Australia's National Science Agency

CO_2 Utilisation Roadmap

Executive summary

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The project team would like to thank the project Sponsors and Supporters as well as the Steering Committee for providing support, guidance and oversight throughout the report's development. Special thank you to our colleagues at CSIRO who provided invaluable contributions to the report: Andrew Ross, Matthew Ironside, Paul Feron, Jenny Hayward and Paul Graham.

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 of the full report.

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

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.

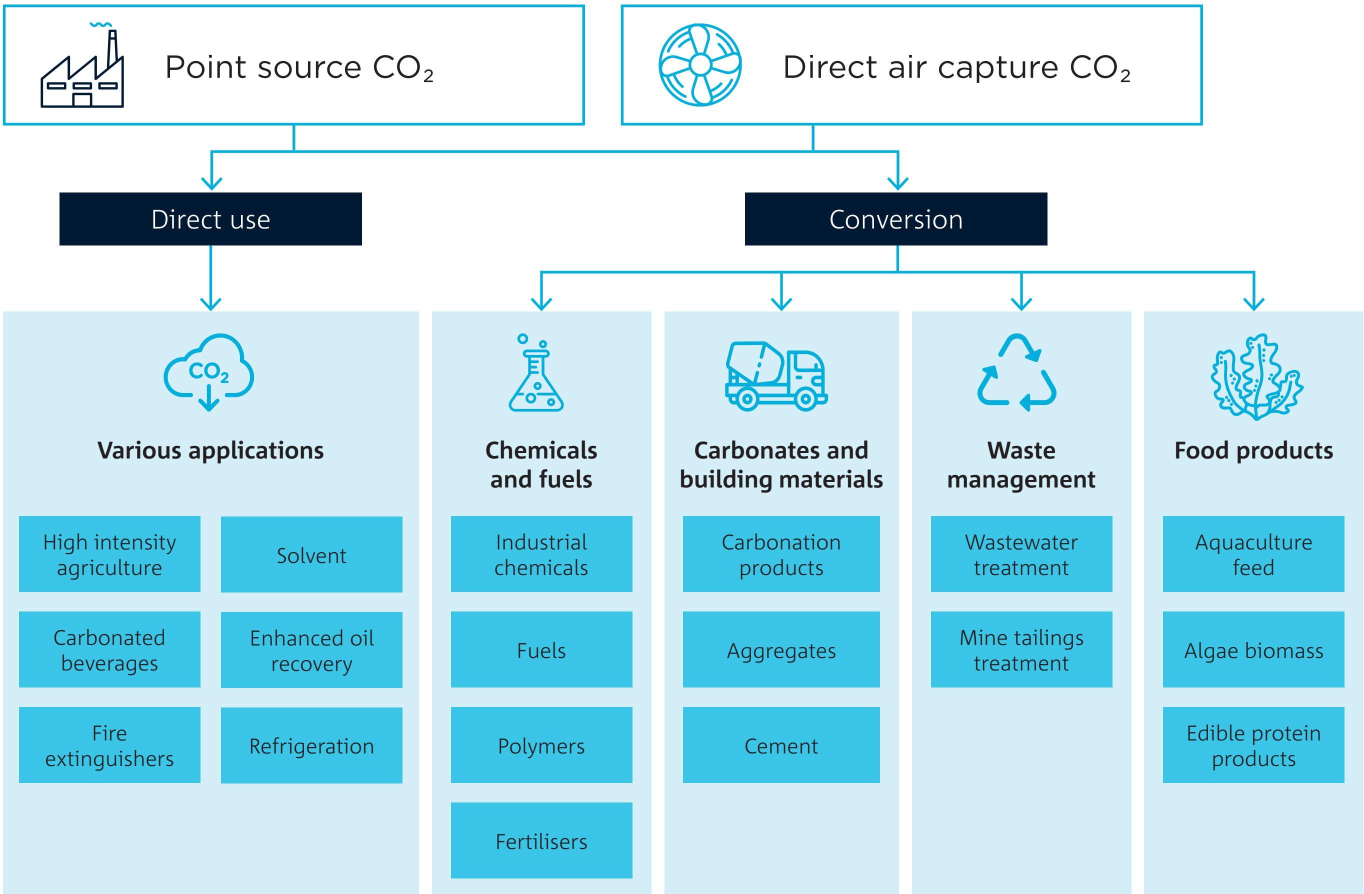
3 Australian Government Department of Industry, Science, Energy and Resources (DISER) (2021) *National Inventory Report Volume 1*. DISER

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.

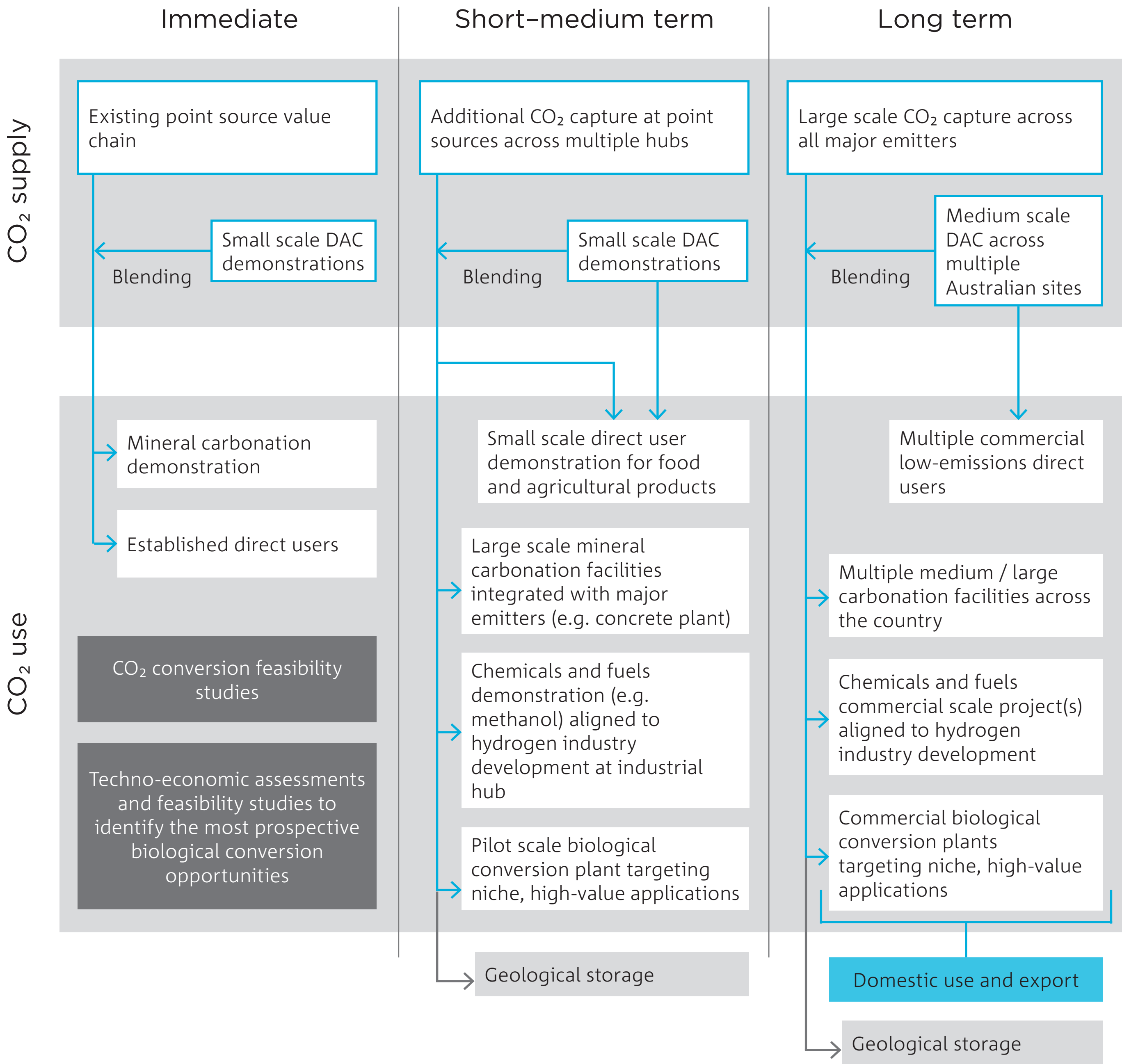
This report focuses on opportunities for the creation of methanol, electrofuel (synthetic jet fuel), olefins (for use in the plastics industry) and synthetic natural gas. These chemicals and fuels require a readily available source of hydrogen and low emissions energy, which can be closely aligned with 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 CO₂ capture at point sources across multiple hubs
Small scale DAC demonstrations
Blending
Large scale CO₂ capture across all major emitters
Medium scale DAC across multiple Australian sites
Blending
Mineral carbonation demonstration
Established direct users
CO₂ 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
	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)

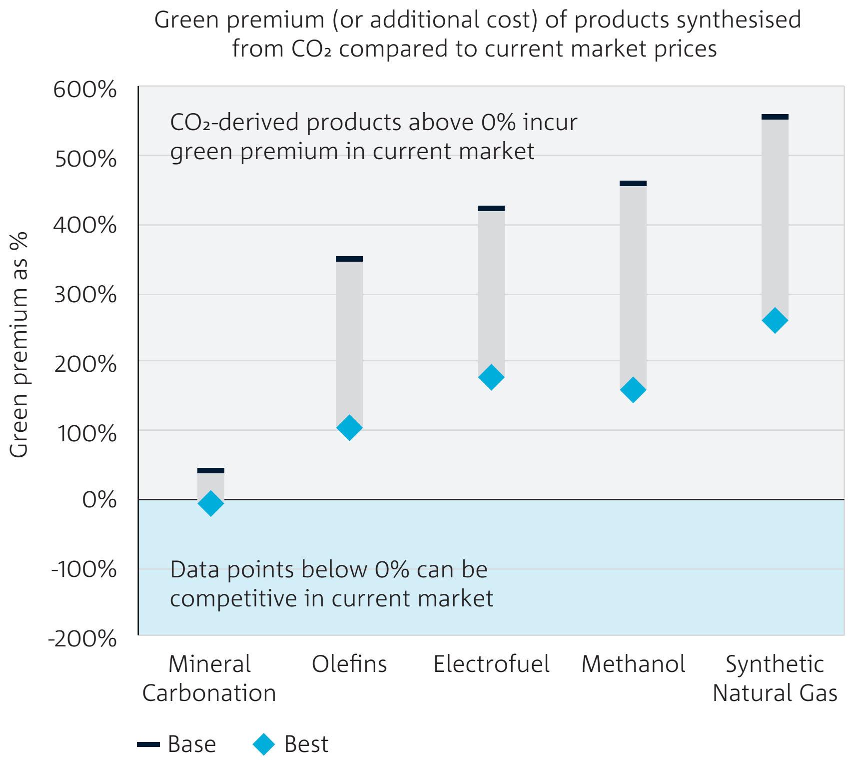
The scenarios developed are illustrative and explore the percent of hard-to-abate emissions that different levels of CCU adoption could achieve per annum. The definition of 'hard-to-abate' industries varies but for the purpose of this report it refers to the following categories in the Australian Government's 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

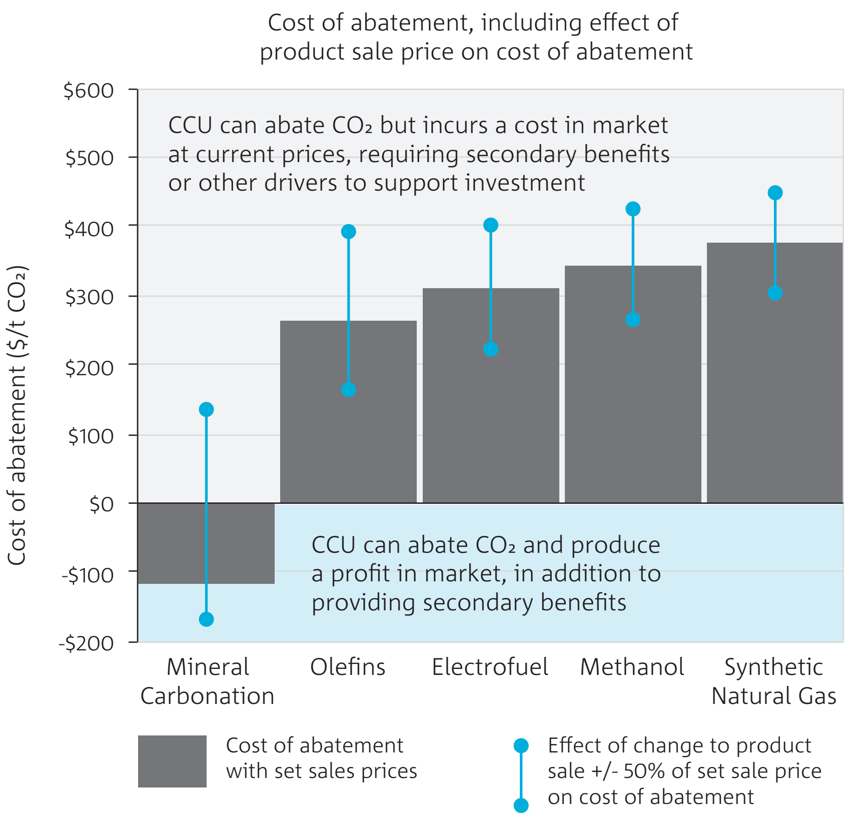
This diagram shows the green premium for each CCU application modelled. For each application, base and best case results are shown. The base case result is assessed on mature technologies available today, with the best case considering projects currently in development and projections for technology 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

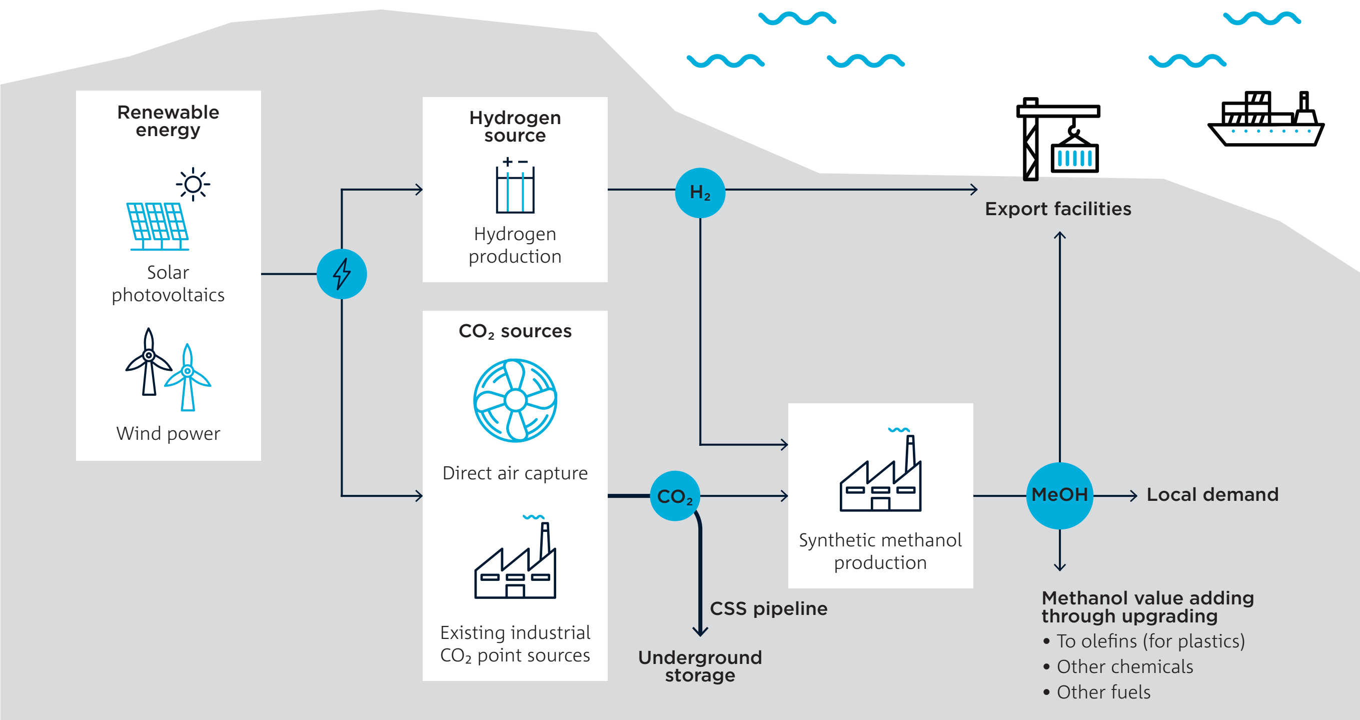
4 Use CCU to support or de-risk investment in existing and planned infrastructure

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 120km^2 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 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 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

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