Australia's National Science Agency

# The State of Energy Transition Technologies

# Carbon Management

TECHNICAL APPENDIX

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**Citation and authorship**

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**Acknowledgement**

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# 1 Executive summary

## Carbon management

Effective carbon management is needed to support the decarbonisation of hard to abate industries, reduce Australia's emissions and reach net-zero targets by 2050.

### Challenge

Carbon management will play a critical role in sectors that are not straightforward to decarbonise with renewable energy technologies. These sectors are typically described as 'hard-to-abate' as they often rely on carbon from fossil fuels as building blocks for products (e.g. steel, chemicals, plastics), require high energy density fuels for long-distance transport (e.g. long-haul aviation), or produce emissions inherently in their processes (e.g. cement production).

Beyond this, carbon management will be needed to counterbalance residual emissions in the atmosphere and to achieve and sustain net negative emissions, which will be critical to stabilising the global climate. While achieving significant emissions reductions is first and foremost essential, durable carbon removals will be critical to meeting the goals of the Paris Agreement to limit warming to below 2°C.

### Scope of analysis

Technologies discussed in this report have not been filtered using *The State of Energy Transition Technologies* methodology. As a result, this report is not an exhaustive discussion of all carbon management technologies and more detailed discussion can be found in *CSIRO's $CO_2$ Utilisation Roadmap (2021)*[1] and *CSIRO's Australian CDR Roadmap (2025)*[2]. This analysis highlights RD&D opportunities that could support the scale-up, de-risking, and deployment of carbon management technologies:

- **$CO_2$ capture** explores high-level RD&D opportunities across point source capture and direct air capture (DAC) technologies.
- **$CO_2$ storage** and **$CO_2$ utilisation** summarise RD&D opportunities identified in *CSIRO's $CO_2$ Utilisation Roadmap (2021)* and *CSIRO's Australian CDR Roadmap (2025)*.

[1] Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) $CO_2$ Utilisation Roadmap. CSIRO.

[2] CSIRO (2025) Australian Carbon Dioxide Removal Roadmap. CSIRO, Canberra.

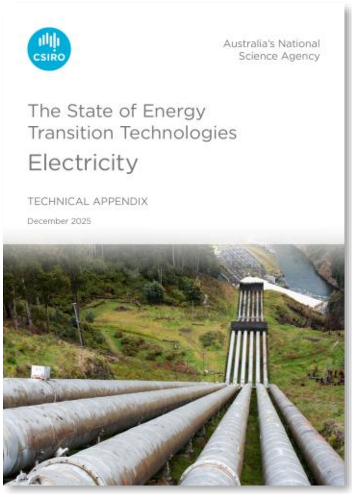
# 2 Carbon management overview

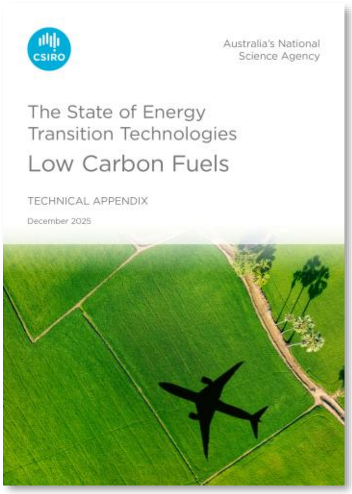
Research, development and demonstration (RD&D) will be pivotal in informing and driving the change required to achieve the energy transition and Australia’s net zero ambitions. However, with limited resources and a broad array of emerging low emissions technologies, Australia faces the important task of strategically and collaboratively optimising its RD&D efforts to maximise national benefit.

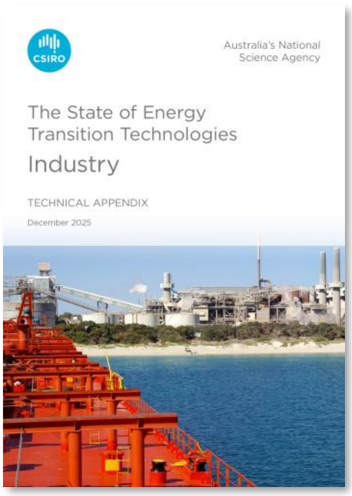
This study, *The State of Energy Transition Technologies*, highlights RD&D opportunities that could support the scale-up, de-risking, and deployment of low emissions technologies, advancing Australia’s decarbonisation efforts. It is not intended to prescribe research strategies for Australia or any individual organisation. Rather, it serves as a resource to support constructive dialogue and help navigate the energy transition by leveraging the nation’s RD&D strengths.

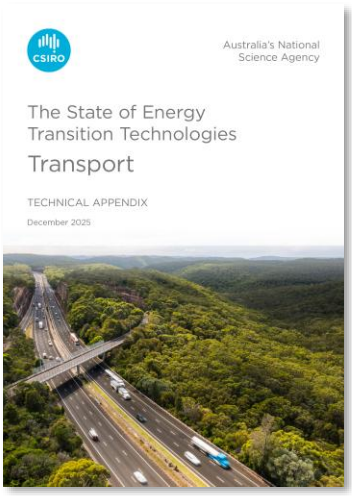
## 2.1 This report

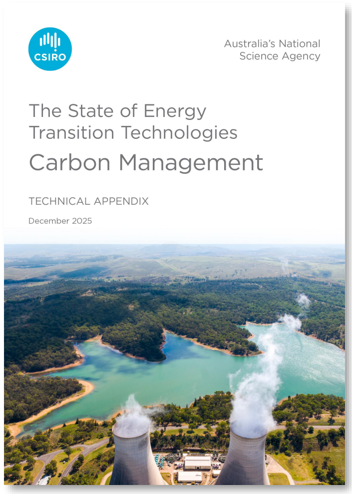
The *State of Energy Transition Technologies* consists of a Synthesis report and five technical appendices spanning a range of Australian energy supply and demand related sectors. This report, focused on carbon management, is to be considered alongside the other appendices and primarily explores RD&D opportunities associated with the $CO_2$ capture technologies identified in other subsectors.



## 2.2 Australia's carbon management needs

Greenhouse gases (GHGs) emitted as a result of human activities are continuing to accumulate in the atmosphere. Concentrations of $CO_2$, the most abundant long-lived anthropogenic GHG, now exceed 423 parts per million (ppm),[3] over 50% higher than in the millennia leading up to the Industrial Revolution.[4] In the context of this report, carbon management refers to a suite of approaches that reduce, reuse, or remove $CO_2$ that are all essential to achieving net zero objectives and limiting warming to well below 2°C.

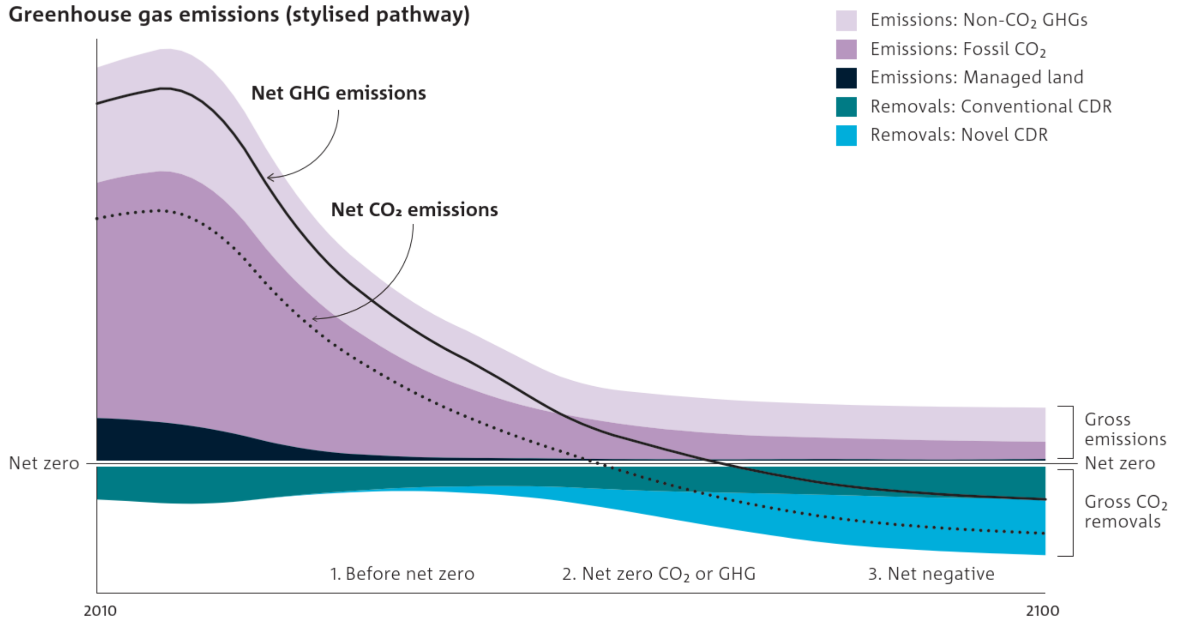
As identified in *The State of Energy Transition Technologies*, effective carbon management is needed to reduce Australia's emissions and reach net-zero targets by 2050. Specifically, carbon management will play a critical role in the decarbonisation of the Australian and global economy, in particular reducing emissions in sectors that are not easy to decarbonise with renewable energy technologies alone. These sectors are typically described as 'hard-to-abate' as they often rely on carbon from fossil fuels as building blocks for products (e.g. steel, chemicals, plastics), require high energy density fuels for long-distance transport (e.g. long-haul aviation), or produce carbon emissions inherently in their processes regardless of the energy source used (e.g. cement production). The *capture and storage*, or *capture and use*, of carbon emissions from these industries can provide an important solution to their emissions footprint as the energy transition progresses.

While rapid and significant emissions reductions are a priority, these alone are now insufficient to reduce the $CO_2$ concentration in the atmosphere and limit warming to below 2°C. In parallel, carbon management will also be needed to remove any remaining gross $CO_2$ emissions from the atmosphere when net zero and subsequently net negative emissions is reached (see Figure 1).

[3] Cape Grim Greenhouse Gas Data (n.d.) Commonwealth Scientific and Industrial Research Organisation (CSIRO) Marine and Atmospheric Research and the Australian Bureau of Meteorology (Cape Grim Baseline Air Pollution Station), Australia. <https://capegrim.csiro.au>.

[4] Atmospheric $CO_2$ reached 422 ppm in December 2023, from approximately 280 ppm prior to the mid-18$^{th}$ century, which had been stable for millennia, see; NASA (n.d.) Climate change: vital signs of the planet – carbon dioxide. <https://climate.nasa.gov/vital-signs/carbon-dioxide/>; CSIRO (n.d.) $CO_2$ data and Twitter: how a tweet sparked a conversation about climate. <https://blog.csiro.au/co2-data-twitter/>; Copernicus Climate Change Service (2025) 2024 is the first year to exceed 1.5°C above pre-industrial level. European Centre for Medium-Range Weather Forecasts (ECMWF), Reading, UK. <https://climate.copernicus.eu/copernicus-2024-first-year-exceed-15degc-above-pre-industrial-level>.

**Figure 1: Stylised visualisation of the net effect of carbon management pathways. Both $CO_2$ emissions reduction and $CO_2$ removals will be needed to reach net zero**[5]




## 2.3 Scope of this report

**This report highlights RD&D opportunities that could support the scale-up, de-risking and deployment of point source capture and direct air capture (DAC) technologies to support the decarbonisation of energy supply and demand sectors, while presenting a foundation for advancing Australia's efforts across carbon management pathways.**

There are three types of carbon management pathways (Table 1): carbon capture and storage (CCS), carbon capture and utilisation (CCU),[6] and carbon dioxide removal (CDR). CCS and CCU have shared processes and technology with some CDR approaches and are two pathways that can complement removal efforts within broader emissions reduction strategies. CCS is the process of capturing $CO_2$ from a point source, such as a power plant or industrial site, and durably storing it. CCU does the same but reuses the $CO_2$ to form new products. Unlike CCS and CCU, CDR systems result in additional net removal of $CO_2$ from the atmosphere, meaning they create atmospheric removals that would not have happened without direct intervention.[7]

**Table 1: Definitions of carbon management pathways**

| PATHWAY | DESCRIPTION |
|---|---|
| **CCS** | $CO_2$ captured from a point source and permanently stored. |

[5]CSIRO (2025) Australian Carbon Dioxide Removal Roadmap. CSIRO, Canberra, modified from Smith SM, Geden O, Gidden MJ, Lamb WF, Nemet GF, Minx JC, Buck H, Burke J, Cox E, Edwards MR, Fuss S, Johnstone I, Müller-Hansen F, Pongratz J, Probst BS, Roe S, Schenuit F, Schulte I, Vaughan NE (Eds) (2024) The State of Carbon Dioxide Removal 2024 – 2nd Edition. <DOI:10.17605/OSF.IO/F85QJ>.

[6] Note, CCU carbon management systems can be integrated with $CO_2$ storage, and these systems are typically referred to as CCUS.

[7] Shukla P.R, Skea J, Reisinger A, Slade R, Fradera R, Pathak M, Al Khourdajie A, Belkacemi M, van Diemen R, Hasija A, Lisboa G, Luz S, Malley J, McCollum D, Some S, Vyas P (2022) Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC <10.1017/9781009157926.001>

| | |
|---|---|
| **CCU** | $CO_2$ captured from a point source or the atmosphere and used to form a product.[8] |
| **CDR** | $CO_2$ captured from the atmosphere and permanently stored. |

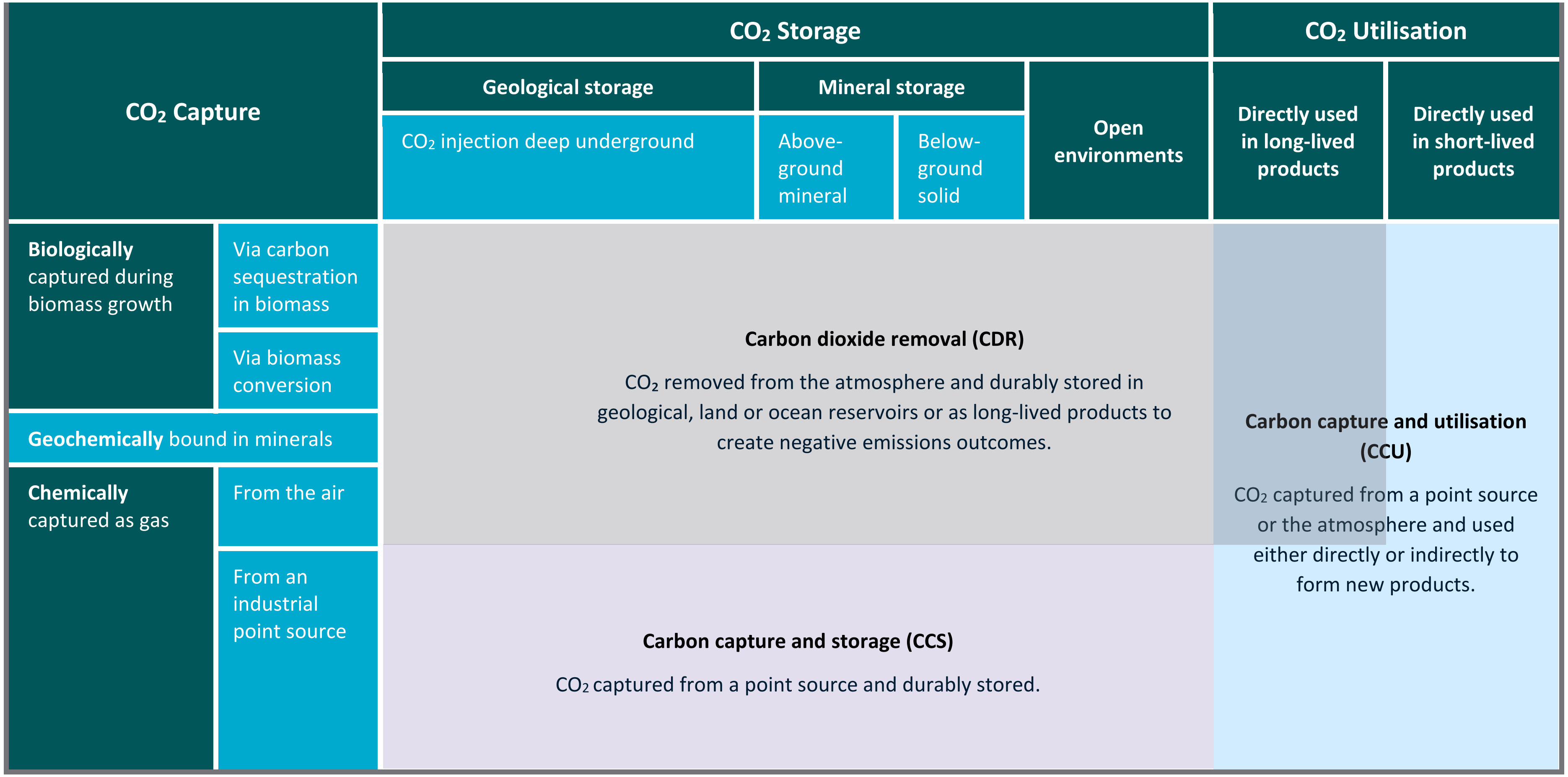
The technologies that make up these systems can be viewed as complementary, with many of them capable of serving a dual purpose. For example, a DAC system that captures $CO_2$ from the atmosphere and permanently stores it, is CDR. Alternatively, if it uses the atmospheric $CO_2$ to make synthetic fuels, it is CCU. While it is acknowledged that these technologies can assume different roles depending on how they are deployed, the opportunities presented in this chapter are relevant irrespective of the intended carbon management pathway.

Based on the analysis conducted across electricity, low carbon fuels, transport and industry sectors, this report focuses on specific RD&D opportunities for point source capture and DAC, along with high level opportunities relating to $CO_2$ storage and utilisation. The scope is focused on technologies that could feasibly be used to abate emissions in industry, or as viable sources of $CO_2$ for key use cases. As a result, this chapter is not an exhaustive discussion of all carbon management technologies. While more detailed discussion can be found in *CSIRO's $CO_2$ Utilisation Roadmap (2021)*[9] and *CSIRO's Australian CDR Roadmap (2025)*, consideration could be given to expand the scope in the future. A comprehensive discussion of RD&D opportunities across all $CO_2$ capture, storage and utilisation technologies would support the scale up and adoption of effective carbon management in Australia, especially given the interconnected nature of technologies and processes across CCS, CCU and CDR pathways (see Figure 2).

[8] The climate effect of CCU depends on the product lifetime, the product it displaces, and the $CO_2$ source (fossil, biomass or atmosphere).

[9] Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) $CO_2$ Utilisation Roadmap. CSIRO.

**Figure 2: Overview of various combinations of capture and storage processes or systems that make up different carbon management pathways, including CDR, CCS and CCU**



# 3 $CO_2$ capture

**While carbon management technologies will play a significant role in Australia's energy transition, adoption will require additional RD&D to reduce their cost and energy requirements.**

### Technology landscape

| Point source | Direct air capture (DAC) |
|---|---|

Several technologies explored across the *State of Energy Transition Technologies* analysis, particularly in the *Industry* and *Transport* sectors, could leverage carbon management technologies (technologies that capture, store or use $CO_2$) as part of their transition strategy. Carbon capture technologies could **be used to** reduce hard-to-abate emissions in sectors that are not easy to decarbonise with renewable energy technologies alone, or remove $CO_2$ from the atmosphere directly and permanently store it.

### RD&D opportunities

| $CO_2$ Capture | |
|---|---|
| **Point source** | Advancing capture materials and process optimisation for point-source carbon capture could improve capture efficiency, lower energy requirements and reduce the need for capital intensive infrastructure. |
| **Direct air capture** | • Developing durable, efficient and low-cost capture materials could extend DAC infrastructure lifetimes and maximise $CO_2$ capture.<br>• RD&D aimed at emerging low-TRL DAC technologies could help reduce their cost and energy demands. These reductions could be furthered through modular plant designs or by DAC systems that integrate waste heat or energy from other industrial processes. |

**Auxiliary**

- Optimising retrofit strategies could expand the use of point source carbon capture in existing industrial facilities.
- Effective deployment and widespread adoption of these technologies will require the development of supporting renewable energy production and storage infrastructure.

### Levelised cost analysis

Note: $CO_2$ capture technologies are referred to in the *Electricity*, *Low Carbon Fuels, Industry,* and *Transport* reports, with potential applications extending beyond the scope of this project. This subsector presents RD&D opportunities associated with point source and direct air capture, for information purposes only. As no use case was defined, no levelised cost analysis was performed.

## 3.1 RD&D opportunity analysis

**Table 2: Summary of RD&D opportunities – $CO_2$ capture[10]**

| | | **$CO_2$ CAPTURE** | |
|---|---|---|---|
| | | **POINT SOURCE** | **DAC** |
| Primary technologies | **Commercial** | Absorption (chemical and physical) | |
| Primary technologies | **Mature** | Adsorption (chemical and physical), membranes, electrochemical separation | Solid adsorbent DAC, liquid absorbent DAC |
| Primary technologies | **Emerging** | Calcium (carbonate) looping, cryogenic separation, electrochemical separation, advanced cycles | Membrane DAC, Cryogenic DAC, Mineral-based solid adsorbent DAC, Electrode-based DAC, Moisture-swing solid adsorbent DAC |
| *Primary RD&D* | | • Improve the cost and capture efficiencies **(Target: >95%, cf. 90%)** through:<br>○ E.g. Improving material design and performance<br>○ E.g. Developing novel reactor designs<br>- E.g. Optimising capture-application fit and process conditions | • Reduce the cost of DAC technologies through:<br>○ E.g. Developing higher capacity, lower energy and more durable sorbents and solvents<br>○ E.g. Adopting and developing low-TRL DAC technologies<br>○ E.g. Modular designs for solid DAC or electrifying liquid DAC with renewable energy |
| Auxiliary RD&D | | • Support the adoption of point source capture technologies in existing industrial facilities by:<br>○ E.g. Optimising retrofit strategies, such as modifying flue gas and exhaust connections<br>○ E.g. Optimising flue gas ducting to minimise pressure drops and potential leakage<br>○ E.g. Developing advanced $CO_2$ measurement and verification systems<br>• Support low emission point source carbon capture by:<br>○ E.g. Establishing renewable energy production and storage infrastructure<br>• Support the development of co-products that could create an additional revenue stream | • Support the adoption of DAC technologies through:<br>○ E.g. The continued refinement of advanced $CO_2$ monitoring, reporting and verification (MRV) systems<br>• Support the development of co-products that could create an additional revenue stream<br>• Support low emission DAC deployment by:<br>○ E.g. Establishing renewable energy production and storage infrastructure |

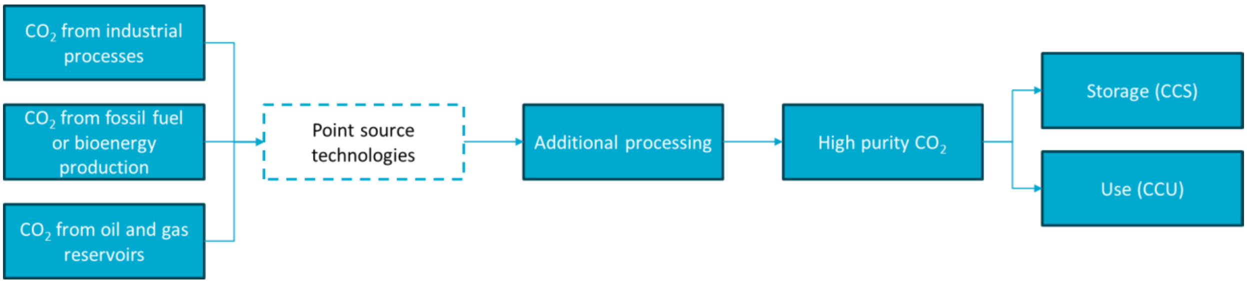
[10] TRL categories: emerging = TRL 4-6, mature = TRL 7-9, commercial = CRI 2-6; Please note, here, all cost-related targets are obtained literature, reflecting aspirational costs required to make a technology cost competitive, agnostic of country-specific RD&D. While converted into Australian currency, these figures assume large impacts from economies of scale which may not represent Australia's capacity for manufacturing. Elsewhere, Levelised Cost forecasts have been determined, referring to 2050 costs or assumptions, as calculated via CSIRO levelised cost analysis during technology filtering.

## Point source

Point source technologies capture $CO_2$ from concentrated $CO_2$ streams that are created as waste, from industrial processes, electricity generation from fossil fuels, or from some oil and gas reservoirs.[11] $CO_2$ captured from point sources is underpinned by mature technologies and has been deployed at commercial scale around the world primarily for enhanced oil recovery, to support fertiliser production and at natural gas facilities and ethanol plants.[12] The most advanced and widely adopted capture technologies are chemical absorption and physical separation, with emerging technologies such as membranes and looping cycles (e.g., chemical looping and calcium looping) under development. Figure 3 illustrates how point source capture technologies are integrated in carbon management pathways.

The preferred approach to point source capture differs by application/scenario. Currently, in the absence of an established carbon market where the expense of point source capture will be weighed against the value of avoided emissions or captured $CO_2$, the widespread adoption of these technologies is currently limited by high energy and cost requirements, as well as retrofitting complexity, i.e., existing industrial plants need expensive modifications to integrate capture systems. To enable wider deployment, reducing both capital and operating costs is critical.[13] Several RD&D opportunities exist that can support achieving these objectives. Further detail on point source capture and its role in carbon management pathways can be found in *CSIRO's 2021 $CO_2$ Utilisation Roadmap*.[14]

**Figure 3: A high-level example illustrating the integration of point source capture technologies in carbon management pathways (CCS and CCU)**




### Primary technologies

**Improving material design and performance could improve capture efficiency and lower system costs.**

Reducing energy use and improving capture efficiency, could lower the cost of point source capture technologies.[15] RD&D efforts to improve material performance, such as developing sorbents with higher absorption or adsorption rates and capacities, could increase the capture efficiency in both pre

[11]Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) $CO_2$ Utilisation Roadmap. CSIRO.

[12]Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) $CO_2$ Utilisation Roadmap. CSIRO.

[13] Bajpai S, Shreyash N, Singh S, Memon A.R, Sonker M, Tiwary S.K, Biswas S (2022) Opportunities, challenges and the way ahead for carbon capture, utilisation and sequestration (CCUS) by the hydrocarbon industry: Towards a sustainable future. Energy Reports <https://doi.org/10.1016/j.egyr.2022.11.023Get rights and content>

[14] Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) $CO_2$ Utilisation Roadmap. CSIRO.

[15] Dziejarski B, Krzyżyńska R, Andersson K (2023) Current status of carbon capture, utilization, and storage technologies in the global economy: A survey of technical assessment. Fuel <https://doi.org/10.1016/j.fuel.2023.127776>

and post combustion systems. Adding catalysts to solvent and chemical regeneration processes could reduce total energy consumption and extend solvent lifespan. These opportunities could lead to more compact, cost effective and durable point source capture systems.[16]

**Developing novel reactor designs could also help achieve high $CO_2$ capture rates, particularly those > 95%.**

Currently, power and industrial plants with carbon capture systems are designed to capture around 90% of $CO_2$ from flue gas, but performance in less established applications often falls short of target capture rates.[17] In steelmaking, for example, the Al Reyadah facility in the United Arab Emirates (UAE) is the only commercial-scale carbon capture plant. Based on the nominal capture capacity (0.8Mt), and annual emissions of 3Mt$CO_2$, only 26% of total $CO_2$ emissions are captured using this system.

Achieving capture rates >98% requires larger equipment, additional processing steps and higher energy consumption, increasing total unit costs.[18] As a result, there is an opportunity to develop new reactor designs (including hybridised or modularised self-contained, plug-in systems), with improved cooling and heat integration systems to increase $CO_2$ yield.

**Identifying the most suitable point source capture technologies for specific applications and optimising process conditions, could lower operating costs and improve feasibility for industry adoption.**

Matching point source capture technologies to applications that emit $CO_2$ at higher concentrations and pressures could enable emitters to capture the $CO_2$ more cheaply.[19] This is because less energy is required to separate $CO_2$ from other gasses and compress it in these conditions.[20] Alternatively, developing tools, such as metrology protocols and measurement methodologies that accurately measure the concentration and quality of $CO_2$ streams, could maximise capture efficiency, reduce energy requirements and drive down system costs.[21]

[16] Dziejarski B, Krzyżyńska R, Andersson K (2023) Current status of carbon capture, utilization, and storage technologies in the global economy: A survey of technical assessment. Fuel <https://doi.org/10.1016/j.fuel.2023.127776>; Yulia F, Sofianita R, Prayogo K, Nasruddin N (2021) Optimization of post combustion $CO_2$ absorption system monoethanolamine (MEA) based for 320 MW coal-fired power plant application – Exergy and exergoenvironmental analysis. Case Studies in Thermal Engineering <https://www.sciencedirect.com/science/article/pii/S2214157X21002562>; Hua W, Sha Y, Zhang X, Cao H (2023) Research progress of carbon capture and storage (CCS) technology based on the shipping industry. Ocean Engineering <https://www.sciencedirect.com/science/article/pii/S0029801823013136>

[17] Somers J (2022) Technologies to decarbonise the EU steel industry. Publications Office of the European Union <https://data.europa.eu/doi/10.2760/069150>; Nicholas S, Basirit S (2024) Carbon Capture for Steel? CCUS will not play a major role in steel decarbonisation. Institute for Energy Economics and Financial Analysis <https://ieefa.org/sites/default/files/2024-04/Carbon%20capture%20for%20steel-April24.pdf>

[18] Budinis S, Fajardy M, Greenfield C (2024) Tracking Carbon Capture, Utilisation and Storage. International Energy Agency <https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage>

[19] CCUS Set-plan (2021) CCUS Roadmap to 2030 https://www.ccus-setplan.eu/wp-content/uploads/2021/11/CCUS-SET-Plan_CCUS-Roadmap-2030.pdf; It should be noted, that when considering the utilisation of the captured carbon, the effect of point source $CO_2$ capture on downstream production costs are relatively minor. Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) $CO_2$ Utilisation Roadmap. CSIRO.

[20] See, e.g., Gerardo G, Patiño E, Nápoles-Rivera F, Jiménez-Gutiérrez A (2023) Thermal integration of a natural gas combined cycle plant with carbon capture and utilization technologies. Energy Conversion and Management <https://www.sciencedirect.com/science/article/pii/S0196890423009652>; Li Y, Wang N, Guan H, Jia Z, Zhang Y, Zhao G, Go M (2022) Optimization study of $CO_2$ capture unit for subcritical coal-fired power generation unit based on Ebsilon and Aspen plus. Energy Conversion and Management <https://linkinghub.elsevier.com/retrieve/pii/S0196890422008962>

[21] See, e.g., Gerardo G, Patiño E, Nápoles-Rivera F, Jiménez-Gutiérrez A (2023) Thermal integration of a natural gas combined cycle plant with carbon capture and utilization technologies. Energy Conversion and Management <https://www.sciencedirect.com/science/article/pii/S0196890423009652>; Li Y, Wang N, Guan H, Jia Z, Zhang Y, Zhao G, Go M (2022) Optimization study of $CO_2$ capture unit for subcritical coal-fired power generation unit based on Ebsilon and Aspen plus. Energy Conversion and Management <https://linkinghub.elsevier.com/retrieve/pii/S0196890422008962>

### Auxiliary technologies

Refer to *section CO2 capture auxiliary technologies.*

## Direct air capture

DAC technologies utilise chemical or physical processes to separate and extract $CO_2$ from the atmosphere. $CO_2$ is captured and filtered using a liquid solution (liquid DAC) or a solid material (solid DAC) and once the material is saturated, it undergoes a regeneration process to release the $CO_2$ for storage or utilisation.[22] Figure 4 illustrates how DAC technologies can be integrated into carbon management pathways.

Despite its significant potential to remove atmospheric $CO_2$, support emissions reduction in hard to abate sectors and offset emissions from incumbent fossil fuel infrastructure, DAC is extremely energy and resource intensive. Additionally, capital intensive infrastructure and low material durability increase overall system costs.[23] According to CSIRO's Australian CDR Roadmap (2025), the projected 2050 cost for an Nth-of-a-kind solid adsorbent DAC plant ranges from $400 to $480 per tonne of $CO_2$ captured and stored. While lower than today's First-of-a-kind estimate of $1,100 to $1,300, the 2050 price points are still significant.

Scaling DAC for effective carbon management will require significant RD&D to improve energy efficiency, enhance material performance and reduce costs. Several RD&D opportunities exist that could help achieve this goal. For a more detailed overview of DAC as a carbon management solution in Australia, see *CSIRO's Australian CDR Roadmap* (2025) and *CSIRO's $CO_2$ Utilisation Roadmap*.[24]

**Figure 4: A high-level example illustrating the integration of DAC technologies in carbon management pathways (CDR and CCU)**


### Primary technologies

**Developing durable, efficient and low cost sorbents and solvents could reduce the costs associated with operating DAC technologies.**

Material replacement in DAC systems is costly. RD&D aimed at improving the durability of sorbents and reducing the corrosiveness of current liquid solutions, could lower material demand per tonne of $CO_2$ captured. Additionally, adopting low-cost sorbents and optimising their material performance parameters, such as reaction kinetics and $CO_2$ capture efficiency, could also reduce overall costs. For example, low-cost hydrogels that increase the contact surface area between $CO_2$ and sorbents (amine) to speed up the rate of reaction.[25]

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[22] Pett-Ridge et al. (2023) Roads to removal: options for carbon dioxide removal in the United States. Lawrence Livermore National Laboratory; Carbon Dioxide Removal Mission (2022) Carbon dioxide removal technology roadmap: innovation gaps and landscape analysis.

[23] CSIRO's (2025) CDR Roadmap (unpublished); Pett-Ridge et al. (2023) Roads to removal: options for carbon dioxide removal in the United States. Lawrence Livermore National Laboratory; Carbon Dioxide Removal Mission (2022) Carbon dioxide removal technology roadmap: innovation gaps and landscape analysis.

[24] Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) $CO_2$ Utilisation Roadmap. CSIRO.

[25] Bruce S et al. (2020) Opportunities for hydrogen in commercial aviation. CSIRO.

**The capital costs of solid and liquid DAC are a large driver of total expenses, making it a key area for RD&D driven cost reductions.**

Capital costs of solid adsorbent DAC plants could be reduced through RD&D which considers modular plant designs.[26] For liquid absorbent DAC, the integration of renewable electricity could result in lower emissions and provide net cost benefits, however, requires R&D to electrify the system. For example, developing high temperature electric kilns could co-enable renewable-powered liquid absorbent DAC.[27]

**Emerging low-TRL DAC technologies could offer promising pathways to reduce both cost and energy consumption.**

Examples include polymeric membranes that capture $CO_2$ from the atmosphere[28], cryogenic DAC that transforms $CO_2$ from gaseous to solid state (i.e. dry ice) for capture,[29] or electrode-based DAC which uses electrochemical cells to capture and/or release $CO_2$ for storage.[30] Other examples of emerging technologies are summarised in Table 3.

**Table 3: Emerging DAC technologies, sourced from CSIRO's 2025 Australian CDR Roadmap**

| TECHNOLOGY | DESCRIPTION | KEY R&D CHALLENGE |
|---|---|---|
| **Membrane DAC** | Uses polymeric membranes to capture $CO_2$ from the atmosphere.[31] | Low capture efficiency.[32] |
| **Cryogenic DAC** | Uses very low temperatures to transform $CO_2$ from gaseous to solid state (i.e. dry ice) for capture.[33] | High energy requirement for cooling.[34] |
| **Mineral-based solid adsorbent DAC** | Uses crushed solid minerals (e.g. calcium oxide) to react with $CO_2$ from the atmosphere and form a solid carbonate product (e.g. calcium carbonate or limestone).[35] | High temperature and energy intensity requirement to process the solid carbonate product to release the $CO_2$ for storage and regenerate it to the original composition for use in other cycles.[36] |
| **Electrode-based DAC** | Uses electrochemical cells to capture and/or release $CO_2$ for storage, with the potential to be integrated with a liquid absorbent or solid adsorbent DAC process.[37] | Uncertainty in material cost and durability, adsorption and regeneration kinetics, and overall energy efficiency.[38] |

[26] CSIRO (2025) CDR Roadmap (unpublished).

[27] CSIRO (2025) CDR Roadmap (unpublished).

[28] RMI (2023) The applied innovation roadmap for CDR. <https://rmi.org/insight/the-applied-innovation-roadmap-for-cdr/>.

[29] RMI (2023) The applied innovation roadmap for CDR. <https://rmi.org/insight/the-applied-innovation-roadmap-for-cdr/>.

[30] RMI (2023) The applied innovation roadmap for CDR. <https://rmi.org/insight/the-applied-innovation-roadmap-for-cdr/>.

[31] RMI (2023) The applied innovation roadmap for CDR. <https://rmi.org/insight/the-applied-innovation-roadmap-for-cdr/>.

[32] CSIRO (2022) Australia's carbon sequestration potential: a stocktake and analysis of sequestration technologies; RMI (2023) The applied innovation roadmap for CDR. <https://rmi.org/insight/the-applied-innovation-roadmap-for-cdr/>.

[33] RMI (2023) The applied innovation roadmap for CDR. <https://rmi.org/insight/the-applied-innovation-roadmap-for-cdr/>.

[34] CSIRO (2022) Australia's carbon sequestration potential: a stocktake and analysis of sequestration technologies; RMI (2023) The applied innovation roadmap for CDR. <https://rmi.org/insight/the-applied-innovation-roadmap-for-cdr/>.

[35] RMI (2023) The applied innovation roadmap for CDR. <https://rmi.org/insight/the-applied-innovation-roadmap-for-cdr/>.

[36] RMI (2023) The applied innovation roadmap for CDR. <https://rmi.org/insight/the-applied-innovation-roadmap-for-cdr/>.

[37] RMI (2023) The applied innovation roadmap for CDR. <https://rmi.org/insight/the-applied-innovation-roadmap-for-cdr/>.

[38] Pett-Ridge et al. (2023) Roads to removal: options for carbon dioxide removal in the United States. Lawrence Livermore National Laboratory.

| | | |
|---|---|---|
| **Moisture-swing solid adsorbent DAC** | Captures $CO_2$ under dry conditions and releases $CO_2$ for storage under humid conditions. Potential solid adsorbents for this process include activated carbon, nanostructured graphite, and iron and aluminium oxide nanoparticles.[39] | Potential high-water requirement if deployed in hot and dry climates.[40] |

### Auxiliary technologies

Refer to section *CO2 capture auxiliary technologies.*

## $CO_2$ capture auxiliary technologies

The following section is a non-exhaustive summary of RD&D opportunities related to the technologies required for the deployment or enhanced performance of carbon capture technologies.

**Expanding the use of point source carbon capture in existing industrial facilities requires more RD&D to optimise retrofit strategies**.

Retrofitting may involve the expansion of cooling systems and modifying flue gas and exhaust connections, both of which present cost and complexity challenges.[41] Cooling systems could benefit from developing and integrating high-efficiency heat exchangers, while flue gas ducting could be optimised to minimise pressure drops, improve flow in confined spaces and enhance sealing techniques to prevent leakage.[42]

**Developing advanced monitoring, reporting and verification (MRV) systems supports the adoption of all carbon capture technologies.**

Monitoring, reporting and verifying the quantity and quality of $CO_2$ captured is critical to determining the effectiveness of a capture technology. Precise, high-resolution data enables more accurate quantification. Automating the MRV process using digital methods such as sensors, satellite data, blockchain, and AI could significantly reduce costs associated with manual sampling. Improvements to data capture technologies could improve technology credibility and enable system scale up.

**Establishing renewable energy production and storage infrastructure is needed to support carbon capture adoption.**

Carbon capture technologies require significant amounts of energy to meet operational demands. As a result, RD&D focused on building out Australia's renewable energy capacity and integrating this capacity into carbon management pathways presents as a significant and cross-cutting opportunity. For detailed RD&D opportunities related to renewable electricity generation, see the *Electricity* technical appendix.

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[39] Shindel B, Hegarty J, Estradioto J.D, Barsoum M.L, Yang M, Farha O.K, Dravid V.P (2025) Platform Materials for Moisture-Swing Carbon Capture. Environmental Science and Technology 59 (17) <10.1021/acs.est.4c11308>

[40] Pett-Ridge et al. (2023) Roads to removal: options for carbon dioxide removal in the United States. Lawrence Livermore National Laboratory.

[41] Kearns D, Liu H, Consoli C (2021) Technology Readiness and Costs of CCS. Global CCS Institute <https://www.globalccsinstitute.com/wp-content/uploads/2022/03/CCE-CCS-Technology-Readiness-and-Costs-22-1.pdf>

[42] Fang M, Dong W, Zhang Y, Zhao R, Li Y, Lu S, Wang T, Wang Q (2021) Study on the chemical absorption main heat exchanger and process modification for 150kt/y CCS demonstration project. International Journal of Greenhouse Gas Control. <https://doi.org/10.1016/j.ijggc.2021.103470Get rights and content>

# 4 $CO_2$ storage

$CO_2$ storage is the storage of $CO_2$ after it has been captured (either from point source emissions or the atmosphere). Broadly there are three main types of $CO_2$ storage: geological, open environment and mineral (see Figure 2).[43]

- Geological $CO_2$ storage involves compressing $CO_2$ into a supercritical state and injecting it deep into porous underground rock formations where it is securely contained.[44] The durability of geological $CO_2$ storage systems is dictated by physical trapping mechanisms, but is generally considered durable.
- Open environment storage refers to the storage of captured carbon in open environments, such as the ocean or on land, in a way that prevents it from re-entering the atmosphere.[45] Carbon can be stored inorganically, as carbonate or bicarbonate ions, or organically as living biomass, soil carbon or biochar, with different levels of durability. Open environment storage typically involves geochemical and biological processes that are a part of the natural carbon cycle.
- Mineral storage describes mineral carbonation (or carbon mineralisation). Mineral carbonation reactions occur in nature, as a product of rock weathering at the earth's surface or in groundwater systems that come into direct contact with dilute carbonic acid in rainwater or $CO_2$-rich groundwater. Weathering reactions happen very slowly and are dependent on the composition of the rocks being weathered. In addition to rock weathering at the (near) surface, mineral carbonation reactions also occur during rock-forming processes, where $CO_2$-rich hydrothermal fluids from deep in the earth's crust react with subsurface rocks at elevated pressures and temperatures.

$CO_2$ stored organically in open environments has a high risk of reversal. For example, forests release stored $CO_2$ during natural disasters, insect outbreaks, or cropland management changes. As a result, these systems are characterised by low storage permanence (10-100 years).[46] In contrast, geological $CO_2$ storage and mineral storage is characterised by high storage durability (>10,000 years).[47] This durability is due to natural 'trapping' mechanisms that keep the $CO_2$ locked deep below the earth's surface or locked up in solid minerals.[48]

The storage system used depends on the carbon management pathway chosen. For example, if the goal is to achieve durable $CO_2$ removal, this can only be achieved with long-term storage that prevents $CO_2$ from re-entering the atmosphere. In contrast, other projects or industries might choose to adopt

[43] International Energy Agency (2025) The State of Energy innovation <https://iea.blob.core.windows.net/assets/26e9f71e-3a3f-4c82-802b-c2ed97aaae24/Thestateofenergyinnovation.pdf>

[44] Global CCS Institute (2025) CCS explainer: storage. <https://www.globalccsinstitute.com/wp-content/uploads/2025/03/CCS-Explainer_3_Storage_20250317.pdf>.

[45] The State of Energy Innovation

[46] International Air Transport Association (2025) Carbon Dioxide Removal (CDR) Technologies: An overview of different methods for capturing and storing carbon dioxide from the atmosphere. <https://www.iata.org/globalassets/iata/publications/sustainability/carbon-dioxide-removal-cdr-technologies-facts.pdf>

[47] Shukla P.R, Skea J, Reisinger A, Slade R, Fradera R, Pathak M, Al Khourdajie A, Belkacemi M, van Diemen R, Hasija A, Lisboa G, Luz S, Malley J, McCollum D, Some S, Vyas P (2022) Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC <10.1017/9781009157926.001>

[48] Bashir A, Ali M, Patil S, Aljawad M.S, Mahmoud M, Al-Shehri D, Hoteit H, Kamal M.S (2024) Comprehensive review of $CO_2$ geological storage: Exploring principles, mechanisms, and prospects. Earth-Science Reviews <https://doi.org/10.1016/j.earscirev.2023.104672>

open environment approaches or choose $CO_2$ utilisation pathways. The decision about the fate of captured $CO_2$ will be closely related to proximity costs.

For this iteration of *The State of Energy Transition Technologies* report, specific RD&D opportunities for each $CO_2$ storage option have not been comprehensively identified, however some high-level examples include:

- Improving the classification of Australia's geological storage potential to open up additional siting options for captured $CO_2$.
- Prioritising classification of geological storage in areas with a large potential for DAC, through renewable energy generation potential.
- Assessing the feasibility, scalability and cost effectiveness of emerging storage technologies, such as mineral storage and open environment storage.
- Developing innovative approaches to monitoring, drilling, and asset management, to reduce the cost of $CO_2$ storage.[49]
- Developing and optimising technologies, models and procedures to monitor, report and verify $CO_2$ migration and trapping; characterise and model storage sites and operations, including fluid trapping processes; detect environmental changes or all storage mechanisms, including open environment and mineral carbonation.

[49] CCUS Set-plan (2021) CCUS Roadmap to 2030 https://www.ccus-setplan.eu/wp-content/uploads/2021/11/CCUS-SET-Plan_CCUS-Roadmap-2030.pdf

# 5 $CO_2$ utilisation

Carbon utilisation is the process of re-using captured $CO_2$ either in conversion processes for the synthesis of new products, or in non-conversion processes where $CO_2$ is used directly (see Box 1).[50] $CO_2$ utilisation decreases reliance on carbon derived from fossil resources and supports a circular carbon economy.

Applications for $CO_2$ utilisation are varied but can be grouped into five categories:[51] (1) Direct use; (2) Chemicals and fuels; (3) Carbonates and building materials; (4) Waste management (5) Food products, as set out in Figure 5. While RD&D opportunities for $CO_2$-derived fuels are covered in the *Low Carbon Fuels* technical appendix, *CSIRO's 2021 $CO_2$ Utilisation Roadmap* discusses RD&D opportunities for the remaining application groups. High level examples include:

- Advancing catalytic conversion technologies, particularly through the development of novel catalysts, could improve the conversion efficiency in chemical, fuel, and materials manufacturing.
- Demonstrating the long-term durability of new products and providing rapid and low-cost certification processes for low-carbon concrete could accelerate industry uptake.[52]
- Continued genetic engineering and advanced bioengineering could enable the production of a broad range of high-value products.
- Non-technological assessments such as life cycle analyses, techno-economic assessment studies, and comprehensive social acceptance studies could help ascertain the potential of $CO_2$ applications.[53]

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[50] CCUS Set-plan (2021) CCUS Roadmap to 2030 https://www.ccus-setplan.eu/wp-content/uploads/2021/11/CCUS-SET-Plan_CCUS-Roadmap-2030.pdf

[51] Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) $CO_2$ Utilisation Roadmap. CSIRO.

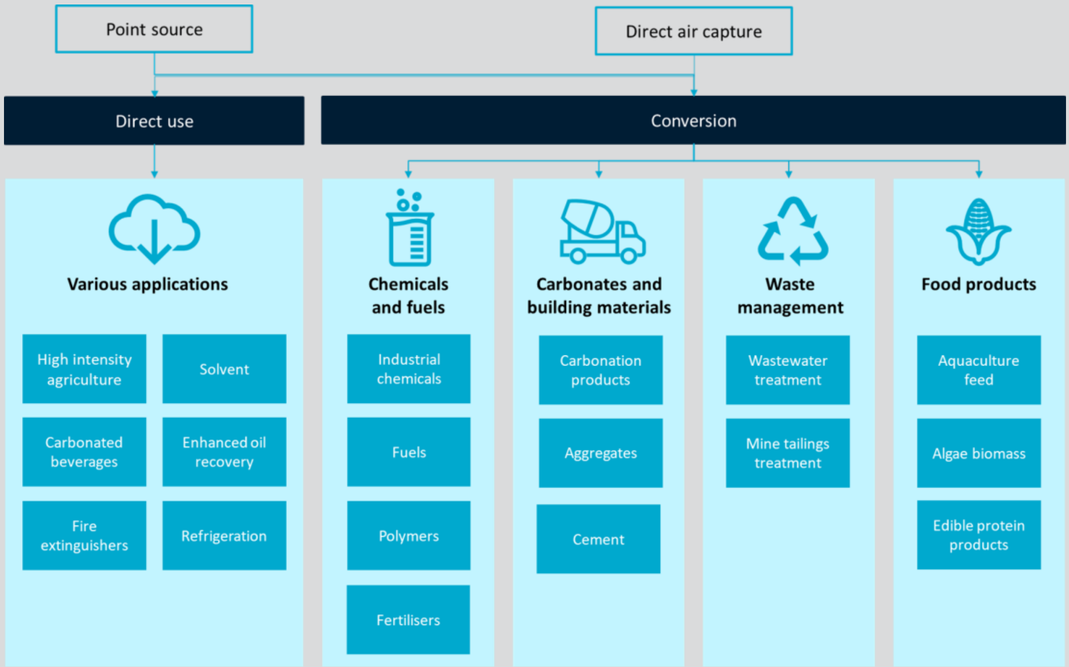
[52] Alberici S et al. (2017) Assessing the potential of $CO_2$ utilisation in the UK. Imperial College London & ECOFYS.

[53] CCUS Set-plan (2021) CCUS Roadmap to 2030 https://www.ccus-setplan.eu/wp-content/uploads/2021/11/CCUS-SET-Plan_CCUS-Roadmap-2030.pdf

**Box 1: $CO_2$ utilisation**

CCU is defined as a process in which $CO_2$ is captured and the carbon then used in a product. The climate effect of CCU depends on the product lifetime, the product it displaces, and the $CO_2$ source (fossil, biomass or atmosphere).[54] *CSIRO's $CO_2$ Utilisation Roadmap* identified over 50 different use cases or products for $CO_2$ utilisation, some of which are summarised in Figure 5.

**Figure 5: A summary of potential carbon capture use cases, adapted from CSIRO's 2021 $CO_2$ Utilisation Roadmap[55]**




[54] https://mission-innovation.net/missions/carbon-dioxide-removal/

[55] Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) $CO_2$ Utilisation Roadmap. CSIRO.

# Part 3: Appendix

## A.1 Glossary

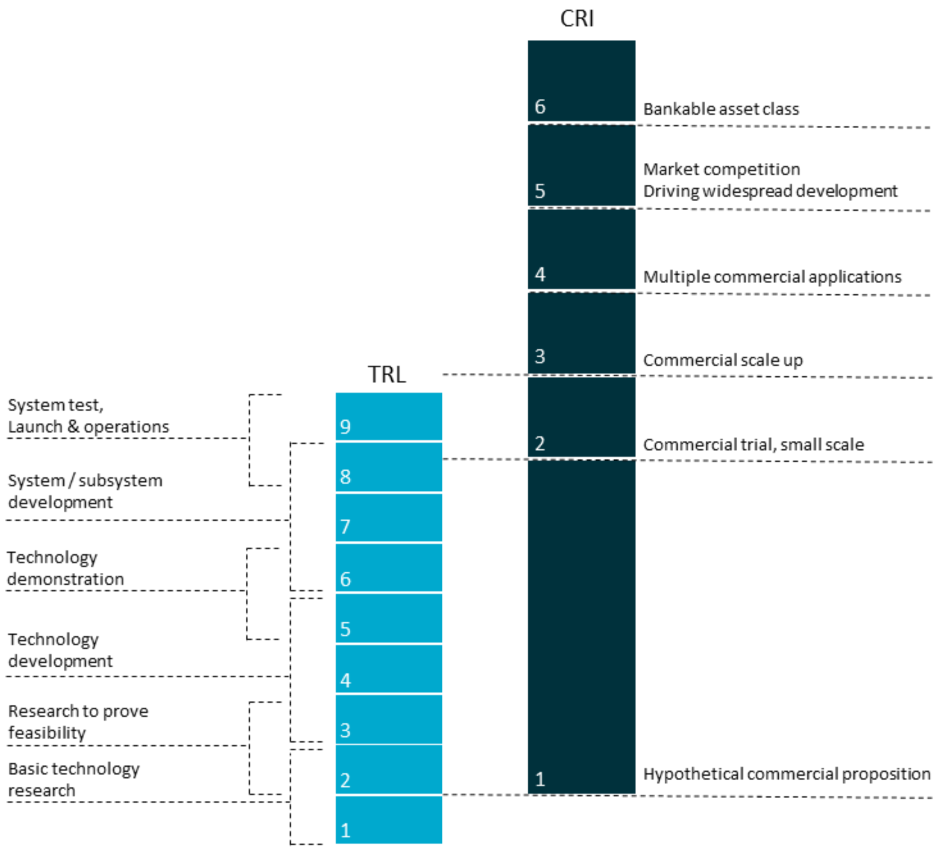
| TERMINOLOGY | DEFINITION |
| --- | --- |
| **Additionality** | A measure of whether carbon removals would have occurred without deliberate intervention, and is essential for validating carbon credits. |
| **Advanced cycles** | Innovative thermodynamic or chemical process cycles designed to improve the efficiency and effectiveness of $CO_2$ capture. |
| **Biologic $CO_2$ storage** | Storing $CO_2$ in natural systems such as forests, soils, and biomass. |
| **Biomass carbon removal and storage (BiCRS)** | Plants and algae produce biomass via photosynthesis, which removes $CO_2$ from the atmosphere. Biomass carbon removal and storage is the process of extracting $CO_2$ from this biomass, through processes such as combustion, fermentation, pyrolysis and conversion and storing it underground or durably in long-lived products to prevent its release back into the atmosphere. |
| **Calcium carbonate looping** | A process where calcium oxide reacts with $CO_2$ to form calcium carbonate, which can be heated to release $CO_2$ and regenerate the calcium oxide. |
| **Carbon capture and storage (CCS)** | Process including the separation and removal of $CO_2$ from the atmosphere, fuel combustion, industrial processes, or similar; its potential transport; and its durable storage via methods such as storage in geological formations or mineralisation. |
| **Carbon capture and utilisation (CCU)** | A process in which $CO_2$ is captured and the carbon then used in a product. The climate effect of CCU depends on the product lifetime, the product it displaces, and the $CO_2$ source (fossil, biomass or atmosphere). |
| **Carbon capture utilisation and storage (CCUS)** | Commonly referred to by its acronym CCUS, carbon capture utilisation and storage refers to the process of capturing $CO_2$ from point source emissions or the atmosphere and using it either directly or indirectly to form new products as well as integrating it with $CO_2$ storage. |
| **Carbon dioxide removal (CDR)** | Activities that deliberately remove $CO_2$ from the atmosphere and durably store it in natural carbon reservoirs (e.g. rock formations, soils, plants, oceans), or in long-lived products. These activities can be nature-based or technological-based approaches, or a combination of the two (i.e. a hybrid approach). |
| **Carbon management** | A project specific term used to describe the suite of technologies that capture, store or use $CO_2$ |
| **Chemical absorption** | A $CO_2$ capture method where $CO_2$ reacts chemically with a liquid solvent, often an amine. |
| **Chemical adsorption** | $CO_2$ binds chemically to the surface of a solid sorbent material. |
| **$CO_2$ capture** | The process of capturing and separating $CO_2$ produced from emissions sources or the atmosphere. |
| **$CO_2$ storage** | The storage of $CO_2$ after it has been captured (either from emissions sources or the atmosphere). |
| **$CO_2$ utilisation** | Carbon utilisation is the process of using captured $CO_2$ in conversion processes for the synthesis of new products, or in non-conversion processes where $CO_2$ is used directly. |
| **Conversion** | The chemical transformation of $CO_2$ into fuels, chemicals, or building materials. |
| **Cryogenic DAC** | Uses very low temperatures to transform $CO_2$ from gaseous to solid state (i.e. dry ice) for capture. |
| **Cryogenic separation** | A $CO_2$ capture method that involves cooling gases to extremely low temperatures to separate $CO_2$ in solid or liquid form. |
| **Direct air capture (DAC)** | Commonly referred to by its acronym DAC, direct air capture is the process of capturing $CO_2$ directly from ambient air and storing it underground or durably in long-lived products to prevent its release back into the atmosphere. |

| | |
|---|---|
| **Direct ocean capture (DOC)** | Commonly referred to by its acronym DOC, direct ocean capture is a technology that captures $CO_2$ already dissolved in water using electrochemical or chemical methods that acidify or alkalize seawater. |
| **Direct use** | The application of captured $CO_2$ without changing its chemical structure (e.g. in greenhouses, beverage carbonation, or enhanced oil recovery). |
| **Durability** | The length of time that removed $CO_2$ is expected to remain out of the atmosphere. |
| **Electrochemical separation** | A process that uses electric current to drive $CO_2$ capture or release in a controlled system. |
| **Electrode-based DAC** | Uses electrochemical cells to capture and/or release $CO_2$ for storage, with the potential to be integrated with a liquid absorbent or solid adsorbent DAC process. |
| **Emissions reduction** | The process of reducing the amount of greenhouse gases released into the atmosphere through clearer technologies or operational changes. |
| **Emissions removal** | The process of removing $CO_2$ from the atmosphere and permanently storing it. |
| **Enhanced rock weathering (ERW)** | A novel CDR approach that accelerates natural rock weathering to capture atmospheric $CO_2$ and improve soil health. See 'mineral carbonation' |
| **Ex-situ mineral carbonation** | A novel CDR approach or process where minerals are reacted with $CO_2$ (either atmospheric or concentrated), leading to durable removal. |
| **Geological storage** | Long-term containment of $CO_2$ in subsurface geological formations, such as saline aquifers or depleted oil and gas reservoirs, or un-minable coal seams or shales. |
| **In -situ mineral carbonation** | In-situ carbon mineralisation is the process whereby $CO_2$ injected into subsurface geological formations reacts with reactive minerals (such as silicates, oxides, and ultramafic minerals) in the host rock to form stable carbonate minerals, thereby durably storing $CO_2$. This process can occur naturally or be enhanced through engineered interventions. |
| **Liquid adsorbent DAC** | DAC process using liquid chemicals to absorb $CO_2$ from air and regenerate them for reuse. |
| **Measurement, reporting and verification** | In the context of carbon management, process whereby achieved emission avoidance, reductions and removals are measured, reported and verified to ensure the accuracy of reporting data and to allow stakeholders, including emitting facilities, to track changes in emissions and emissions reduction over time. |
| **Membrane DAC** | Uses polymeric membranes to capture $CO_2$ from the atmosphere. |
| **Membranes** | Materials that selectively allow $CO_2$ to pass through while blocking other gases, enabling $CO_2$ separation. |
| **Mineral-based solid adsorbent DAC** | Uses crushed solid minerals (e.g. calcium oxide) to react with $CO_2$ from the atmosphere and form a solid carbonate product (e.g. calcium carbonate or limestone). |
| **Moisture-swing solid adsorbent DAC** | Captures $CO_2$ under dry conditions and releases $CO_2$ for storage under humid conditions. Potential solid adsorbents for this process include activated carbon, nanostructured graphite, and iron and aluminium oxide nanoparticles. |
| **Net zero emissions** | Condition in which anthropogenic greenhouse gas (GHG) emissions are balanced by anthropogenic GHG emissions removals over a specified period. The quantification of net-zero GHG emissions depends on the metric chosen to compare emissions and removals of different gases, as well as the time horizon chosen for that metric. |
| **Ocean alkalinity enhancement (OAE)** | Commonly referred to by its acronym OAE, ocean alkalinity enhancement is an approach to marine-based CDR that involves adding alkalinity to seawater to enhance the ocean's natural carbon sink. Adding alkalinity to the ocean removes $CO_2$ from the atmosphere through a series of reactions that convert dissolved $CO_2$ into bicarbonate and carbonate molecules, which in turn causes the ocean to draw down $CO_2$ from the atmosphere to restore equilibrium. |
| **Permanence** | The length of time $CO_2$ remains sequestered without re-entering the atmosphere; a key factor in evaluating CDR effectiveness. |
| **Physical absorption** | Captures $CO_2$ using physical solvents (e.g., organic molecules) to absorb $CO_2$ from flue gases. |

| | |
|---|---|
| **Physical adsorption** | $CO_2$ adheres to the surface of a solid sorbent through weak physical forces (van der Waals interactions). Captures $CO_2$ using solid materials (e.g. zeolites, metal organic frameworks, activated carbon) that adsorb $CO_2$ at high pressure. |
| **Point source** | A single, identifiable source of $CO_2$ emissions, such as a power plant, cement factory, or industrial facility. |
| **Regeneration** | The process of releasing captured $CO_2$ from a sorbent or solvent so it can be reused. |
| **Residual emissions** | Remaining gross emissions when net-zero, and subsequently, net-negative, emissions are reached. Can apply to both net-zero $CO_2$ and net-zero GHG emissions, from local to global scales and at company or sector level. To reach net-zero emissions, the amount of CDR must equal the amount of residual emissions over a given period. To reach net-negative emissions, the amount of CDR must exceed residual emissions. |
| **Solid adsorbent DAC** | DAC process using solid materials to adsorb $CO_2$ from air and release it upon regeneration. |
| **Sorbents** | Materials that absorb or adsorb $CO_2$ during capture processes, including solids or liquids. |
| **Sustainable co-products** | Useful products generated alongside $CO_2$ removal or capture processes that do not compromise environmental sustainability, e.g. hydrogen. |

## A.2 Technology maturity rating index

**Figure 6: Technology Readiness Levels and Commercial Readiness Index[56]**




[56] Adapted from ARENA (2014) Commercial Readiness Index. <https://arena.gov.au/assets/2014/02/Commercial-Readiness-Index.pdf>

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