climate-friendly protein with investment*. Viewed 12 July 2021, https://solarfoods.fi/our-news/solar-foods-accelerates-production-of-climate-friendly-protein-with-investment-from-the-finnish-climate-fund/

236 Dowson G, Styring P (2017) *Demonstration of CO2 Conversion to Synthetic Transport Fuel at Flue Gas Concentrations*. Frontiers in Energy Research

237 Department of Health (2018) *The Third Review of the National Gene Technology Scheme.* Department of Health

Environmental and social

Public awareness and acceptance: Provide information to the public on the benefits of genetic engineering and synthetic biology, and the mechanisms in place to ensure risks are managed.

Lifecycle emissions: The lifecycle emissions are varied and subject to end use, however, low emissions feedstocks and inputs are required. Bulk fuels would release CO_2 on use compared to other biologically derived products such as bioethylene which could store CO_2 for longer periods when used for long-term applications.

RD&D

Genetic engineering and synthetic biology: While currently low TRL, synthetic biology could boost efficiency of production and enable the creation of new organisms that can manufacture a broad range of high-value products.[238,239] Advances in genetic engineering and synthetic biology could enable tailoring more efficient microorganisms and expand the range of high value products they can make.

Scaling up biological systems: Many systems have been proven in laboratory environments. Demonstration of systems at scale is the next step for more advanced biological conversion technologies.

Emerging technology: Bio-electrochemical systems generate small organic molecules from CO_2 via artificial photosynthesis, in a hybrid electrochemical and biological system. This technology is currently at an early laboratory research level.[240]

238 Kondaveeti S et al. (2020) *Advanced Routes of Biological and Bio-electrocatalytic Carbon Dioxide (CO2) Mitigation Toward Carbon Neutrality*. Frontiers in Energy Resources

239 Wang B et al. (2012) *Application of synthetic biology in cyanobacteria and algae*. Frontiers in Microbiology

240 National Academies of Sciences, Engineering, and Medicine (2019*) Gaseous Carbon Waste Streams Utilisation Status and Research Needs*. The National Academies Press

7 Long-term opportunities

Beyond the CO_2 utilisation technologies that are nearing commercial application, there are many emerging applications which warrant consideration for long-term investment, particularly considering Australia's investment in advanced manufacturing and materials capabilities (see Table 11 for examples).

In general, these opportunities fall into one of two categories:

- Applications where CO_2 replaces existing inputs for manufacturing processes. This includes carbon fibre and carbon black, made from petrochemical feedstocks; and graphite, which is mined directly.
- Applications where CO_2-based methods may present the optimal way to carry out a new process entirely or synthesise a new product that is currently very difficult to make. This includes graphene and carbon nanotubes, which have only been synthesised at scales under 1kg, and new processes for recycling battery metals.

While it is unlikely that large volumes of CO_2 will be utilised for these products in the near term, it is expected that CO_2 could be stored in these materials for long periods of time. Additionally, these materials could provide emissions reduction benefits in other technologies by offering potentially significant efficiency improvements across applications such as aeroplanes and enhancing the performance of renewable energy technologies.

For Australia, these opportunities are worth considering as the markets for many of these materials are growing, despite current limitations to manufacturing scale.[241] The carbon fibre market, for example, is expected to grow from $3.2 billion in 2019 to $9.2 billion by 2029.[242] If developed, lower cost production methods could lead to even faster growth. The production scale of these materials could be quite large given their desirable characteristics and potential applicability. The commercial value of these products could offset the high costs associated with making them from CO_2. Additionally, for some of the opportunities described, CO_2-based methods would be competing with other methods that also haven't been achieved at scale.

However, given they are in their infancy, significant R&D is required to scale up these technologies and improve the energy efficiency of the required reactions. Scaling up above kilogram levels, building demonstration scale facilities, increasing the structural quality of products, and conducting general lifecycle assessments are priorities for these technologies.[243]

241 Sandalow D, Aines R, Friedmann J, McComick C & McCoy S (2017) *Carbon Dioxide Utilization (CO2U) ICEF Roadmap 2.0*. Innovation for Cool Earth Forum

242 Markets and Markets (2019) *Carbon Fiber Market*. Viewed 3 May 2021, https://www.marketsandmarkets.com/Market-Reports/carbon-fiber-396.html. USD to AUD exchange of 0.69 used.

243 Sandalow D, Aines R, Friedmann J, McComick C & McCoy S (2017) *Carbon Dioxide Utilization (CO2U) ICEF Roadmap 2.0*. Innovation for Cool Earth Forum

Table 11: Examples of long-term CO_2 utilisation opportunities[244]

MATERIAL	EXISTING SOURCE	POTENTIAL USES
Carbon fibre	Polyacrylonitrile (PAN) or pitch derived from petrochemicals	• Reinforce composite materials in the aerospace, automotive, and renewable energy sectors • Carbon fibre wind turbine blades
Carbon black	Petrochemicals	• Tyres and rubbers, plastics • Small amounts to be used in renewable energy tech
Graphite	Found naturally in deposits	• Mature use in batteries and fuel cells; demand expected to increase • Used in composite materials for wind turbines
Graphene	Various mechanical and chemical methods	• Used to enhance Li-ion battery performance • Alternative graphene battery or supercapacitor • In composite materials for wind turbines
Carbon nanotubes	Graphite, or carbon-containing gases such as CO	• Used in various electrical applications such as solar cells and batteries • Used for hydrogen storage
Battery recycling	N/A	• Strip out precious metals from end of life batteries. Elements such as lithium and cobalt can be converted to carbonates, from which pure metal can be harvested for use in new batteries.[245]
Nanodiamonds[246]	Detonation synthesis	• Medical imaging and testing • Plating for electrochemistry • Electronics and sensors

244 Sandalow D, Aines R, Friedmann J, McComick C & McCoy S (2017) *Carbon Dioxide Utilization (CO2U) ICEF Roadmap 2.0*. Innovation for Cool Earth Forum

245 Septavaux J et al. (2020) *Simultaneous CO2 capture and metal purification from waste streams using triple-level dynamic combinatorial chemistry*. Nature Chemistry

246 Kamali A (2017) *Nanocatalytic conversion of CO2 into nanodiamonds*. Carbon

8 Summary of CCU applications

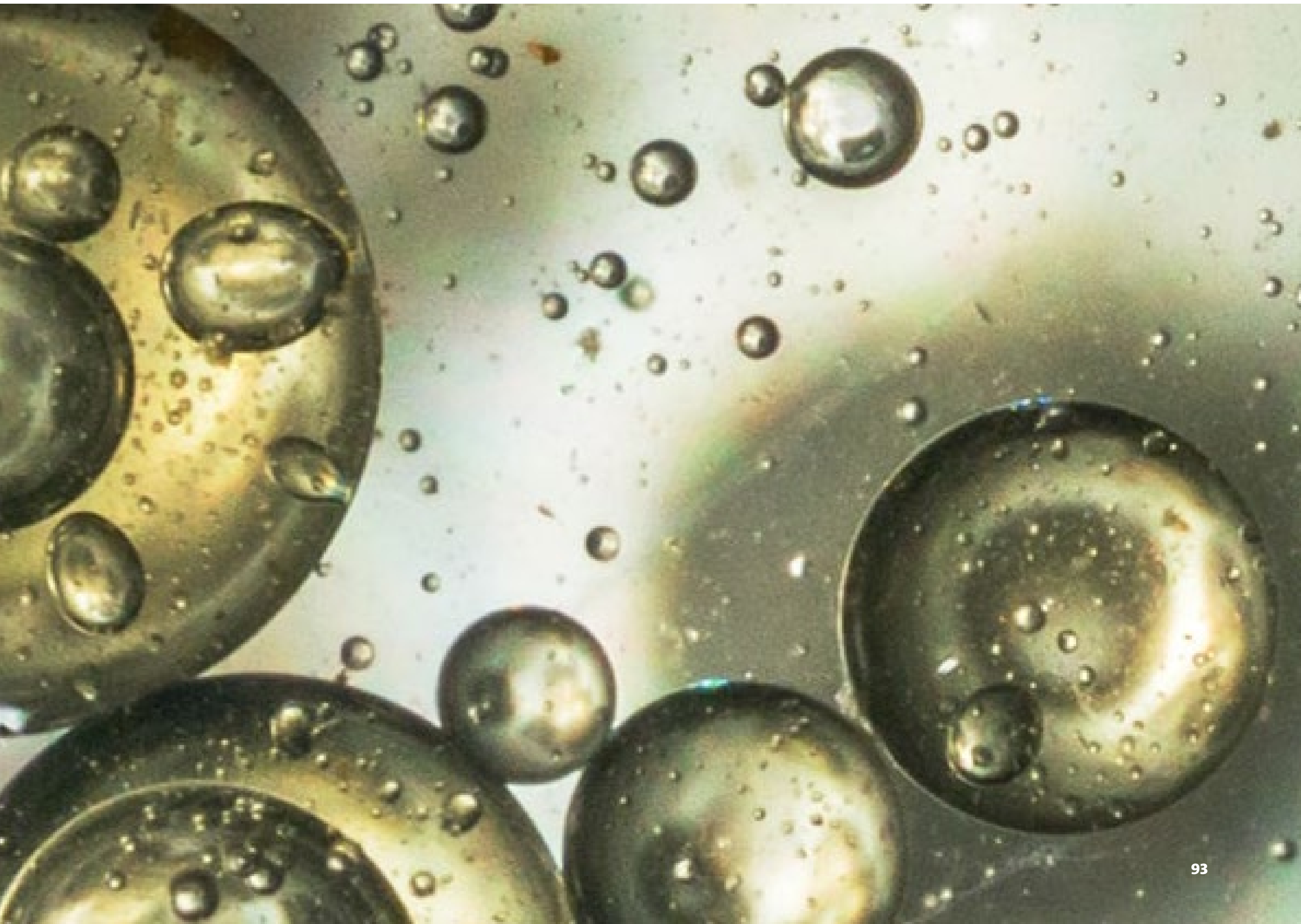
Table 12: Summary of key CO_2 applications for Australia

APPLICATION OR PRODUCT	PRODUCTION OPPORTUNITY		
	DOMESTIC PRODUCTION CAPABILITIES	SCALE-UP INFRASTRUCTURE REQUIREMENTS	GREEN PREMIUM
Direct use – Food and Beverage	Widespread domestic use across beverage carbonation, food processing, refrigeration, and others.	Opportunity to blend capture sources with current supply but will need to consider purification and pressurisation infrastructure for food-grade CO_2.	Green premium may be present if CO_2 is sourced from point sources with low partial pressure or DAC.
Direct use – Greenhouses	Widespread domestic use with CO_2 sourced locally for use in greenhouses	Transport of CO_2 for lower partial pressure point sources or scale up of distributed DAC.	Green premium may be present if CO_2 is sourced from point sources with low partial pressure or DAC.
Methanol	Domestic production stopped in 2016, with Victorian facility placed in care and maintenance mode. Feasibility studies into new production underway. Fossil fuel derived methanol is imported.	Large volumes of low-cost renewable hydrogen required. Hydrogen availability is the primary limitation to further scale-up. Existing plant can be adapted. There is an opportunity to scale up production using a hybrid model blending natural gas and hydrogen.	High
Jet fuel	Currently produced by refining crude oil. Only two refineries remain in Australia.	Increased methanol production with associated renewable hydrogen requirements. New methanol upgrading synthesis infrastructure.	High
Polymers/olefins	Currently produced from cracking of hydrocarbons. Declining production in favour of imported products.	Olefin production is dependent on methanol synthesis. As such, hydrogen availability is the primary limitation to further scale-up.	Medium
Synthetic natural gas	Natural gas abundant in Australia, no domestic production of synthetic natural gas.	Can integrate into existing natural gas supply. Compatible with domestic and industrial appliances. Hydrogen availability is the primary limitation to further scale-up. Synthesis infrastructure also required.	Very high
Carbonate products	Currently produced in Australia.	Mineral carbonation plants required. Transport of feedstock or CO_2 where co-location not possible. Low purity of CO_2 can be used.	Likely to be competitive but this will be application dependent.
Concrete	Cement and concrete production widespread.	Some can be retrofitted to existing facilities; others require new processing plants. CO_2 may need to be transported to cement plant.	Concrete mineralisation has been shown to have small premium. Further research required to evaluate premiums as TRL increases.
Biological conversion of CO_2	Bulk products, like ethanol, are domestically manufactured.	Currently very low scale. Plants can be retrofitted to CO_2 capture source, or CO_2 needs to be transported to plant.	Likely to exist but this is not quantified in the scope of this report.

	ABATEMENT POTENTIAL	
LONG TERM DEMAND	ABATEMENT CONSIDERATIONS	DURATION OF CO_2 STORAGE
Established CO_2 demand, growth in fresh food and food processing demand for Australia and surrounding regions.	Currently through displacement of fossil CO2; net zero if low emission CO_2 sources are applied	Released on consumption.
Established CO_2 demand, growth in fresh food and food processing demand for Australia and surrounding regions.	Currently through displacement of fossil CO_2; net zero if low emission CO_2 sources are applied	Released on consumption, decomposition or stored in soil.
Potential for significant growth if used as feedstock for other synthetic fuels and chemicals.	Access to clean H_2. When using DAC, potential for low net emissions but point source CO_2 can only theoretically avoid further emissions by 50%. If used as feedstock, significant potential to displace fossil fuel use.	Released on use for some downstream applications (e.g. fuels) or locked away for the life of the product (e.g. polymers).
Growing demand for jet fuel due to increased travel and long lifespan of aircraft. Consideration for sovereign security in fuel supply.	Access to clean H_2. When using DAC, potential for low net emissions but point source CO_2 can only theoretically avoid further emissions by 50%.	Released on use.
Growing demand for new plastic feedstocks, despite increased recycling rates. Potential demand for emerging CO_2-derived plastics.	Using DAC, potential for low net emissions but point source CO_2 can only theoretically avoid further emissions by 50%.	Locked away until product is oxidised via incineration (ranging from years to decades depending on the use case of the plastic).
Long life span of appliances, industrial plants and distribution infrastructure is likely to maintain demand over time. Potential for gas powered generation to play a role in demand.	Using DAC, potential for low net emissions but point source CO_2 can only theoretically avoid further emissions by 50%.	Released on use.
Various products with independent often large scale demand profiles. Potential to grow with low-cost carbonate market growth.	If paired with DAC, carbonate products could result in negative emissions.	Permanently locked away under most use cases.
Incumbent concrete demand projected to grow.	CO_2 concrete processes have various CO_2 abatement profiles. Potential for cement displacement can reduce emissions.	Permanently locked away.
Desire for low emission products may drive demand.	Low emission feedstocks and inputs required. DAC or atmospheric CO_2 use could result in net zero products.	Locked away for life of product.

Part III –

Roadmap to scale-up



CCU can play a key role in global decarbonisation efforts and provide Australian industry with a range of low carbon and low emissions technology opportunities.

However, many CCU applications are still emerging and far from equal in their strategic value. The applications will be developed over different time-horizons and have large associated costs when compared to continuing to rely on low cost fossil fuels. While CCU can have a significant impact on the carbon intensities of CO_2 emitting industries, the applications lock in CO_2 for different time periods, which impacts their carbon abatement and storage potential. Further, for the transition to low emissions products, many will require renewable energy and hydrogen, while some will require substantial quantities of other feedstocks.

A strategic and well-informed approach to the scale up of CCU is needed.

This report, through extensive consultation, literature review, modelling and analysis, proposes that scale-up focuses on current direct use applications and mineral carbonation due to their near-term potential. Upscaling and development of chemicals and fuels is also a significant opportunity due to predicted increasing global demand and the transition away from traditional fossil fuel sources that can be aligned with the development of Australia's hydrogen industry. Biological conversion represents a smaller and lower TRL opportunity, but can also be scaled up to supply niche, high value markets.

In addition, direct air capture technologies have the potential to significantly change the CCU landscape through the ability to be deployed almost anywhere. The technology is still emerging and requires significant investment to reduce the costs and demonstrate long term viability at scale.

For such a scale-up to be successful it must be paired with action and broader change across the country, particularly given that understanding of CCU is still nascent in Australia. As such, this report has identified four key recommendations to support scale-up and increase impact from CCU, which could be considered by Australian industry, government and the research community.

Key recommendations to support CCU development in Australia

1. Diversify and engage across the value chain and multiple CCU applications
2. Use CCU as part of a portfolio of decarbonisation solutions
3. Create incentives and minimise barriers to entry
4. Use CCU to support or de-risk investment in existing and planned infrastructure

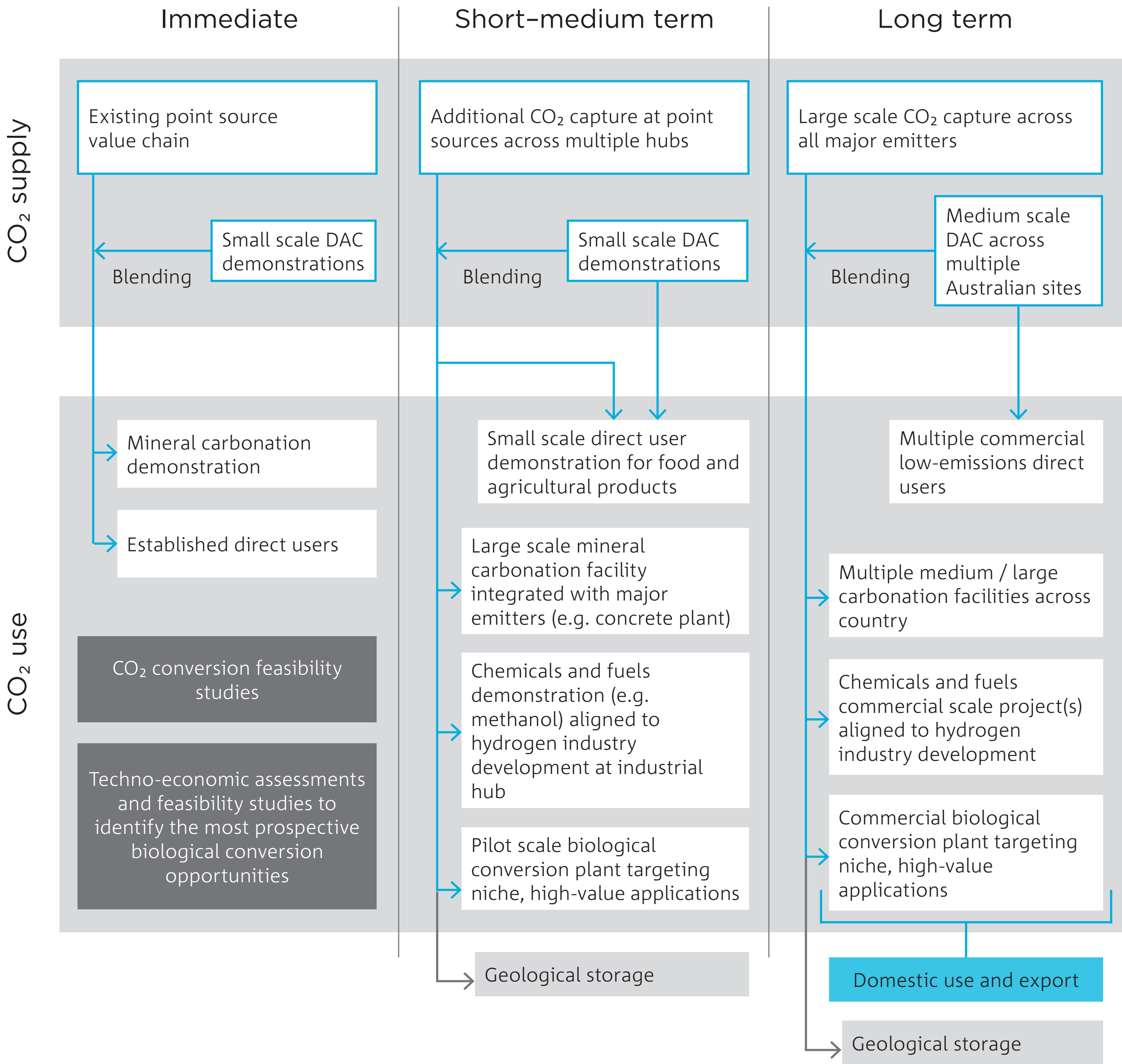


Figure 41: Scale-up approach

9 Key recommendations for scale-up

9.1 Diversify and engage across the value chain and multiple CCU applications

This report identified over 50 different use cases or products possible for CO_2 utilisation grouped into broad areas: direct use of CO_2, mineral carbonation, conversion of CO_2 into chemicals and fuels and biological conversion of CO_2. This diversity in CO_2 use cases is important and should be leveraged as part of a CCU scale-up strategy.

To avoid duplication, attract investment and improve outcomes, it is important that scale-up of different CCU applications is supported by strong engagement both domestically and internationally, and clear communication on Australia's position on CCU and its role in the decarbonisation challenge. Diversifying Australia's CCU investments and products can:

- **Provide flexibility to pursue/enter a range of green markets as CCU technologies evolve:** A diversification strategy creates flexibility to pivot as global green markets develop and associated carbon policies evolve. This includes providing time for CCU technologies to come down in costs through larger scale demonstrations, operational efficiency and R&D breakthroughs (such as DAC), as well as time for growth in CO_2 capture in Australia and development of the required distribution infrastructure (such as pipelines).
- **Provide optionality for a broad range of emitters:** The many ways to utilise CO_2 provides optionality for organisations (with different emissions profiles) to incorporate CCU in their strategies for decarbonisation. Leveraging CCU also provides opportunities for commercial benefit, particularly if the emitter is within an industrial hub and can leverage existing infrastructure or sell a CO_2-derived product to a neighbouring organisation. If an emitter wishes to minimise investment in carbon offsets and reach carbon neutrality with CCU, they'll have no choice but to choose applications that result in permanent storage of CO_2 or invest in low emission CO_2 sources, such as DAC, to create a closed loop systems for their emissions.
- **Create options for industries with no current viable option for fuel switching:** Industries that face barriers to abatement, such as the commercial aviation industry, have announced ambitious goals to curb emissions. With battery and fuel cell technology and its supporting infrastructure some time away, low emission fuels could be used in the interim. As such, the aviation industry is looking at biofuels and synthetic fuels via CCU to support decarbonisation objectives.
- **Reduce the risk of flooding markets with CO_2-derived products given excess CO_2 available:** Diversification as CCU scales can be used in part to help avoid flooding markets with more product than is required. For example, while this would not be an immediate challenge in the international fuels market, biological systems can be used to create large volumes of high value products, such as nutraceuticals, which could exceed current market demand given the large volumes of CO_2 available. It is important to note that in the long-term, lower cost product could help stimulate new uses beyond existing markets.

Engagement and close collaboration across the CO_2 value chain in Australia and overseas can avoid duplication, minimise risk and attract investment.

CCU industry development is emerging internationally but there is little formal collaboration. Given its industry strengths, as detailed in this report, Australia has an interest in and could play a leading role in promoting international collaboration in CCU development in the same way it has taken on that role with hydrogen.

To maximise impact and reduce investment risk, it is important to encourage collaboration across the CO_2 value chain – from CO_2 capture and distribution through to use. Given the nascency of the industry and emerging CCU technology developments, collaboration also needs to be encouraged across industry, technology providers and research institutions. These value chains and disciplines are complex, integrated and global, demonstrating the need for coordination. Encouraging joint ventures of industry players across the value chain will help to pool expertise and share risk.

Leveraging existing ecosystems at industrial hubs and being a part of early discussions around new CCS and hydrogen hubs that are under development will encourage the integration of CCU at lower costs due to shared infrastructure and expertise. This may require incentives for industry, technology providers and researchers to collaborate and de-risk technologies within hubs and demonstrators.

Clear public, industry and government communication of CCU and its role in the decarbonisation puzzle will be vital.

A strong understanding of the potential benefits and limitations of CCU will be essential to maintain public support for CCU demonstration projects and encourage uptake of new technologies. Given the range and complexity of CCU technologies, clear communication of how CCU technologies could reduce emissions for specific applications will be important. Equally, the distinction between CCU and CCS should be made clear.

Part of communicating the benefits of CCU will be the development of transparent product lifecycle and energy efficiency assessments to accurately determine abatement potential. This will encourage public support and give assurance to industry that they are meaningfully reducing their emissions.

Engage and integrate with existing strategies and green mechanisms, such as the development of the circular economy.

CCU is complementary to many existing goals and strategies already being pursued. Educating industry on how CCU can be integrated into these will raise the profile of CCU and its potential. In terms of the circular economy, continued investment in closed loop systems can also accelerate investment in CO_2 technologies. Creating a closed loop CO_2 system can make the case for increasing utilisation of CO_2 as capture sources continue to become more economical. Conversely, should CO_2-derived products reach high cost margins, there is also opportunity to reinvest this into scale-up of capture technologies.

9.2 Use CCU as part of a portfolio of decarbonisation solutions

As highlighted earlier, there is a portion of Australian and global emissions that are unavoidable or difficult to abate within the timeframe required or without heavy reliance on offsets or emerging negative emissions technologies. These industries can be broadly sub-divided into three categories: industries where CO_2 emissions are inherent to their processes (e.g. cement and steel); industries that require carbon and sell products derived from fossil fuels (e.g. plastics and chemicals); and heavy transport industries dependent on fossil fuels (e.g. aviation and maritime). CCU creates an alternate option to generate revenue streams in the short term to offset the associated costs and support the longer-term trend away from fossil fuels.

Unfortunately, there is no silver bullet to the challenges related to climate change and it will require a portfolio of decarbonisation solutions, which includes the utilisation of CO_2. Incentivising CCU as part of a portfolio of decarbonisation options would provide opportunities to:

- **Pro-actively position CCU as complementary, rather than competitive, with investment in other vital decarbonisation technologies:** It is extremely important for CCU to be viewed alongside other decarbonisation technologies. Renewables, CCU, CCS, DAC, solar thermal and emerging negative emissions technologies can all play a role in the scale of the challenge that exists, particularly for hard-to-abate industries.
- **Develop world class sites and demonstrations for investment, support the transition towards lower-emissions products and contribute to global decarbonisation efforts for the third of global emissions that have limited alternatives:** Australia represents a microcosm of the global emissions challenge, creating a suitable industrialised testbed to demonstrate and scale up CCU technologies for use in other international markets and at larger scales.
- **Scale up CCU projects alongside manageable infrastructure and feedstock requirements, maintaining alignment with the Australian Government's National Hydrogen Strategy**: A portfolio strategy can take advantage of existing national strategies and industry objectives to ensure that CCU scale-up aligns with existing or planned infrastructure investments from CO_2 pipelines to hydrogen and CCS hubs. Alignment with existing strategies would also help encourage a whole of government and industry approach to CCU scale-up.

- **Create opportunities for further scale-up aligned to longer term CCU-related export:** A portfolio strategy can be used to manage and align scale-up to achieve long-term export opportunities. For example, as Australia's hydrogen industry scales, it creates further potential for the export of renewable feedstocks that help the plastics and chemicals industry move away from fossil fuels. Another example is the CO_2 lock-in potential of mineral carbonation, which if paired with DAC, could result in negative emissions, creating valuable offsets for trading on international markets.

Importantly, any CCU investment should be paired with product LCAs to ensure and provide transparency on the associated emissions. These assessments will need to analyse each step of the process, from cradle to grave, to quantify the lifetime environmental effects of production and use. This will help assess the carbon intensity of CO_2-based products to ensure that they are providing an alternative that produces an emissions benefit comparative to incumbents. This information will be valuable in meeting industry emissions standards, qualifying products for carbon intensity accreditation and incentive schemes including scope 3 emissions accounting, improving transparency and supporting engagement with the public.

To illustrate this portfolio strategy and support further discussion, three scenarios have been developed exploring how a portion of hard-to-abate emissions could be managed via deployment of various CCU applications.

These scenarios use 5,000 tonnes per day capture volumes (i.e. best case assumptions) for each facility stated. Where possible, the analysis provides examples of the necessary infrastructure and feedstock that would be required to support the different levels of CCU adoption. For example, hydrogen and DAC in the case of CO_2 conversion to chemicals and fuels; and CO_2 requirements in the case of mineral carbonation.

These illustrative examples would likely take place in existing and planned industrial hubs. This would allow CCU projects to take advantage of existing infrastructure and feedstocks; and help support regional and industry-based net-zero ambitions associated with these hubs.

The three scenarios are described as follows:

- **Scenario 1 – Low CCU adoption:** CCU adoption is slow and poorly integrated in national and industry strategies resulting in low levels (8–10%) of abatement across hard-to-abate industries. The scenario results in the deployment of only two mineral carbonation facilities and two methanol facilities, servicing domestic market with small export volumes.
- **Scenario 2 – Moderate CCU adoption:** CCU adoption is proactively used to further decarbonisation, abating 23–30% of hard-to-abate emissions. Mineral carbonation is scaled with six facilities across the country. The domestic methanol and olefins markets are serviced with Australian production targeting 3% of today's global methanol market and electrofuel is used to service 7% of domestic jet fuel demand.
- **Scenario 3 – Stretch CCU adoption:** CCU is widely used to achieve decarbonisation objectives and build longer-term global export opportunities with 39–50% of Australia's hard-to-abate emissions abated using CCU. Mineral carbonation use is widespread with 10 facilities across the country. The domestic methanol and olefins markets are serviced with Australian players taking up over 5% of the global methanol market. Electrofuel is used to service 10% of domestic jet fuel demand and a small portion (1% of today's natural gas market) uses synthetic natural gas for specific applications.

Abatement potential	Methanol	Electrofuel	Olefins	SNG	Mineral carbonation
LOW CCU ADOPTION ~8–10% Hard to abate emissions	2.6–4.4Mt CO_2 avoided from 2 facilities				3.8Mt CO_2 permanently stored using 2 facilities
	Requirements: 3 GW of H_2 electrolyser capacity, 3.7Mt CO_2 from point sources and/or DAC				Requirements: Feedstock + 3.7Mt CO_2 from point sources and/or DAC (for negative emissions)
MODERATE CCU ADOPTION ~23–30% Hard to abate emissions	3.9–6.6Mt CO_2 avoided from 3 facilities	2.3–4.2Mt CO_2 avoided from 2 facilities	1.4–2.5Mt CO_2 avoided from 1 facility		11.4Mt CO_2 permanently stored using 6 facilities
	Requirements: 8 GW of H_2 electrolyser capacity, 11Mt CO_2 from point sources and/or DAC				Requirements: Feedstock + 11Mt CO_2 from point sources and/or DAC (for negative emissions)
STRETCH CCU ADOPTION ~39–50% Hard to abate emissions	6.5–11Mt CO_2 avoided from 5 facilities	3.6–6.3Mt CO_2 avoided from 3 facilities	1.4–2.4Mt CO_2 avoided from 1 facility	1.2–2.1Mt CO_2 avoided from 1 facility	19Mt CO_2 permanently stored using 10 facilities
	Requirements: 15 GW of H_2 electrolyser capacity, 18Mt CO_2 from point sources and/or DAC				Requirements: Feedstock + 18Mt CO_2 from point sources and/or DAC (for negative emissions)

Figure 42: Scenarios to illustrate abatement potential and requirements for different levels of CCU adoption

The scenarios developed are illustrative and explore the percent of hard-to-abate emissions that different levels of CCU adoption could achieve. CO_2 abatement potential uses production as a boundary condition and does not consider full lifecycle emissions. See Appendix D for abatement potential approach. The percentage of hard-to-abate emissions relates to the percentage of ~82Mt per annum from Australian 2019 emissions (see Figure 1). The variance in abatement potential for methanol, electrofuel, olefins and SNG relate to the differences in abatement potential for CO_2 sourced from a point source vs DAC. Hydrogen electrolyser sizes relate to assumption of a grid connection with high capacity factor.

9.3 Create incentives and minimise barriers to entry to reduce and bridge green premiums

Creating the right incentives and minimising barriers to entry will be key for scale up and transition to low emissions products. Almost all low emission CCU applications will incur a green premium (i.e. the additional cost of choosing the low-carbon alternative) in the near term. The commercial potential will hinge on the speed at which these can be reduced and how incentives can be used to bridge the remaining gap. An exception is mineral carbonation which could be competitive in the near-term depending on the use case.

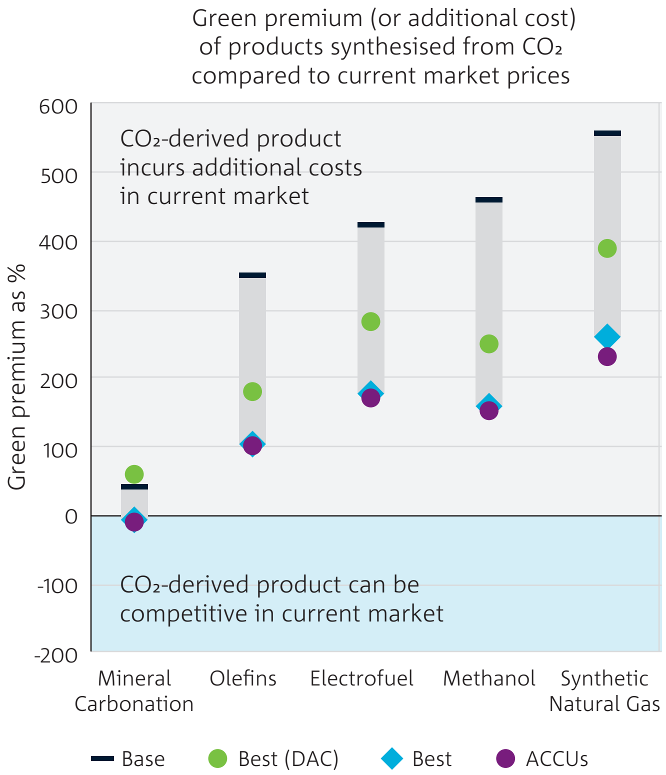


Figure 43: Effect of capture sources on green premiums of CCU applications

This diagram shows the green premium for each CCU application modelled. For each application, the effect of different CO_2 capture sources are shown as different data points. A green premium of greater than 0% indicates the low emission alternative is more expensive than the incumbent high carbon product. Applying carbon pricing, such as through ACCUs can lower green premiums.

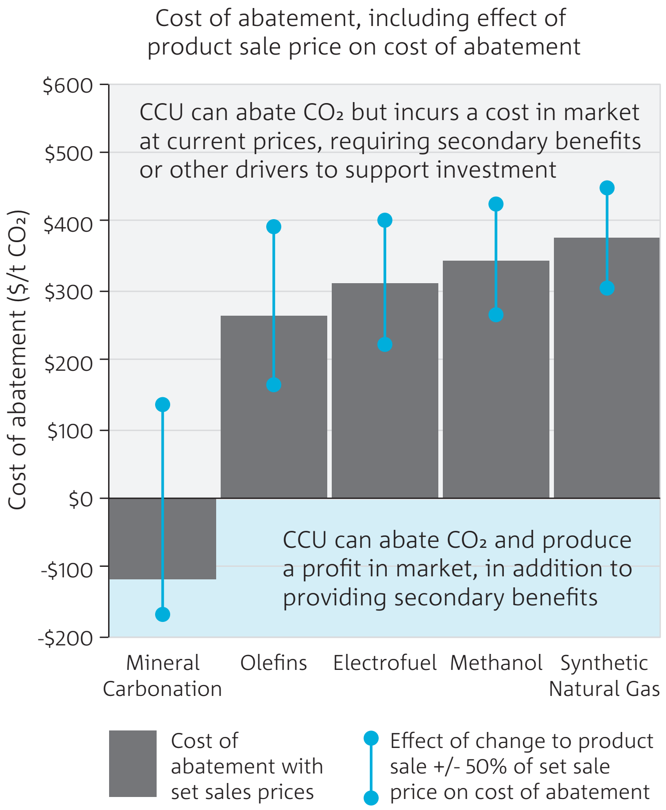


Figure 44: Effect of changing product sale prices on cost of abatement of CCU applications

Cost of abatement calculates how much each tonne of CO_2 costs to avoid. The diagram examines each CCU application's best case, where 5,000t/day of CO_2 is consumed, with the products sold at a set market price. The cost of abatement factors in the costs associated with green premiums. Even if a green premium exists, it may still be the cheapest way for an organisation to decarbonise.

247 Van Leeuwen H (2021) *European Parliament backs carbon border tax*. Viewed 27 January 2021, https://www.afr.com/policy/energy-and-climate/european-parliament-backs-carbon-border-tax-20210311-p579o9

Green premiums can be reduced by driving down the cost of CCU production, rising costs of carbon intensive incumbents, or a combination of both.

EXAMPLE DRIVERS TO REDUCE PRICE OF LOW-CARBON CCU PRODUCTS
• **Continuous improvement and process integration**. R&D will continue to lower costs through improved processes and more durable lower-cost materials. • **Breakthrough technologies.** Lower TRL technological breakthroughs could change processes entirely by removing energy intensive process steps alltogether. • **Utilise existing infrastructure.** Selecting established industrial hubs for CCU scale-up can enable asset sharing.

EXAMPLE DRIVERS THAT CAN INCREASE PRICE OF CARBON INTENSIVE INCUMBENTS
• **Increased market prices.** Upwards movement in incumbent product prices will reduce green premiums. • **Carbon penalties or incentives.** This includes carbon taxes, carbon credits and border taxes, a concept that is gaining traction with recent plans from European Parliament to consider the GHG emissions on imports[247] • **Increases in electrification and fuel switching.** Renewable technology adoption could impact petrochemical refinery margins and costs. • **Geopolitics and supply chain disruptions.** Trade routes are susceptible to disruption due to changes in geopolitics and black swan events.

With a minimised green premium, incentives can help to bridge the final gap. Some incentives already exist, brought on by a social drive for change, and organisational goals to achieve net zero targets. In many cases, to achieve these targets, extra costs will need to be absorbed by industry. To do so, emitters will seek the most cost-effective method to achieve the goals they have set out, aiming for the lowest cost of abatement available.

- The products to the left have the lowest cost of abatement and from an emitter's perspective are likely to be pursued first. A negative cost of abatement results in a profit from abatement. For comparison, cost estimates for CCS range from $35–249/tonne of CO_2 avoided, depending on the CO_2 source.[248]
- Similar to green premiums, changes in market price will influence the cost of abatement or can create a new revenue stream. As seen in the chart below, as sale prices increase, more costs can be offset with a higher revenue. Therefore, as prices increase, the cost of abatement will be reduced.

The cost of abatement calculations in this report do not take into consideration the broader value proposition beyond managing CO_2 liabilities, risks and the co-benefits of CCU products. For example, mineral carbonation can in some cases permanently store CO_2 in contrast to other applications and also aid in neutralising mine waste. Further, synthetic fuels burn more efficiently and with fewer contaminants.[249]

Where the above mechanisms and incentives fail to promote the adoption of various CCU options, there are a broad range of international industry and policy frameworks that can assist with creating incentive and minimising barriers to entry.

- **Tax credits and incentives could help companies bridge the premium gap.** This includes programs where credits given to producers of low-carbon fuel products could support the scale-up of synthetic fuels. These credit systems can offset production costs and deliver environmental benefits, while ensuring increasing demand for low emissions fuels. The California low carbon fuel standard (LCFS) is an example of such a scheme.
- **Settling on CCU related carbon intensity accreditation and guarantees can help verify and reward low carbon investments**. This could include tiers for the level of carbon emissions reduced. They will also be critical for shifting from existing CO_2 supplies to emerging sources of CO_2, which have varying degrees of emission intensity, such as DAC and point source capture.
- **Quotas to guarantee offtake of CO_2-based products.** Blending mandates and public procurement could serve to guarantee the offtake of CO_2-based products. Such guarantees could provide industry greater confidence to invest in CO_2 capture and manufacturing facilities to meet this demand. The Honolulu resolution to consider CO_2 mineralisation is an example of such a scheme to encourage the use of CO_2 where favourable.
- **Mandating lower carbon emission intensities of products.** The obligation to meet higher standards for carbon emission intensities in products such as fuels and building materials could encourage the uptake of CCU technologies to reduce overall emissions intensity.

248 Irlam L (2017) *Global costs of carbon capture and storage.* Global CCS Institute
249 Argonne National Labs (2012) *Life Cycle Analysis of Alternative Aviation Fuels in GREET*. US DOE

- **Commercial mechanisms to demonstrate and scale technologies.** Demonstration and scale-up of emerging technologies is both cost- and time-intensive, particularly for start-up companies who face barriers to securing capital. Government and industry initiatives to connect emitters with offtakers may be a mechanism to improve demonstration pathways and ignite new projects. This is particularly important in CO_2 commercialisation projects, where finding synergies between emitters and offtakers of CO_2 can significantly impact project economics. If such initiatives are to be effective, there should be consideration of which types of project can best match emitters to offtakers. Mechanisms to streamline the process to commercialisation can also benefit from collaborative demonstration sites. UK energy company Drax Group has developed an incubation area for technology demonstration.

Base Study: Drax Group CCUS incubation area[250,251,252]

Energy company Drax Group has established a CCU incubation area within their power station site to support the development of new technologies which make use of CO_2. Partner companies can test and demonstrate their CCU technologies using CO_2 flue gas streams generated at Drax's power plant, allowing the demonstration of processes in industrial conditions. Companies including Deep Branch and Econic Polymers are currently operating in the incubation sites, using CO_2 to produce animal feed protein and synthesis polyurethane plastic, respectively. Building on the Deep Branch technology, a consortium of technology demonstrators, agri-food businesses and food retailers have come together to translate this technology to produce higher-value protein products.

9.4 Use CCU to support or de-risk investment in existing and planned infrastructure

All CCU applications require infrastructure to capture, distribute and utilise CO_2, as well as substantial quantities of renewable energy to carry out each of these processes. Further, where CO_2 is converted into chemicals and fuels, large quantities of hydrogen will be required. Therefore, the most efficient deployment of CCU technologies will be at sites where it can leverage infrastructure that already exists or is planned for construction. CCU deployment should consider how CCU can add value to industrial and energy hubs and de-risk investment.

CCU can be an offtaker to support the deployment of hydrogen and other industrial hubs, de-risking investment.

Given CCU is a technology that can take advantage of CO_2 emissions, industrial waste or hydrogen, it can be used to de-risk and/or produce additional return on infrastructure investment. Creating industrial hubs can bring emitters, CO_2 offtakers and hydrogen producers together.

It can also be used to offset some of the costs of CO_2 capture through revenue generated from CCU. In the case of CO_2 conversion to chemicals and fuels, CCU can become a CO_2 and hydrogen offtaker, allowing the creation of a higher value-added product (e.g. methanol, fuels) that could support hydrogen production. In the case of mineral carbonation, CCU can go a step further by supporting investment in mine tailings management infrastructure.

There is an opportunity to align CCU infrastructure with existing national strategies and industry objectives. For example, the use of hydrogen, which is planned to be scaled up as part of the Australian Government's National Hydrogen Strategy. CCU can also play a role in the nation's manufacturing capability, alongside the Modern Manufacturing Strategy, which includes large emitters (such as minerals processing and energy) and low emissions manufacturing pathways.

250 Drax (2021) *New carbon capture technology could help industry and agricultural sector decarbonise.* Viewed 10 June 2021, https://www.drax.com/press_release/new-carbon-capture-technology-help-industry-agricultural-sector-decarbonise/

251 Drax (2021) *Negative emissions pioneer Drax announces new CCUS projects during Energy Minister's visit.* Viewed 10 June 2021, https://www.drax.com/press_release/negative-emissions-pioneer-drax-announces-new-ccus-projects-during-energy-ministers-visit/

252 Drax (2021) *Ground-breaking carbon recycling project launches with £3million Innovate UK funding.* Viewed 10 June 2021, https://www.drax.com/press_release/ground-breaking-carbon-recycling-project-launches-with-3million-innovate-uk-funding/

Methanol hub concept

To reduce the input costs of hydrogen and CO_2, transport and distribution of feedstocks can be minimised by co-locating hydrogen synthesis facilities with production facilities. Co-location of production facilities near existing or planned industrial sources of CO_2 is recommended. DAC offers major potential reductions in transport costs, as they are not location-dependent.

Hubs could also incorporate multiple facilities which make up subsequent steps of a supply chain. For example, CO_2-to-methanol facilities could be co-located with methanol-to-olefins facilities to produce olefins for use in the plastics industry. Additionally, pipelines at hubs, or those which lead to hubs, could be shared by multiple emitters/offtakers to reduce capital and operating costs.

Hydrogen and CCS hubs are beginning to be mapped out and these locations could be examined for CCU demonstration plants. Figure 45 describes a concept for a methanol hub, which makes use of hydrogen and CO_2 capture infrastructure to produce methanol, and subsequently, upgrade methanol to other value-added products.

While CCU will be leveraging infrastructure, it will be important to understand how much renewable energy, land and water will be required.

Hydrogen will be required as a feedstock for many of the products discussed in this report. To produce hydrogen, electrolysers will demand cheap renewable electricity, water supply, and land. For example, for every kilogram of methanol produced, 0.21kg of hydrogen is required.

Given the growing demand for hydrogen across the energy and transport sectors, there may be competition for access to hydrogen for CCU processes. Consideration should be given as to whether it would be more efficient to use hydrogen directly for a given application to achieve an overall CO_2 reduction benefit, rather than converting the hydrogen into a hydrocarbon before being used and re-releasing CO_2. However, CCU can also be seen as a potential offtaker of hydrogen, which creates further demand and supports the industry's growth.

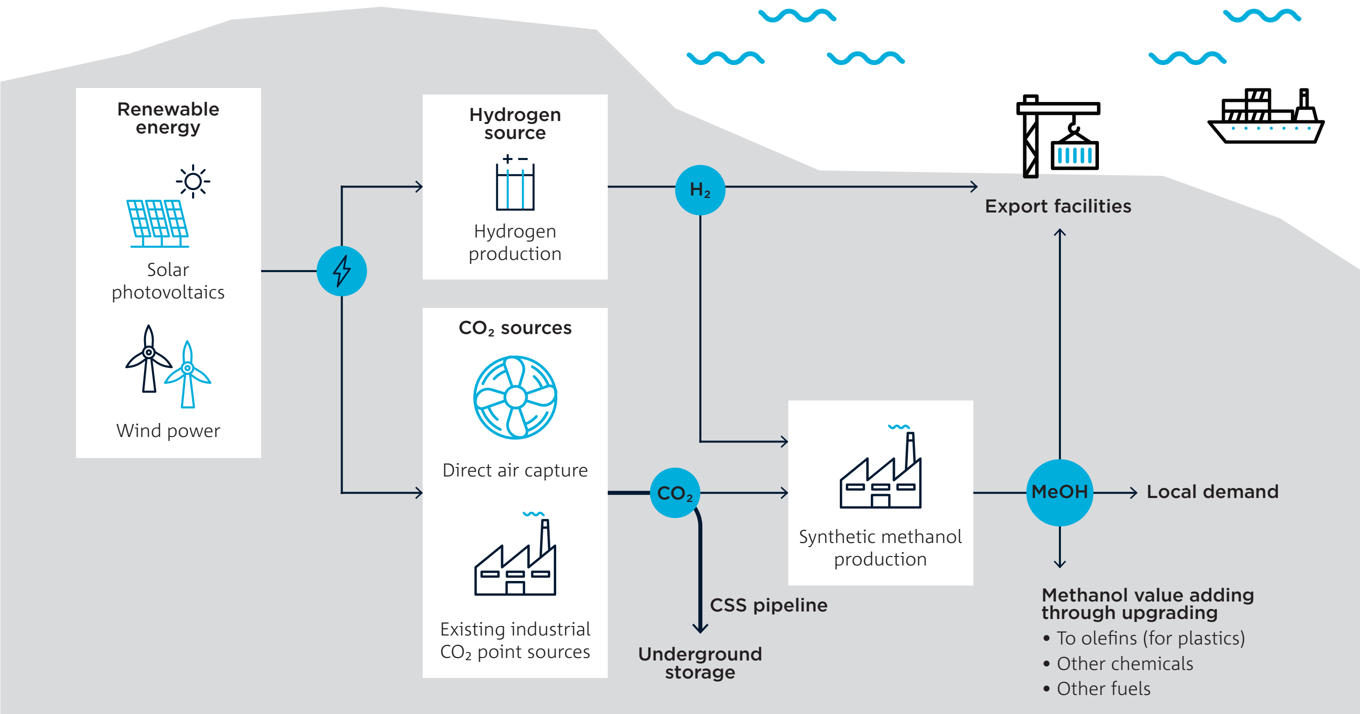


Figure 45: Methanol hub- Scale-up alongside existing/planned infrastructure to complement and de-risk investment

Renewable energy demands are significant. It will be required in large quantities in every application for the chemical conversion of CO_2 itself or for related processes, ranging from CO_2 reduction into hydrocarbons or feedstock grinding for mineral carbonation. To achieve net zero and negative emissions across the applications discussed, large DAC capacities will be required.

There is a balance between the extent that CCU could compete for renewable energy, and the extent to which CCU can support their deployment. There is risk of competition with renewable energy which would be used for electrification or production of hydrogen. In future, it is expected Australia will have vast amounts of low-cost renewable energy which will be available for electrification, hydrogen production, and CCU applications. Renewable technology scale-up will occur as costs continue to decrease; and large-scale adoption will increase as Australia and its industries electrify and hydrogen demand increases. In the next 30 years, it is unclear how much competition there will be for renewable energy.

Land will be needed for all of the infrastructure described, often in remote areas. In particular, renewable energy capacity and DAC systems will need a substantial amount of land.

Example of infrastructure requirements for methanol plant

The table below describes the requirements for a methanol plant operating at a capacity of 3,182 tonnes/day, which consumes 5,000 tonnes of CO_2, obtained from point source industrial emissions. Roughly 5,000MW of solar power is estimated to be required largely to power hydrogen production, with smaller amounts of energy needed for the methanol synthesis facility and CO_2 capture.

For perspective, the Star of the South project could generate up to 2,200MW of offshore wind renewable capacity on Victoria's coast,[253] the proposed Asian Renewable Energy Hub in Western Australia could generate 26,000MW of offshore wind and solar capacity, and the recently proposed Western Green Energy Hub could see the production of up to 50,000MW of hybrid wind and solar power.[254] The 120km^2 land required for 5,000MW solar PV capacity is approximately 3 times the land size of the average Australian farm.[255] Land use requirements depend on the capacity factors of the renewables, which is reflected in the ranges shown in the table below. With Australia's vast land resources, this requirement could potentially be accommodated, with the appropriate land rights and environmental approval.

SCENARIO	HYDROGEN REQUIRED	RENEWABLE ENERGY CAPACITY REQUIRED	LAND USE FACTOR[256]	LAND REQUIRED
Solar PV (high-low capacity)	~670 t/day	4.6–5.2 GW	2.5 ha/MW	112–126 km^2
Wind (high-low capacity)	~670 t/day	3.1–3.7 GW	18.1 ha/MW	549–659 km^2

Land required relates to overall land requirements, however only about 3% of land for wind power will be used for development of turbines and supporting infrastructure.[257] Land use factors vary depending location factors and the factors used are high level estimates only.

253 Star of the South Wind Farm (2020) *Project Overview*. Viewed 11 June 2021, https://www.starofthesouth.com.au/project-overview

254 The Western Green Energy Hub (2021) *Western Green Energy Hub in Australia set to transform global green fuels production in historic partnership with the Mirning People*. Viewed 20 July 2021, https://intercontinentalenergy.com/announcements/WGEH-PressRelease-20210713.pdf

255 Australian Bureau of Statistics (ABS) (2017) *7121.0 – Agricultural Commodities, Australia, 2015–16*. ABS.

256 National Renewable Energy Laboratory (NREL) (2021) *Land Use by System Technology*. Viewed 13 July 2021, https://www.nrel.gov/analysis/tech-size.html

257 LDC Infrastructure (2021) *Australia Wind Power – Wind Turbine Leases Explained*. Viewed 13 July 2021, https://ldcinfrastructure.com.au/wind-energy-lease-explained/

10 Summary of investment priorities

Australia can build on past successes and comparative advantages to position itself as a leader in CCU, but it requires action. CCU has the potential to play a major role in addressing the challenge of a stable and rapid transition while creating commercial outcomes for a low emissions economy. However, CCU must be viewed as part of the puzzle and leveraged in parallel with other solutions.

This report proposes a roadmap to support scale-up of CCU in Australia supported by four actions for Australian industry, government and the research community to consider. As awareness of CCU is nascent in Australia, this report also aims to be the start of a broader conversation about CO_2 utilisation, to expand thinking, guide investment and communicate trade-offs between different CCU applications.

The following tables summarise key investment priorities for each application over the short- to long-term as well as specific policy and regulatory investment priorities that can support scale-up.

Table 14: Investment priorities for CO_2 applications

	IMMEDIATE (2020–2025)	SHORT-MEDIUM (2025–2030)	LONG-TERM (2030–2040)
DIRECT USE (F&A PRIORITISED)			
Food and beverage	• Explore long-term contracts for point source CO_2 emitters • Identify greenhouse/point source co-location candidates • Demonstrate supply at offtaker sites	• Secure long-term contracts for medium partial pressure CO_2 • Demonstrate integrated point source/greenhouse CO_2 flows and heat supply • Blend CO_2 sourced from new technologies into existing sources	• Establish commercial offerings for small scale CO_2 customers, e.g. pubs and restaurants • Demonstrate offerings for small greenhouses • Integrate CO_2 point sources at commercial scale
MINERAL CARBONATION			
Carbonate products	• Demonstrate small scale, technology driven mineral carbonation to inform economic use cases • Inform and establish customer base • Examine scenarios and infrastructure requirements to match source of CO_2 and mineral location	• Establish commercial offerings of mineral carbonation for range of emitters and end users	• Achieve larger scale adoption of carbonate products • Establish industry standard of mineral carbonate aggregates in wide range of mixes
Concrete	• Demonstrate CO_2-curing and aggregates in low risk non-reinforced concrete • Integrate CO_2-derived aggregates into concrete mixes at one or more concrete plant	• Demonstrate CO_2-curing and aggregates in medium risk structural concrete (e.g. houses)	• Establish industry standard of mineral carbonate aggregates and cured concrete in wide range of mixes
CONVERSION OF CO_2 INTO CHEMICALS AND FUELS			
Methanol	• Demonstrate hybrid methanol facility using combination of fossil fuels and renewable H_2	• Establish methanol base case scale facility in industrial hub • Set up methanol feeds into new offtakers	• Achieve operation of best case scale methanol facility • Explore potential for methanol export
Jet fuel	• Conduct feasibility studies for electrofuel production site selection	• Demonstrate blending of electrofuels from fuel plant into fossil fuel supply	• Secure large electrofuel offtakers • Establish best case electrofuel scale facilities to serve airports

	IMMEDIATE (2020–2025)	SHORT-MEDIUM (2025–2030)	LONG-TERM (2030–2040)
Polymers	• Conduct feasibility studies for Methanol-to-olefin (MTO) synthesis plants • Establish potential synthetic olefin customers	• Demonstrate base case MTO plant • Demonstrate integration of CO_2-based polymer feedstocks into existing polymer production plants	• Establish best case scale MTO facilities • Explore potential for synthetic olefin export
SNG	• Demonstrate distributed SNG plants	• Establish SNG base case plant to blend into existing supply	• Establish best case SNG plant
BIOLOGICAL CONVERSION OF CO_2			
Bulk chemicals and fuel products, niche products	• Conduct feasibility studies to understand most economic niche and bulk products • Demonstrate biological systems for converting small quantities of CO_2	• Integrate demonstration bioreactors into existing plants	• Establish commercial offerings of bioreactors for emitters • Scale-up applications based on market demand for products
FEEDSTOCK PRODUCTION			
DAC	• Demonstrate DAC at small scale	• Demonstrate DAC at medium scale • Demonstrate blending of DAC and point source CO_2	• Establish at least one large scale plant
Point sources	• Conduct feasibility studies to assess commercial viability with respect to CO_2 use	• Integrate technology demonstration in most suitable application	• Demonstrate technology in multiple sectors
Hydrogen	• Establish hydrogen production projects at 100–300MW or equivalent[258]	• Establish a clean hydrogen production project at 500–1000MW or equivalent[259]	• Establish multiple GWs of electrolyser capacity

While there is a range of broad initiatives that can support growth in CO_2 applications discussed here, each application has specific policy and regulatory investment priorities that can support scale-up as shown in Table 15.

Table 15: Summary of policy and regulation investment priorities

APPLICATION	POLICY AND REGULATION LEVERS
Direct use	• Carbon footprint labels on food and beverages
Conversion of CO_2 into chemicals and fuels	• Schemes to guarantee origin and verify low emission intensity of fuels and chemicals • Rebates for low emission fuels • Regulatory standards to increase synthetic fuel content and use methanol-derived fuels • Blending mandates or quotas • International collaboration to support scale-up
Mineral carbonation	• Performance based concrete standards • Government procurement targets for low emission building materials • Consideration of CO_2 mineralised product into government tendering processes • Develop emissions intensity standards and ratings which are slowly ramped up over time
Biological conversion	• Regulating developments in genetic engineering and synthetic biology products

258 COAG Energy Council Hydrogen Working Group (2019) *Australia's National Hydrogen Strategy.* COAG Energy Council

259 COAG Energy Council Hydrogen Working Group (2019) *Australia's National Hydrogen Strategy.* COAG Energy Council

Appendices

Appendix A: Stakeholder consultation list

EXTERNAL ORGANISATIONS
ABEL Energy
Advisian
Airbridge
Air Liquide
Alcoa
APA Group
Asahi
Austrade
Australia National University
BASF
BHP
Carbon Capture and Storage Association
CarbonCure
Carbon Engineering
Carbon180
Cemvita Factory
Clean Energy Finance Corporation
CO_2 Value Australia
CO_2 Value Europe
Coogee Chemicals
Department of Industry, Science, Energy and Resources
Drax
Future Fuels Cooperative Research Centre
Government of Victoria
Hazer
Incitec Pivot
Johnson Matthey
J-POWER
KBR
Linde Gas
Mineral Carbonation International
Mitsubishi Corporation
Monash University
Orica
RMIT University
Santos
Supagas
Thyssenkrupp
University of Melbourne
University of Michigan
University of New South Wales
University of Queensland
Wesfarmers Chemicals and Fertilisers
Woodside

CSIRO SUBJECT MATTER EXPERTS
Aaron Cottrell
Allison Hortle
Anna Kaksonen
Chris Vernon
Christian Hornung
Deborah Lau
Dietmar Tourbier
Graeme Puxty
Graeme Moad
Hai Yu
Jim Patel
Jin-Soo Kim
John Tsanaktsidis
Ka Yu Cheng
Kangkang Li
Nawshad Haque
Paul Feron
Paul Graham
Pete Cass
Robbie McNaughton
Sarb Giddey
Xavier Mullet
Yanping Sun
Yen Soo Too

Appendix B: Glossary

ACCUs	Australian carbon credit units represent one tonne of carbon dioxide equivalent (tCO_2-e) stored or avoided by a project, which can be traded for a price.
Aggregates	Granular filling materials such as sand, ground rock and gravel that make up 60–80% of a concrete's volume.
Bbl	Barrels – common measurement for jet fuel that is equal to 42 gallons or 159 litres.
Carbon credits	Tradable certificate or permit representing the right to emit one tonne of carbon dioxide or the equivalent amount of a different greenhouse gas.
Carbon price	A price on carbon that is emitted.
CCS	Carbon capture and storage – CO_2 captured from emissions sources or the atmosphere and stored permanently in geological underground formations.
CCU	Carbon capture and utilisation – The use of CO_2 captured from emissions sources or the atmosphere to make valuable products, or for valuable processes such as waste rehabilitation.
CCUS	Carbon capture, utilisation, and storage – an umbrella term including both CCS and CCU.
CO_2	Carbon dioxide – a greenhouse gas released through human activities.
CO_2-e	Carbon dioxide equivalent – a unit used to describe, for a given quantity of a greenhouse gas, the amount of CO_2 which would have the same global warming impact.
Cost of abatement	Quantifies how much each tonne of CO_2 costs to avoid from conventional products and processes.
CRI	Commercial readiness index.
DAC	Direct air capture.
Demonstration project	A project designed to demonstrate the performance of a technology at small scale in its intended environment and conditions.
Electrofuels	A drop-in fuel produced from hydrogen derived from electrolysis and captured CO_2.
EOR	Enhanced oil recovery
Flue gas	Gas exiting into the atmosphere via a flue, which is a pipe or channel for gas.
Green premium	The additional cost of choosing a product with a low emission profile over one that emits a greater amount of greenhouse gases.
Gt	Gigatonne (1,000,000,000 tonnes).
GW	Gigawatt (1,000,000,000 watts).
Hard-to-abate industries	Heavy industry (cement, steel, chemicals and aluminium) and heavy-duty transport (shipping, trucking and aviation) where emissions are difficult or unavoidable with efficiency improvements and implementation of renewable technology alone.

Industrial hubs	Industrial and manufacturing organisations that are co-located and share infrastructure.
LCA	Lifecycle assessment.
LNG	Liquified natural gas.
MeOH	Abbreviation for methanol.
Mt	Million tonnes (1,000,000 tonnes).
MTO	Methanol-to-olefins – the process of converting methanol to the olefins ethylene and propylene.
MW	Megawatt (1,000,000 watts).
NERA	National Energy Resources Australia.
Partial pressure	The product of total pressure and concentration of a gas stream.
Point source	Stationary locations where CO_2 is emitted.
Polymers	Produced from olefins and other chemicals, polymers are a group of chemicals commonly known as plastics.
RD&D	Research, development & demonstration.
SMR	Steam methane reforming – a process to produce hydrogen from methane.
SNG	Synthetic natural gas.
Syngas	Mixture of gases containing carbon monoxide and hydrogen that can be upgraded to a range of chemicals and fuels.
TRL	Technological readiness level.

Appendix C: Technical modelling appendix

Overarching assumptions

The table below provides a summary of the key economic and model parameters used for the analysis of all CCU applications. It was assumed that each kind of project would run for 30 years, so as to compare each of the technologies on a like-for-like basis. It was also assumed that these projects were funded by 100% debt financing. While unlikely to occur in practice, this was designed to understand the impact of a lower cost of capital that may be accessible for low emission projects.

Cost assumptions used in this report were informed by desktop analysis and project consultations, including consultations conducted for the CSIRO National Hydrogen Roadmap[260] and CSIRO Opportunities for hydrogen in commercial aviation report.[261] They are designed to reflect estimates of the costs that could be achieved for different scale projects at the time of writing. These costs can be expected to reduce as the industry grows in scale.

The electricity prices used were developed with the assumption that a low-cost long-term power purchase agreement (PPA), that includes transmission, could be negotiated given the significant energy offtake requirements (1GW+). This arrangement is similar to large energy users such as smelters, who are able to negotiate low cost electricity offtake agreements given their demand. Given the impact of electricity prices on hydrogen production, and as a result CCU applications in chemicals and fuels, this report has aligned the price assumptions with CSIRO National Hydrogen Roadmap and the Australian Industry Energy Transitions Initiative.[262] Sensitivities of different hydrogen prices have also been included in the analysis to support discussion. Finally, it is acknowledged electricity price modelling varies widely across Australia due to a variety of factors such as weather and geographical location and that the assumptions used do not account for transmission infrastructure upgrades.

5,000 t/day for the best case is based on analysis by the Intergovernmental Panel on Climate Change that profiled worldwide large CO_2 stationary sources emitting more than 0.1Mt CO_2 per year. The average emissions per year for 7,584 point sources was found to be 1.76MtCO_2 per annum, which equates to 4,822t/day. The base case of 1,000 t/day is informed by the best case assumption as a partial treatment for one of those plants. These plant capacities are used throughout the report for capture and conversion technologies for consistency. Increases to plant capacity has a significant effect on reducing carbon capture costs.

VARIABLES	UNIT	BASE CASE	BEST CASE
Gas price	$/GJ	8.00	8.00
Electricity price	c/kWh	6.00	4.00
Water price	$/kl	1.82	1.82
Discount rate[263]	%	7.00	7.00
Interest rate	%	7.00	5.00
Length of loan	Years	20.00	20.00
Plant life	Years	30.00	30.00
CO_2 captured or used	t	1,000	5,000

260 Bruce S, Temminghoff M, Hayward J, Schmidt E, Munnings C, Palfreyman D, Hartley P (2018) National Hydrogen Roadmap. CSIRO, Australia.

261 Bruce S, Temminghoff M, Hayward J, Palfreyman D, Munnings C, Burke N, Creasey S (2020) Opportunities for hydrogen in aviation. CSIRO.

262 Butler C, Maxwell R, Graham P & Hayward J (2021) *Australian Industry Energy Transitions Initiative Phase 1 Technical Report.* ClimateWorks Australia

263 Department of the Prime Minister and Cabinet (2016) Office of Best Practice Regulation. Cost-benefit analysis guidance note. Retrieved from https://www.pmc.gov.au/resource-centre/regulation/cost-benefit-analysis-guidance-note

PEM Electrolyser[264]

For the hydrogen production model, it was assumed that electricity is provided via the grid but with a purchase agreement for electricity from renewable sources. For this reason, the capacity factor for the system is set at 90% at an electricity cost as detailed in the overarching assumptions table. Note that PEM capital costs are direct capital costs, whilst other technologies throughout the appendix refer instead to levelised costs.

VARIABLE	UNIT	BASE CASE	BEST CASE
Capacity factor	%	90	90
Production	kg H_2/day	Case dependent	Case dependent
Direct capital costs	$/kw	546	517
Conversion efficiency	kWh/kg H_2	54	45
Levelised cost of H_2 produced	**$/kg H_2**	**~3.6**	**~2.4**

Point source capture[265]

Point sources are stationary locations where CO_2 is emitted. The main categories of point sources include combustion of fossil fuels for power and heat, industrial production processes that transform materials (such as cement production) and natural gas processing. These point sources can be centralised at facilities to have one emission point or can be distributed throughout a process, resulting in numerous point sources within the one facility.

Sorbent operating costs, and thus levelised capture costs, can be reduced by optimising sorbent selection for specific flue gas/waste stream characteristics. There are a range of other sorbents that could be used such as Purisol, MDEA (methyldiethylamine) and Sulfinol.[266] The sorbent choices made for this analysis, are by no means prescriptive and have been selected in line with data availability.

		LOW PARTIAL PRESSURE		MEDIUM PARTIAL PRESSURE		HIGH PARTIAL PRESSURE	
VARIABLE	UNIT	BASE CASE	BEST CASE	BASE CASE	BEST CASE	BASE CASE	BEST CASE
Plant capacity	t CO_2/day	1,000	5,000	1,000	5,000	1,000	5,000
Sorbent	n/a	MEA	FG+	MEA	FG+	Selexol	Selexol
Capacity factor	%	90	90	90	90	90	90
Capital costs	$/t CO_2	47	21	21	10	39	17
Variable opex	$/t CO_2	63	36	55	41	10	8
Fixed opex	$/t CO_2	15	9	6	3	13	6
Levelised cost of CO_2 capture	**$/t CO_2**	**124**	**67**	**82**	**54**	**66**	**33**

264 Informed by the National Hydrogen Roadmap

265 Carnegie Mellon University, Integrated Environmental Control Model (ICEM)

266 Gale J et al. (2005) *IPCC Special Report on Carbon dioxide Capture and Storage.* Intergovernmental Panel on Climate Change

Direct air capture – high temperature[267]

This model uses CO_2 absorption with potassium hydroxide (KOH) aqueous solution. The CO_2 is absorbed to form potassium carbonate (K_2CO_3). In a pellet reactor, the K_2CO_3 precipitates as calcium carbonate ($CaCO_3$). The $CaCO_3$ is then calcinated at 850°C decomposing into CO_2 and CaO to be collected. Natural gas is the source of heat for decomposition, with the resultant CO_2 absorbed by the system.

VARIABLE	UNIT	BASE CASE	BEST CASE
Plant capacity	t CO_2/day	1,000	5,000
Capacity factor	%	90	90
Sorbent/solvent	Type	KOH	KOH
Capital costs	$/t CO_2	327	83
Operating costs	$/t CO_2	152	128
Heat energy required	(GJ/day)	8,810	44,405
LCOCO₂	**$/t CO_2**	**479**	**210**

Direct air capture – low temperature[268]

This model uses CO_2 absorption with an amine solution. The base case uses MEA, while the best case uses an amine salt. This system has conventional packed towers for absorption and desorption, with a water wash section in the base case to reduce MEA evaporative losses. The temperature in the reboiler was 123°C.

KEY COST DRIVER	UNIT	BASE CASE	BEST CASE
Plant capacity	t CO_2/day	1,000	5,000
Capacity factor	%	90	90
Solvent	Type	MEA	Amino acid salt
Capital costs	$/t CO_2	162	25
Operating costs	$/t CO_2	225	137
Electricity required	MW	60	215
Heat energy required	GJ/day	11,889	59,445
LCOCO₂	**$/t CO_2**	**387**	**162**

Carbonate products – Case 1: Mined raw serpentine is transported by rail to steel or cement plant for carbonation using flue gas.

Mined raw serpentinite being transported by rail to a steel or cement plant for carbonation using operational flue gas. In this scenario, the flue gas does not require treatment or purification, reducing capture costs. The costs of mining the serpentinite are included in the levelised cost.

VARIABLE	UNIT	BASE CASE	BEST CASE
Capacity factor	%	90	90
CO_2 processed	t/day	1,000	5,000
Levelised cost of carbonate product	**$/t**	**74**	**49**
Levelised cost of CO_2 capture	**$/t CO_2**	**535**	**356**
Assumed sales price	$/t		Silica: 40MgCO₃: 100
CO_2 abatement cost	**$/t CO_2**	**61**	**-118**

Carbonate products – Case 2: Mined raw serpentine is carbonated on site, with product transported away. Using CO_2 capture from high partial pressure point source.

Mined raw serpentine is carbonated on site, using CO_2 capture from a high partial pressure point source, with the resultant product transported away from this site. The costs of mining the serpentinite are included in the levelised cost.

VARIABLE	UNIT	BASE CASE	BEST CASE
Capacity factor	%	90	90
CO_2 processed	t/day	1,000	5,000
Levelised cost of carbonate product	**$/t**	**95**	**63**
Levelised cost of CO_2 capture	**$/t CO_2**	**443**	**295**
Assumed sales price	$/t		Silica: 40MgCO₃: 100
CO_2 abatement cost	**$/t CO_2**	**129**	**-19**

267 Keith D, Holmes G, Angelo D, & Heidel K (2018) *A Process for Capturing CO2 from the Atmosphere*. Joule

268 Kiani A, Jiang K, Feron P (2020) Techno-Economic Assessment for CO2 Capture From Air Using a Conventional Liquid-Based Absorption Process

Methanol synthesis[269,270]

Methanol synthesis uses direct hydrogenation of CO_2 over a catalyst, with an H_2:CO_2 ratio of 3:1. The reaction occurs between two reactors, with a separation of products occurring between the reactors. The resulting steam undergoes three-stage of distillation to produce a 99.9% pure product. The production of 1 kg of methanol consumes 1.57 kg of CO_2 due to the conversion of some of the oxygen to a water byproduct. Methanol sale price is assumed to be $250/t.

VARIABLE	UNIT	BASE CASE	BEST CASE
Capacity factor	%	94	96
Plant capacity	t MeOH/day	636	3,182
CO_2 required	t/day	1,000	5,000
H_2 required	t/day	132	660
Electrolyser size	MW	330	1,376
Capital costs	$/t MeOH	199	79
Hydrogen cost	$/t MeOH	892	402
CO_2 cost	$/t MeOH	131	55
Operating cost	$/t MeOH	174	109
Levelised cost of MeOH Produced	**$/t MeOH**	**1,396**	**645**
CO_2 abatement cost	**$/t CO_2**	**729**	**344**

Electrofuel synthesis[271,272]

The production of electrofuel first uses the methanol-to-olein (MTO) process. However, following the initial synthesis, the olefin is sent to the Mobil olefins-to-gasoline/distillate (MOGD) process. Here the olefins are converted in a fixed bed reactor over a ZSM-5 catalyst. The gasoline/distillate product ratios can range from 0.12 to >100, and the ratio chosen in this model was 0.12 to maximize the production of distillate. Jet fuel sale price is assumed to be $85/bbl.

The consumption of H_2 and CO_2 in the below table is for methanol production.

VARIABLE	UNIT	BASE CASE	BEST CASE
Capacity factor	%	90	92
Plant capacity	bbl/day	1,179	5,897
CO_2 required	t/day	1,000	5,000
H_2 required	t/day	132	660
Electrolyser size	MW	330	1,376
Capital costs	$/bbl	4.9	2.5
Methanol	$/bbl	116.4	58.5
Hydrogen cost (For MeOH synthesis)	$/bbl	278.4	154.1
CO_2 cost (For MeOH synthesis)	$/bbl	40.8	21.2
Other variables	$/bbl	3.5	1
Fixed O&M	$/bbl	1.6	1
Levelised cost of SynJet Produced	**$/bbl**	**463**	**244**
CO_2 abatement cost	**$/t CO_2**	**736**	**310**

269 Anicic B et al. (2014) Comparison between two methods of methanol production from carbon dioxide
270 Towler G, Sinnott R (2013) *Chemical Engineering Design, Second Edition*
271 Baliban et al. (2013) Biomass and Natural Gas to Liquid Transportation Fuels: Process Synthesis, Global Optimization, and Topology Analysis
272 Bruce et al. (2020) Opportunities for hydrogen in commercial aviation

Olefin synthesis[273]

Modelling for olefin production uses the Methanol to Olefins (MTO) process. First, the reaction occurs in a heated reactor at 400°C and 1.2 bar, with 100% of the MeOH converted. Then, the product stream is fractionated, with paraffins returned to the reactor and the higher-order gasoline cracked to olefins.

The consumption of H2 and CO_2 in the below table is for methanol production and not consumed in the actual MTO process. Olefin sale price is assumed to be $1,000/t.

VARIABLE	UNIT	BASE CASE	BEST CASE
Capacity factor	%	94	96
Plant capacity	t Olefins/ day	211	1,264
CO_2 required	t/day	1,000	5,000
H_2 required	t/day	132	660
Electrolyser size	MW	330	1,376
Capital costs	$/t Olefins	186	112
Methanol cost	$/t Olefins	1126	472
Hydrogen cost (For MeOH synthesis)	$/t Olefins	2,693	1,244
CO_2 cost (For MeOH synthesis)	$/t Olefins	395	171
Opex	$/t Olefins	78	56
Levelised cost of Olefins Produced	**$/t Olefins**	**4,478**	**2,055**
CO_2 abatement cost	**$/t CO_2**	**734**	**266**

Synthetic natural gas[274]

Synthetic natural gas (SNG) is produced by hydrogenation of CO_2 by H_2, with an H_2:CO_2 ratio of 4:1. As the reaction is exothermic, but low temperature promotes methanation, the process occurs over a series of reactors, with coolers between each. The conversion efficiency is 99%. SNG sale price is assumed to be $8/GJ.

VARIABLE	UNIT	BASE CASE	BEST CASE
Capacity factor	%	90	92
Plant capacity	t SNG/day (GJ/day)	360 (~18,000)	1,800 (~90,000)
H_2 required	t/day	183	916
Electrolyser size	MW	458	1,901
Capital costs	$/GJ SNG	2.8	1.4
Hydrogen cost	$/GJ SNG	43.5	24.0
CO_2 cost	$/GJ SNG	3.7	1.8
Fixed O&M	$/GJ SNG	2.6	1.6
Levelised cost of SNG Produced	**$/GJ SNG**	**58.5**	**34.6**
CO_2 abatement cost	**$/t CO_2**	**802**	**375**

273 Hannula I, Arpiainen V (2014) *Light olefins and transport fuels from biomass residues via synthetic methanol: performance and cost analysis*

274 Gutierrez-Martin F, Rodriguez-Anton LM (2016) Power-to-SNG technology for energy storage at large scales

Appendix D: Abatement potential

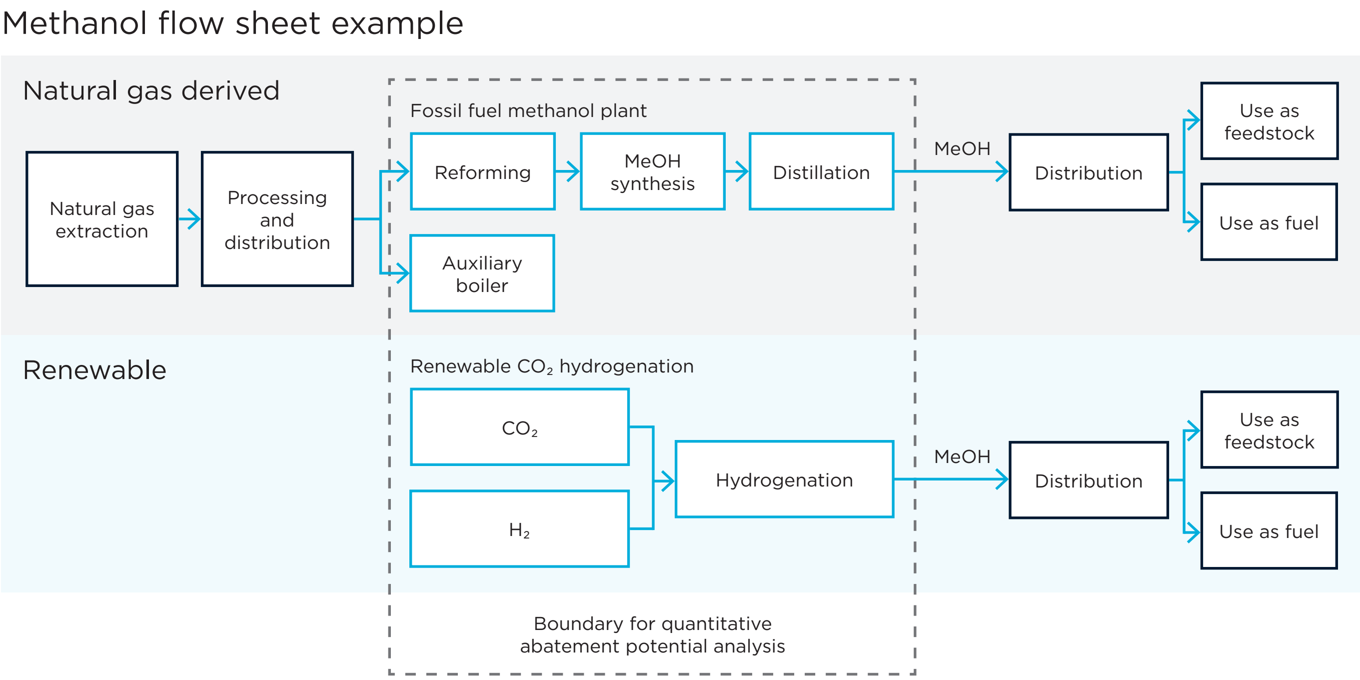
To support a discussion on CO_2 abatement potential from CCU applications, qualitative and quantitative analysis has been conducted.

Qualitative analysis has been provided to examine lifecycle emissions given the breadth of applications and the complexity of the analysis involved. A key recommendation of this report is greater lifecycle assessment studies are required.

Quantitative analysis is based on production emissions as a boundary condition. While limited, this allows direct comparison of CO_2 abatement potential across the various CCU applications discussed in this report.

The quantitative analysis considers production emissions, CO_2 consumed in each production process and the CO_2 source, as well as the CO_2 emissions avoided from not using fossil fuels processes, to calculate a theoretical net CO_2 abatement potential. This theoretical net CO_2 abatement potential is calculated per tonne of product to allow for comparison across the CCU applications. It is important to note that the conversion of CO_2 to chemicals and fuels leads to a larger quantity of CO_2 abated per tonne of a given product as some of the oxygen reacts with hydrogen to form water.

An example of this production boundary can be seen by comparing the production of methanol from natural gas to the production of methanol from renewable CO_2 hydrogenation (see Figure 46 for methanol flow sheet and abatement calculation example).



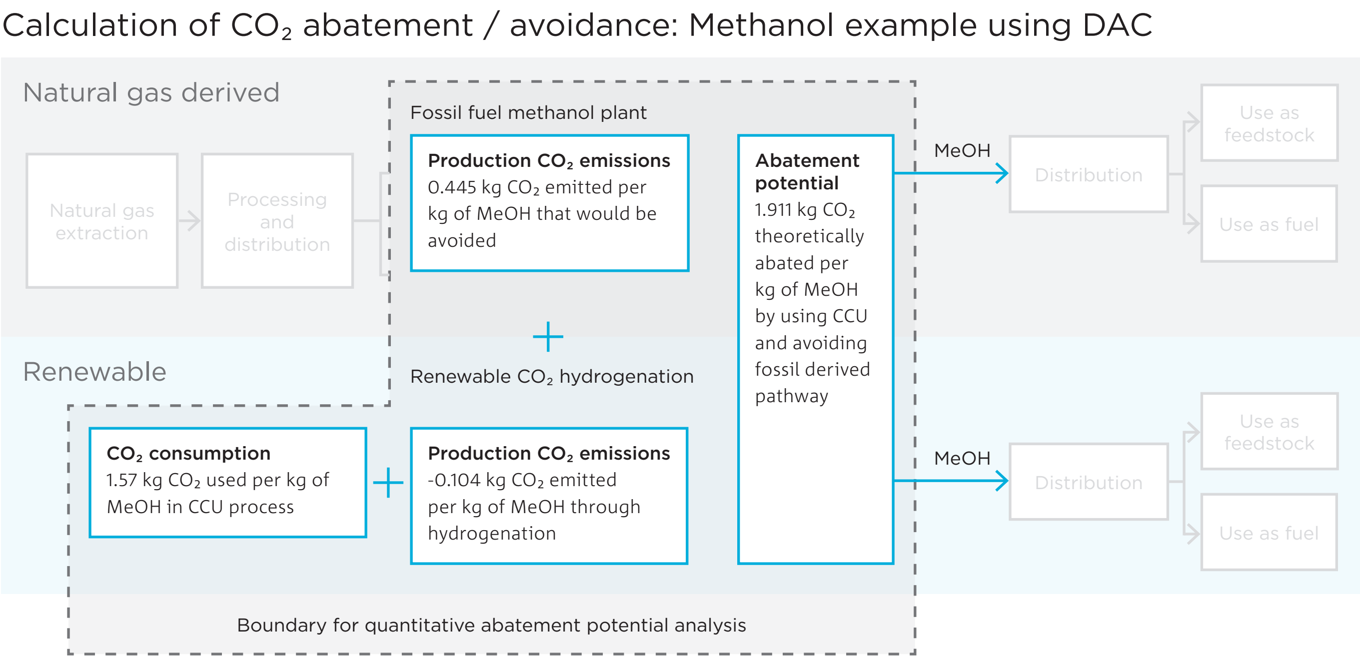


Figure 46: Abatement potential calculation comparison between natural gas and renewable derived methanol

Methanol flow sheet example

Calculation of CO_2 abatement / avoidance: Methanol example using DAC

The CO_2 source varies the abatement potential and is distinct for CCU applications that release CO_2 on use (such as a fuel) compared to those that have the potential to lock in CO_2 permanently (such as most mineral carbonation applications). It is important to stress that these abatement potentials are theoretical, further demonstrating the need for lifecycle assessments to be conducted for each application and CO_2 pathway. The differences are noted in the respective CCU application chapters and a simplified example is provided below.

Abatement potential for applications where duration of CO_2 storage is long-term

Some CCU applications can store CO_2 away for decades, such as some high value polymers, or permanently in the case of most mineral carbonation applications. Regardless of where the CO_2 is sourced (point source vs DAC) for long-term storage applications, the CO_2 is not re-released when the product is used. This ability to lock away CO_2 can result in carbon neutrality when CO_2 is from a point source or negative emissions when CO_2 is captured from the atmosphere using DAC.

Abatement potential for applications where duration of CO_2 storage is short

To simplify the analysis, a theoretical 100% abatement potential is considered for CCU applications where CO_2 is derived from DAC and a theoretical 50% abatement has been considered for CCU applications where CO_2 is sourced from a point source. The theoretical 50% abatement potential is based on analysis by Science Advice for Policy by European Academies which has different carbon flow use cases with and without CCU and considers different sources of CO_2.[275] A simplified example can be seen when considering CCU to produce fuels, as outlined below.

Example without CCU: In a system without CCU, the carbon flows from the ground (extraction of fossil fuels) to the atmosphere for a specific industrial user such as a cement plant. Additional carbon would flow from the ground (extraction of fossil fuels) to the atmosphere when a fuel is used / combusted.

Example with CCU using CO_2 from a point source: In a system with CCU using CO_2 from a point source, the carbon flows from the ground to an industrial user, and that CO_2 is captured and used again for the production of a fuel where the carbon eventually going into the atmosphere when the fuel is combusted / used. Although there is a reduction in the total amount of CO_2 theoretically entering the atmosphere, the fuel derived from CCU cannot be considered neutral.

Example with CCU using CO_2 from DAC: In a system with CCU where the CO_2 is captured from the atmosphere via DAC, the carbon flows from the atmosphere to an industrial user, and that CO_2 is captured and used again for the production of a fuel with the carbon eventually entering the atmosphere when the fuel is combusted / used. This theoretically creates a closed loop for the CO_2 and as such the fuel produced can theoretically be classified as neutral.

275 1. SAPEA, Science Advice for Policy by European Academies (2018*) Novel carbon capture and utilisation technologies: research and climate aspects*

Appendix E: CO_2 capture technologies

Point source capture

Current mature technologies and their preferred users are listed out in the table below. Within each category of technologies are a range of sorbent types produced commercially by vendors.

CO_2 CAPTURE TECHNOLOGY	DESCRIPTION	PREFERRED USER	TRL	COMMENTS
Absorption	A gas stream is contacted with a liquid absorbent (solvent), absorbing CO_2 either physically or chemically depending on the solution. Heat and/or pressure are then applied to release CO_2 and the absorbent is recycled in the system.	Process streams, post and pre-combustion capture. Well-suited for post-combustion.	9[276]	Chemical: Amines Physical: Organic molecules
Adsorption	Involves the intermolecular forces between the CO_2 and the surface of the adsorbent, resulting in CO_2 adhering to the surface. Heat, electricity or pressure is then applied to release CO_2.	Can reduce energy and cost of CO_2 capture in post-combustion. Low adsorption capacities in flue gas conditions.	6[277]	Chemical: Metal oxides, hydrotalcites, metal salts. Physical: Zeolites, Metal organic frameworks, activated carbon.
Membrane	Selective membranes enable separation of substances through various mechanisms such as diffusion, molecular sieve and ionic transport.	Process streams – flue gas (post-combustion), natural gas processing, hydrogen (pre-combustion), or oxygen from nitrogen (oxyfuel combustion).	6[278]	Requires high energy for post-combustion CO_2 capture. Efficient for high CO_2 concentration gas streams.

Direct air capture

TECHNOLOGY	DESCRIPTION	TRL	COMMENTS
Solution-based absorption and electrodialysis (no heat)	Air is drawn in and CO_2 is absorbed using a sodium hydroxide (NaOH) solution. The resulting sodium carbonate (Na_2CO_3) solution is then acidified using sulfuric acid (H_2SO_4), releasing almost pure CO_2. The NaOH and H_2SO_4 are then regenerated through electrodialysis to be used again.	5	Only requires electricity, no thermal energy needed.
Solution-based absorption and calcination (high temp)	CO_2 is absorbed using either a NaOH or potassium hydroxide (KOH) aqueous solution. In the case of KOH, the CO_2 is absorbed to form potassium carbonate (K_2CO_3). In a pellet reactor, the K_2CO_3 is precipitated into calcium carbonate ($CaCO_3$). The $CaCO_3$ is then calcinated at 850°C decomposing into CO_2 and CaO to be collected.	6–8	*Active: Carbon engineering* Combustion of natural gas is needed to produce the required temperatures for calcination. However, the CO_2 generated is then captured as part of the overall process. Natural gas could be displaced by burning pure hydrogen, using concentrated solar power or electrification via renewable electricity.
Solid-based adsorption and desorption (low temp)	Two variations of this technology are commercially available. The first, (Climeworks) fans ambient air over amine compounds bound to dry porous granulates as a filter material. Once the material is fully enriched with CO_2, it is regenerated (i.e. the CO_2 is removed) by applying a combination of pressure and temperature swing (~100°C). Global Thermostat has a different structure of amines and regenerates these materials using low-temperature steam.	6–9	*Active: Climeworks, Global Thermostat* The low thermal requirement can be met by waste heat.

276 Bui M et al. (2018) *Carbon capture and storage (CCS): the way forward.* Energy & Environmental Science

277 Cousins A et al. (2019) *Further assessment of emerging CO2 capture technologies for the power sector and their potential to reduce cost*. CSIRO

278 Cousins A et al. (2019) *Further assessment of emerging CO2 capture technologies for the power sector and their potential to reduce cost*. CSIRO

Appendix F: Technical details of CO_2 utilisation pathways for polymers

Ethylene and propylene synthesis from CO_2. The pre-polymers ethylene and propylene can be synthesised from methanol, via a route known as the methanol-to-olefins (MTO process). Existing MTO plants, which operate at scales between 0.2–0.8MM t/year, make use of fossil-fuel derived syngas to produce the methanol feedstock.[279] However, the methanol could instead be produced from CO_2 and hydrogen, then fed into an MTO plant to produce the ethylene and propylene. CO_2 can also be converted into plastic precursors via conversion to syngas and subsequent petrochemical processing.

Aromatics (benzene, xylene and toluene) synthesis from CO_2. Among their many other uses, these chemicals can be used as feedstocks for various polymers. For example, benzene is a major input to make polystyrene, and xylene is an important precursor for PET plastic. The University of Toyama, Chiyoda Corporation, Nippon Steel Engineering Co., Ltd., Nippon Steel Corporation, HighChem Company Limited, and Mitsubishi Corporation have collectively announced plans to produce xylene from CO_2 and hydrogen, which will be used to make PET for clothing and plastic bottles.[280]

Addition of CO_2 in the synthesis of polyols and polycarbonates. CO_2 is combined with an epoxide to produce polycarbonates or polyols, depending on the catalyst, and reaction conditions applied. Polyols are key building blocks for polyurethane. Germany-based company, Covestro are producing a polyol plastic made up of 20 per cent carbon dioxide.[281] The plastic can be used in mattresses, clothing, insulation boards, and other applications. Their plant has a capacity of 5,000 tonnes of polycarbonates per year.[282] UK-based Econic claims their technology can produce polymers with up to 50% CO_2 by weight.[283] It is estimated that utilising CO_2 to produce CO_2-polyols can result in avoiding up to 3 kg of CO_2 emissions per 1kg of polyol produced, compared to traditional production from fossil fuels alone.[284]

Biological polymer synthesis. Biological systems convert CO_2 into polymers or polymer precursors. Biological polymer synthesis is described in Chapter 6.

279 Gogate M.R (2019) *Methanol-to-olefins process technology: current status and future prospects*. Petroleum Science and Technology

280 Mitsubishi Corporation (2020) *Initiation of "Technology Development for Para-xylene Production from CO2"*. Viewed 3 May 2021, https://www.mitsubishicorp.com/jp/en/pr/archive/2020/files/0000045682_file1.pdf

281 Cormier Z (n.d.) *Turning carbon emissions into plastic*. Viewed 3 May 2021, https://www.bbcearth.com/blog/?article=turning-carbon-emissions-into-plastic

282 Covestro A.G (n.d.) *CO_2 as a new raw material – becoming a jack of all trades*. Viewed 3 May 2021, https://www.covestro.com/en/sustainability/lighthouse-projects/co2-dreams

283 Econic Technologies (2017) *How it works*. Viewed 3 May 2021, https://econic-technologies.com/how-it-works/

284 Von der Assen N & Bardow A (2014) *Life cycle assessment of polyols for polyurethane production using CO2 as feedstock: insights from an industrial case study*. Royal Society of Chemistry

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