Australia's National Science Agency

Australian Carbon Dioxide Removal Roadmap

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CarbonLock is Australia's largest novel carbon dioxide removal research program which brings together research spanning engineering, biology and chemistry to search for integrated CDR solutions. It leads Australia's representation in major global collaborations, and works closely with other countries to further CDR solutions.

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Acknowledgement

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Executive summary

Carbon Dioxide Removal (CDR) is critical to reaching net zero.

CDR refers to human-facilitated activities that:

Remove carbon dioxide (CO_2) from the atmosphere. + Durably store it in geological, land or ocean reservoirs, or products.

To meet the goals of the Paris Agreement the world must reach net zero emissions. However, achieving net zero is only possible if countries simultaneously reduce emissions and remove CO_2 from the atmosphere. Globally, it is estimated that between 7–9 gigatonnes (Gt) of CO_2 per year of CDR will be needed by 2050.[1] In the near term, CDR must complement, not replace, deep emissions reductions, particularly in hard-to-abate sectors.[2] Over the longer term, CDR will play a key role in balancing residual emissions and delivering net-negative outcomes needed to stabilise the climate.

CDR approaches are grouped into two broad categories: conventional and novel. Conventional approaches, such as afforestation, reforestation, and soil carbon sequestration, are already contributing to Australia's progress on climate change and will deliver near-term removals and co-benefits. However, there is uncertainty around the scale and composition of land based sequestration that may be taken up as Australia transitions to net zero.[3] These removals can compete with other land uses such as agriculture or biomass for low-carbon fuels, may saturate over time, and offer shorter term storage. They can also carry reversal risks from climate-driven disturbances like droughts and bushfires.[4]

Novel CDR approaches, by contrast, have the potential to remove large volumes of CO_2 with a relatively small land-footprint, and offer the potential for scalable and durable storage over centuries to millennia. However, these approaches are not yet at the scale needed and face de-risking challenges that include high costs, significant energy and water requirements, and other dependencies.

1 About 25% of current global emissions (2024); which are estimated at 37.4 $GtCO_2$ (Global Carbon Project see: Friedlingstein P et al (2024) Global carbon budget 2024. Earth System Science Data 17(3), 965–1039. <https://essd.copernicus.org/articles/17/965/2025/>; 7–9 gigatonnes (Gt) of CO_2 sourced 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>.

2 Hard-to-abate emissions are emissions from sectors that are not easy to decarbonise with renewable technologies alone as these sectors often rely on carbon from fossil fuels as building blocks for products (e.g. chemicals, plastics, steel), require high energy density fuels for long-distance transport (e.g. aviation), or produce emissions inherently in their processes (cement production, agriculture in the form of methane).

3 Department of Climate Change, Energy, the Environment and Water (2025) Net Zero Report. DCCEEW, Canberra, ACT. <https://www.dcceew.gov.au/sites/default/files/documents/net-zero-report.pdf>.

4 Australian Climate Service (2025) Australia's National Climate Risk Assessment. Australian Climate Service, Canberra, ACT. <https://www.acs.gov.au/pages/national-climate-risk-assessment>.

A portfolio of novel and conventional CDR approaches is required to reach net zero.

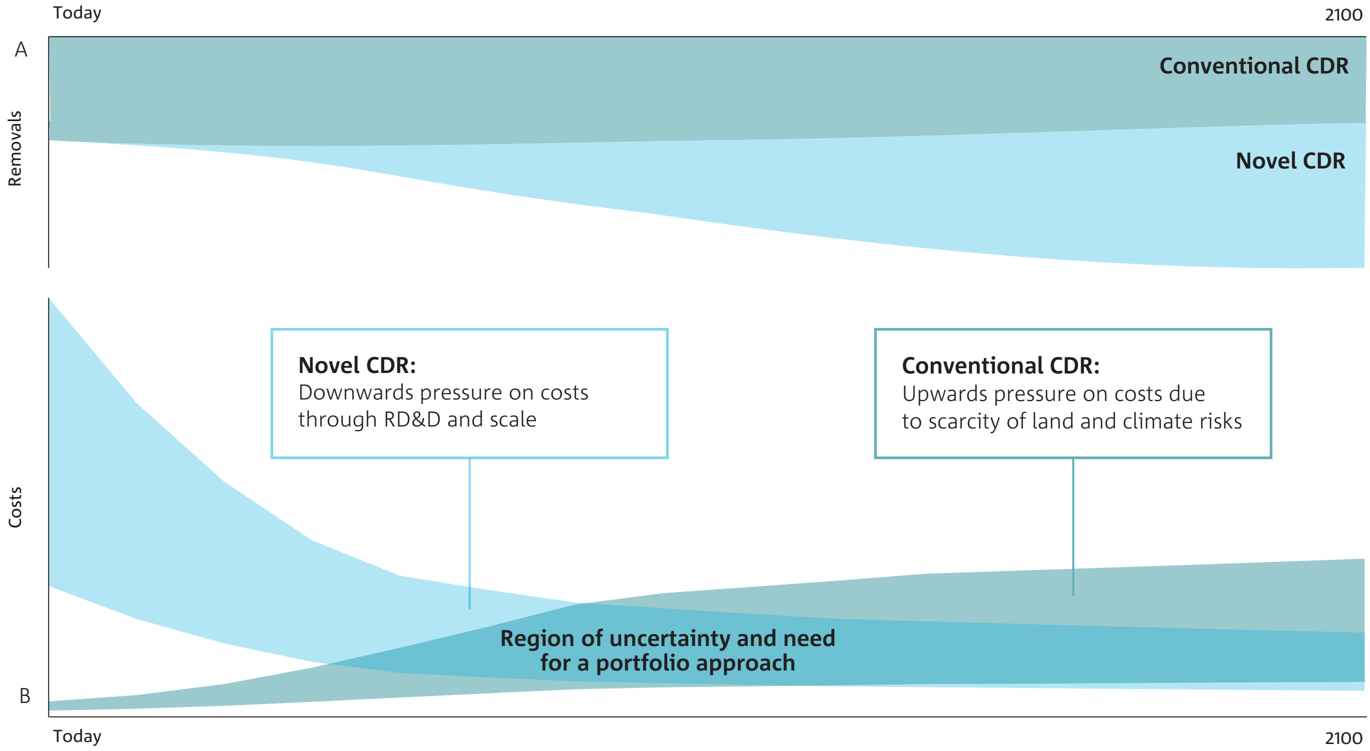
In Australia, it is projected that between 133–200 megatonnes (Mt) of CO_2 per year of CDR will be needed by 2050, depending on how dramatically emissions are reduced. These projections will not be achieved through a single approach or technology. Both existing conventional and novel CDR approaches will be needed.

Conventional CDR approaches will play an important role in reaching net zero, due to their technical feasibility and potential for deployment at scale. Given the magnitude, complexity, and urgency of the climate challenge, a diverse portfolio of solutions will be essential. This includes not only established approaches but also the development of novel CDR approaches.

A portfolio approach can help realise the opportunity presented by emerging novel CDR to deliver durable and scalable removals, while managing the near-term challenges with conventional CDR approaches (see Figure 1-A). This is consistent with Australia's Net Zero Plan, which emphasises the importance of developing a range of approaches beyond land-based options alone to ensure a more robust net zero transition.[5]

This Roadmap quantifies Australia's capacity for different novel CDR approaches, their costs and what would be needed to develop and deploy them at scale. It emphasises how these approaches can complement conventional CDR, especially as ongoing research and development reduces their cost (see Figure 1-B). It also highlights the need for ongoing collaboration and integration across scientific disciplines to rigorously assess the efficacy and integrity of each novel CDR approach, while also identifying their co-benefits and impacts on land, biodiversity, ecosystems and resources.

Figure 1: (A) Stylised removal profile for conventional and novel CDR pathways. (B) Stylised CDR cost ranges over time (2025–2100), anchored in the near term by market prices and in the mid-century by cost modelling from CSIRO's 2024 Multi-sectoral Modelling report[6] and this report.



5 Department of Climate Change, Energy, the Environment and Water (2025) Net Zero Report. DCCEEW, Canberra, ACT. <https://www.dcceew.gov.au/sites/default/files/documents/net-zero-report.pdf>.

6 Green DL, et al., (2025) Multi-sectoral modelling 2024. CSIRO, Australia. <https://www.aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2024/2025-iasr-scenarios/csiro-2024-multi-sectoral-modelling-report.pdf>.

Australia can responsibly harness its rich natural and energy resources to develop large-scale novel CDR.

Australia is uniquely positioned for the deployment of large-scale novel CDR, with advantages few other regions or nations have. These include:

- Abundant land and mineral resources: ideal for biomass cultivation and enhanced rock weathering at scale.
- Stable geological formations and one of the largest marine estates: providing high-capacity, durable storage both on land and in the ocean.
- Vast renewable energy potential: powering energy-intensive processes such as direct air capture and ocean alkalinity enhancement.
- A highly skilled workforce in engineering and resources: capable of designing, deploying and operating novel CDR systems.

Australia could reach net zero by using only a portion of its novel CDR potential to complement emissions reduction.

To inform decision making, this Roadmap examines four CDR approaches, providing national capacity and cost insights, highlighting key challenges, and recommending pathways to greater maturity and lower costs. Other developing approaches, such as ex-situ and in-situ mineral carbonation, offer strong potential and will require ongoing and future quantitative analysis.

The analysis found that, under conservative assumptions, Australia has realisable capacity for up to 330 Mt of CO_2 removals per year by 2050, across all states and territories. When combined with Australia's conventional CDR potential, Australia could surpass its projected national requirements[7] with only a portion of this identified capacity. In many of these locations, Australian novel CDR projects are already active, with 25 identified in this analysis.

While the analysis highlights significant regional opportunities for novel CDR, pursuing these opportunities will require partnership with communities and must occur alongside broader emissions reduction efforts. The evidence and recommendations in this report are intended to support informed decision making that balances environmental, societal, cultural, and economic needs.

In the next decade, Australia must build on global efforts and invest in research to improve CDR maturity, demonstrate performance, lower first-of-a-kind (FOAK) plant costs, inform regional planning and build knowledge. This Roadmap identifies key research areas to reduce risks, understand co-benefits and enable the scale-up of novel CDR in Australia. If constraints were to be relaxed under a high ambition case, Australia's capacity could almost triple to 900 Mt of CO_2 per year.

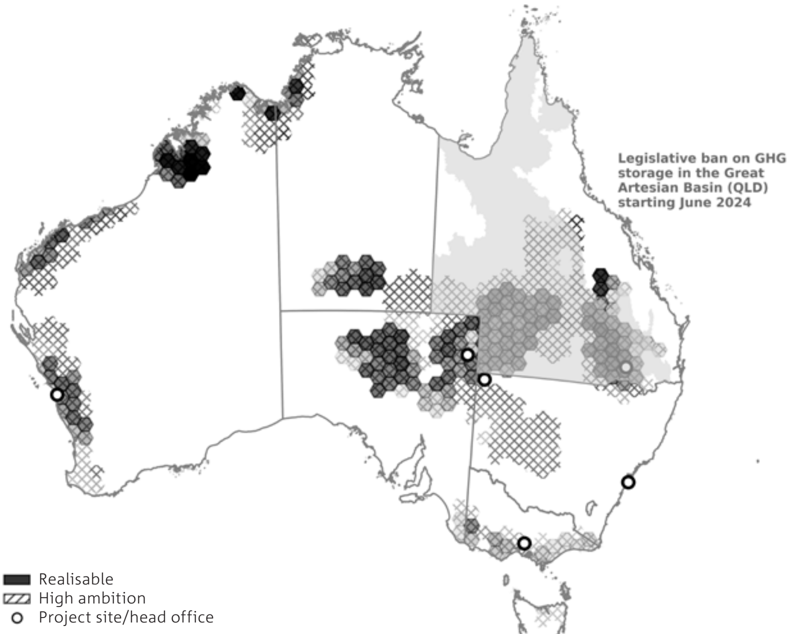
7 Climate Change Authority (2024) Sector Pathways Review 2024. Commonwealth of Australia, Canberra. <https://www.climatechangeauthority.gov.au/sites/default/files/documents/2024-09/2024SectorPathwaysReview.pdf>; Climate Change Authority (2025) 2035 Targets Advice Report. Climate Change Authority, Canberra, ACT. <https://www.climatechangeauthority.gov.au/sites/default/files/documents/2025-09/2035%20Targets%20Advice%20Report.pdf>

Direct air capture + storage (DAC+S) encompasses many approaches that separate and remove CO_2 from the atmosphere and store it durably. Solid adsorbent direct air capture and geological storage is one of two representative DAC+S approaches considered in this Roadmap.

Realisable capacity ($MtCO_2/y$)	216 (excl. QLD)
High ambition capacity ($MtCO_2/y$)	453 (excl. QLD)
2050 cost (\$/tCO_2)	\$400–480

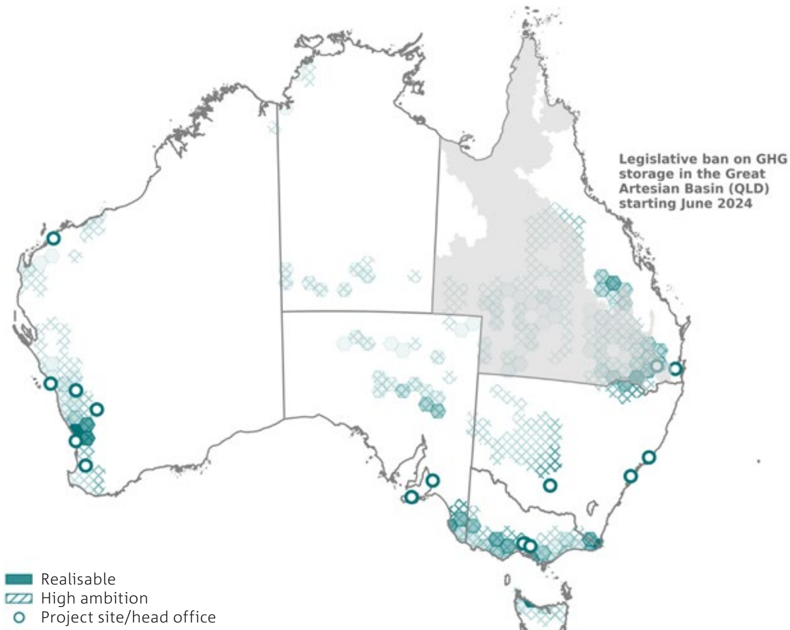
Key research areas:

- Reduce capital costs.
- Conduct climate variability trials.
- Expand renewable energy capacity.
- Reduce operational costs.
- Verify geological storage.



* The colour intensity of shaded areas and hatching indicates capacity, with darker shades and denser hatching representing high capacity.

Biomass carbon removal + storage (BiCR+S) includes approaches that transform biomass carbon into long-lived products, or capture high-purity CO_2 from biomass carbon conversion and durably store it while producing energy or other co-products. Biomass combustion to electricity and geological storage is one of two BiCR+S approaches considered in this Roadmap.



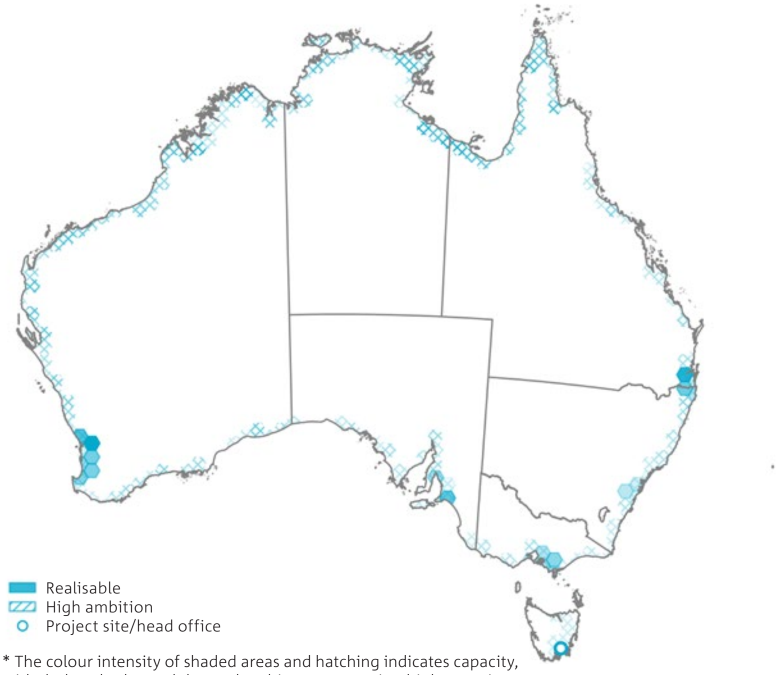
* The colour intensity of shaded areas and hatching indicates capacity, with darker shades and denser hatching representing high capacity.

Realisable capacity ($MtCO_2/y$)	88 (excl. QLD)
High ambition capacity ($MtCO_2/y$)	113 (excl. QLD)
2050 cost (\$/tCO_2)	\$140–260

Key research areas:

- Develop a national biomass inventory and allocation strategy.
- Implement cost effective supply chains.
- Optimise process design.
- Verify geological storage.

Ocean alkalinity enhancement (OAE) refers to multiple ways to increase ocean carbon storage. It utilises the naturally-occurring equilibrium reaction between atmospheric CO_2 and seawater. OAE allows additional atmospheric CO_2 to be taken up by the ocean and durably stored. This Roadmap considers electrochemical ocean alkalinity enhancement as a representative OAE approach.



* The colour intensity of shaded areas and hatching indicates capacity, with darker shades and denser hatching representing high capacity.

Realisable capacity ($MtCO_2$/y)	7 (co-located)
High ambition capacity ($MtCO_2$/y)	114 (standalone)
2050 cost (\$/tCO_2)	80–140 (co-located with existing desalination plant) \$210–390 (standalone)

Key research areas:

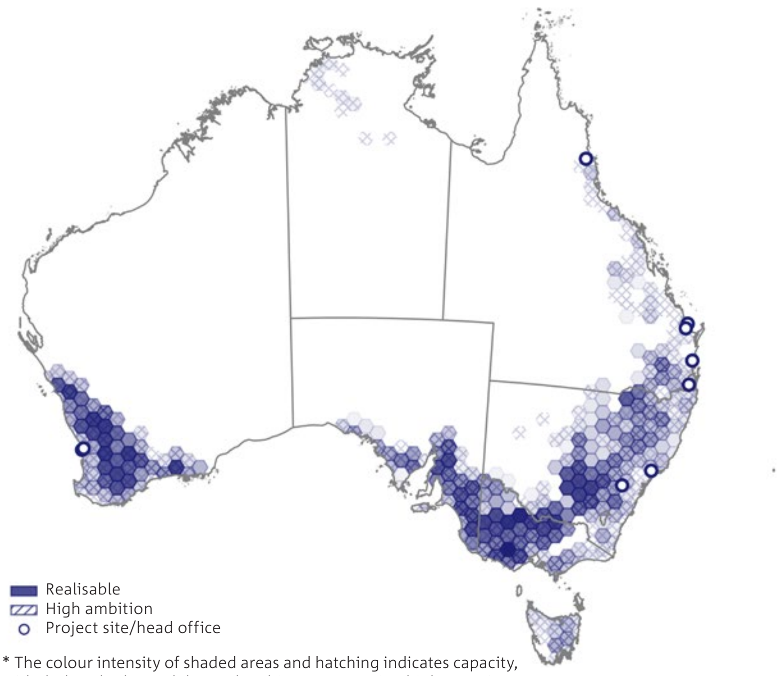
- Determine site feasibility.
- Optimise electrolyser cost and performance.
- Develop MRV for OAE.

Enhanced rock weathering (ERW) is a CDR approach that accelerates natural weathering processes to remove atmospheric CO_2 and durably store it as stable carbonates and bicarbonates. This Roadmap considers agricultural enhanced rock weathering as a representative ERW approach.

Realisable capacity ($MtCO_2$/y)	22
High ambition capacity ($MtCO_2$/y)	~220
2050 cost (\$/tCO_2)	\$190–280

Key research areas:

- Improve MRV.
- Optimise supply chains.
- Understand carbon removal potential and efficiency.
- Demonstrate opportunity for farmers and landowners.



* The colour intensity of shaded areas and hatching indicates capacity, with darker shades and denser hatching representing high capacity.

To realise the opportunity of novel CDR, Australia must build the right enabling conditions.

The opportunity requires establishing a robust enabling environment that directs and supports the emergence of a novel CDR industry in Australia. This Roadmap identifies a set of strategic actions that will nurture this environment. These actions are inherently collaborative, requiring coordination between government, industry, and research stakeholders. The recommendations are not exhaustive or prescriptive, but offer strategic direction informed by international best practices and tailored to the Australian context:

Support the development of measurement, reporting and verification (MRV) across different novel CDR approaches.

Position the scaling of CDR and the need for a portfolio of approaches as a national strategic priority alongside emissions reduction.

Consider developing a target for novel CDR in Australia.

Include novel CDR within an Australian Carbon market.

Continue building a strong science evidence base to support and optimise novel CDR deployments.

Accelerate investment in novel CDR along the innovation pathway.

Leverage existing hub-based models and infrastructure.

Identify and coordinate cost-effective and zero-emission CDR supply chains.

Foster social acceptance and awareness for novel CDR nationally and regionally.

Ensure CDR projects are developed in partnership with communities and Traditional Owners.

Australia could establish itself as a global leader in novel CDR.

Australia is uniquely positioned to lead in novel CDR, drawing on its rich natural resources, advanced industrial base, skilled workforce, and strong global partnerships. Together with targeted investment, novel CDR set Australia on a pathway to:

- Meet its own net zero commitments while supporting global climate goals.
- Create new industries that diversify the economy and build regional resilience.
- Strengthen its international competitiveness in emerging technologies and climate solutions.
- Create an opportunity in emerging international carbon markets.
- Continue to play a leading role in global climate action.

The Roadmap lays out a clear vision for developing a novel CDR industry in Australia, including the milestones and actions needed over the next two decades. It highlights regional opportunities for responsible CDR development and aims to align government, industry and research stakeholders to drive progress.

Part I: Introduction

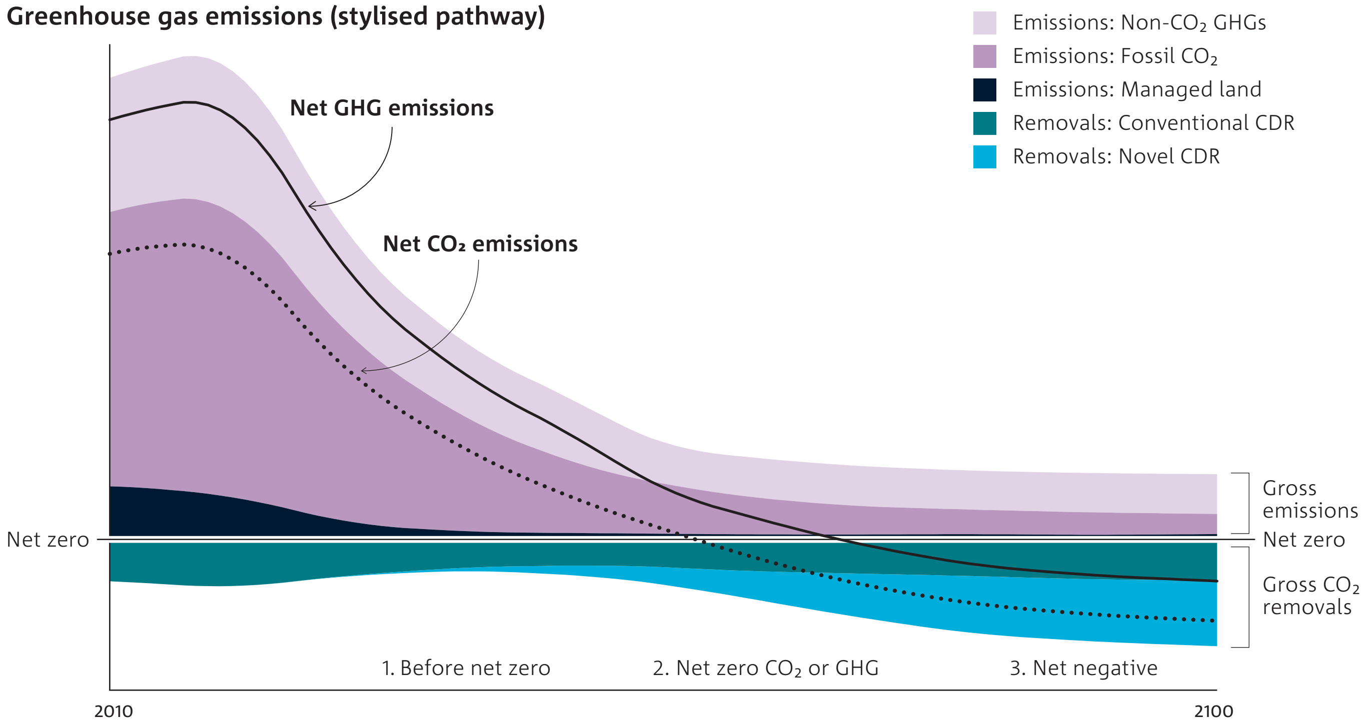
1.1 Why do we need Carbon Dioxide Removal (CDR)?

Removing significant amounts of CO_2 from the atmosphere, combined with substantial emissions reductions, will be required to meet the goals of the Paris Agreement to limit global warming to well below 2°C and achieve the internationally agreed-upon ambition of net zero greenhouse gas (GHG) emissions by 2050.

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),[8] over 50% higher than in the millennia preceding the Industrial Revolution.[9] 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 the near term, CDR is needed as a complement, rather than a substitute, for emissions reductions, to reduce net CO_2 emissions and achieve the net zero emission target by 2050, according to the Intergovernmental Panel on Climate Change's (IPCC) Climate Change 2022: Mitigation of Climate Change report.[10] In the longer term (i.e. beyond 2050), CDR will play a critical role in counterbalancing residual hard-to-abate emissions,[11] as well as achieving and sustaining net-negative emissions, a state in which more CO_2 is removed from the atmosphere than emitted. The effect of both CDR and GHG emissions on net emissions is visualised in Figure 2.[12]

Figure 2: Stylised visualisation of the net effect of CDR relative to GHG emissions, to achieve net zero and net-negative GHG emissions.[13]



8 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>.

9 Atmospheric CO_2 reached 422 ppm in December 2023, from approximately 280 ppm prior to the mid-18th 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>.

10 IPCC (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, p. 36. <https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_FullReport.pdf>.

11 Hard-to-abate emissions are emissions from sectors that are not easy to decarbonise with renewable technologies alone as these sectors often rely on carbon from fossil fuels as building blocks for products (e.g. chemicals, plastics, steel), require high energy density fuels for long-distance transport (e.g. aviation), or produce emissions inherently in their processes (cement production, agriculture in the form of methane).

12 Chamberlain MA, Ziehn T, Law RM (2024) The Southern Ocean as the climate's freight train – driving ongoing global warming under zero-emission scenarios with ACCESS-ESM1. Biogeosciences 21, 3053–3073. <https://doi.org/10.5194/bg-21-3053-2024>.

13 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>.

Global average temperatures are close to exceeding the 1.5°C above pre-industrial levels target,[14] and there is an increasing likelihood of exceeding the 2°C target.[15] Therefore, as emissions continue to rise,[16] it is becoming clear that CDR will be needed to prevent a potential temperature overshoot, which could have a long-lasting and significant impact on the climate and natural environments.[17]

1.2 What is CDR?

CDR removes CO_2 from the atmosphere and durably stores it, creating negative emissions through a combination of different capture and storage processes.

While the categorisation of CDR systems in the public domain varies, this Roadmap adapts definitions from *The State of Carbon Dioxide Removal*,[18] and defines CDR as human-facilitated activities that:

- remove CO_2 from the atmosphere
- durably store it in geological, land or ocean reservoirs, or as long-lived products.

This Roadmap focuses on the removal of atmospheric CO_2, rather than other non-CO_2 GHGs, due to the current lack of scalable techniques to remove non-CO_2 GHGs from the atmosphere. However, it is important to note that achieving global net zero objectives requires the reduction and removal of all forms of GHGs. For simplicity, quantities of CDR in this Roadmap are expressed in terms of CO_2 (i.e. tonnes of CO_2, tCO_2, megatonnes of CO_2, $MtCO_2$ or gigatonnes of CO_2, $GtCO_2$). Other emissions reduction and CDR publications use units of measure that are expressed in CO_2 equivalent (CO_2-e) terms. CO_2-e is a measure that allows the emissions from non-CO_2 GHGs to be compared on the basis of their global warming potential. It does this by converting quantities of non-CO_2 GHGs to the equivalent quantity of CO_2 with the same warming potential.

This Roadmap groups CDR approaches into two broad categories: conventional CDR and novel CDR. Conventional CDR refers to well-established approaches and activities to remove CO_2 from the atmosphere.[19] These approaches typically leverage natural biological systems, including afforestation, reforestation, and agroforestry. Conventional CDR approaches are readily available, deployed at scale, and have attained high technological maturity (technology readiness level, or TRL,[20] of 8–9). In contrast, novel CDR refers to approaches that remove CO_2 from the atmosphere and store it durably. To date, novel CDR approaches tend to be deployed on a small scale and are less mature than conventional CDR approaches.[21]

Durability in the context of CDR refers to the length of time that captured CO_2 remains out of the atmosphere, and it is a key factor differentiating conventional and novel approaches. Durability can range from a few decades to centuries or millennia.[22] At a high level, conventional CDR typically stores CO_2 for shorter timescales (i.e. decades to centuries), and novel CDR approaches are often associated with longer timescales ranging from centuries to millennia.[23]

14 Diffenbaugh NS, Barnes EA (2023) Data-driven predictions of the time remaining until critical global warming thresholds are reached. Proceedings of the National Academy of Sciences of the United States of America 120(5), e2207183120. <https://doi.org/10.1073/pnas.2207183120>.

15 Diffenbaugh NS, Barnes EA (2023) Data-driven predictions of the time remaining until critical global warming thresholds are reached. Proceedings of the National Academy of Sciences of the United States of America 120(5), e2207183120. <https://doi.org/10.1073/pnas.2207183120>; IPCC (2018) Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. World Meteorological Organization, Geneva, Switzerland. <https://www.ipcc.ch/sr15>.

16 Friedlingstein P, O'Sullivan M, Jones MW, Andrew RM, Hauck J, Landschützer P, et al. (2025) Global Carbon Budget 2024. Earth System Science Data 17(3), 965–1039. <https://doi.org/10.5194/essd-17-965-2025>.

17 Santana-Falcón Y, Yamamoto A, Lenton A, et al. (2023) Irreversible loss in marine ecosystem habitability after a temperature overshoot. Nature Communications Earth & Environment 4, 343, <https://doi.org/10.1038/s43247-023-01002-1>.

18 Smith SM, Geden O, Gidden MJ, Lamb WF, Nemet GF, Minx JC, Powis C, Bellamy R, Callaghan M, Cowie A, Cox E, Fuss S, Gasser T, Grassi G, Greene J, Lueck S, Mohan A, Müller-Hansen F, Peters G, Pratama Y, Repke T, Riahi K, Schenuit F, Steinhauser J, Strefler J, Valenzuela JM, Minx J (Eds) (2023) The State of Carbon Dioxide Removal – 1st Edition. <DOI: 10.17605/OSF.IO/W3B4Z>.

19 IPCC (n.d.) Task Force on National Greenhouse Gas Inventories (TFI). <https://www.ipcc.ch/working-group/tfi/>.

20 Technology readiness level (TRL) is a system to assess the maturity of a technology. TRL is often assessed based on a scale from 1 to 9, with 1 indicating the technology is at a basic research level and 9 indicating the technology has been proven through successful operations in operating environment, and ready for full commercial deployment. See; Department of Defence (n.d.) Technology Readiness Level (TRL) Explanations. Defence Science and Technology Group, Australia. <https://www.dst.defence.gov.au/sites/default/files/basic_pages/documents/TRL%20Explanations_1.pdf>.

21 Smith SM, Geden O, Gidden MJ, Lamb WF, Nemet GF, Minx JC, Powis C, Bellamy R, Callaghan M, Cowie A, Cox E, Fuss S, Gasser T, Grassi G, Greene J, Lueck S, Mohan A, Müller-Hansen F, Peters G, Pratama Y, Repke T, Riahi K, Schenuit F, Steinhauser J, Strefler J, Valenzuela JM, Minx J (Eds) (2023) The State of Carbon Dioxide Removal – 1st Edition. <DOI: 10.17605/OSF.IO/W3B4Z>.

22 Bergman A, Rinberg A (2021) The case for carbon dioxide removal: from science to justice. In Carbon Dioxide Removal Primer. <https://cdrprimer.org/read/chapter-1>.

23 Smith SM, et al (2023) The State of Carbon Dioxide Removal – 1st Edition. <DOI: 10.17605/OSF.IO/W3B4Z>.

Achieving CDR involves two essential steps: capturing CO_2 from the atmosphere and durably storing CO_2. These steps can be implemented through various combinations of capture and storage processes, each with distinct technical characteristics, scalability, and suitability depending on the context (see Figure 3). For example, direct air capture (DAC) is a chemical CO_2 capture process that can be paired with geological or mineral storage to form two different CDR approaches. Given the rapidly evolving nature of the global CDR landscape, Figure 3 is not exhaustive and is designed to evolve as emerging processes and data become available.

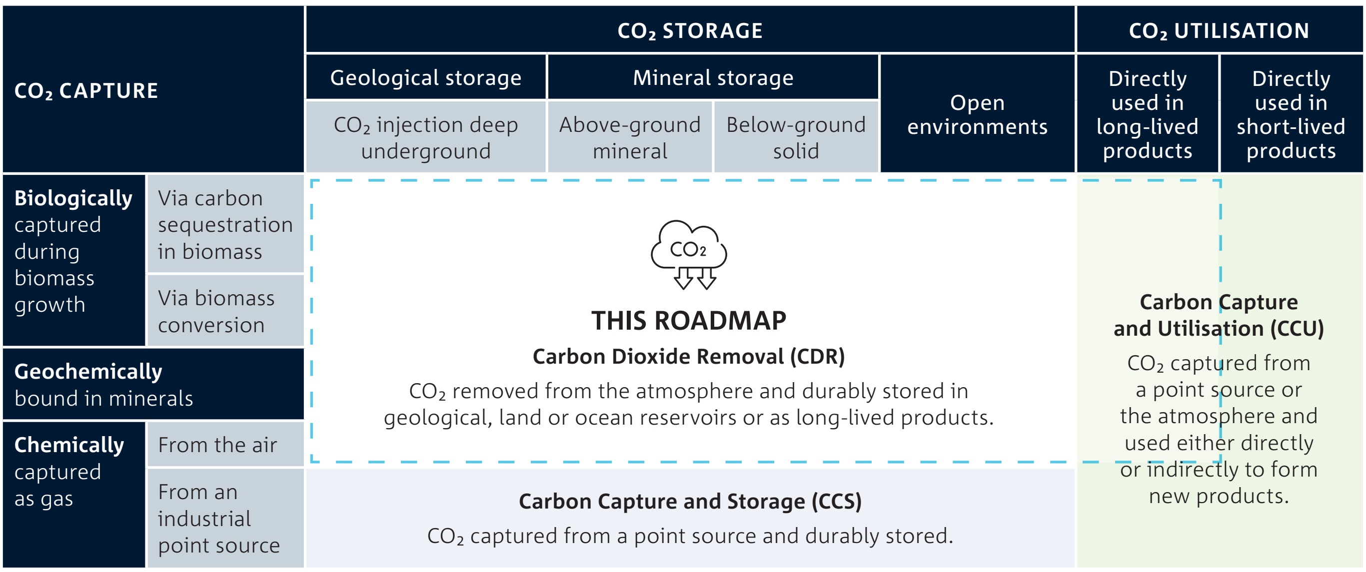
CDR represents one of the three key carbon management pathways alongside Carbon Capture and Storage (CCS) and Carbon Capture and Utilisation (CCU), each with a unique but complementary role to help Australia and the world achieve net zero ambitions. CDR differs from other carbon management approaches which generally seek to prevent carbon from entering the atmosphere, versus CDR which seeks to provide removals, or negative emissions outcomes. See Box 1 for a summary of other carbon management pathways and their interrelation with CDR.

Box 1: Carbon management.

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 in products or industrial processes. 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. Assessing additionality is a key feature of CDR and is important to all carbon credit schemes.[24]

While all three carbon management pathways have a role to play in achieving internationally agreed net zero ambitions, CCS and CCU are out of scope for discussion in this Roadmap. However, it is important to recognise that capture, storage and utilisation processes can serve complementary and dual purposes. For example, a DAC system that captures and durably stores CO_2 from the atmosphere is CDR. Alternatively, if it uses atmospheric CO_2 to produce synthetic fuels, it is considered CCU. As CO_2 capture and storage technologies advance, they can support scaling across all carbon management pathways and progress towards net zero.

Figure 3: Overview of various combinations of capture and storage processes or systems that make up different carbon management pathways, including CDR, CCS and CCU.



24 Climate Change Authority (2024) Coverage additionality and baselines. <https://www.climatechangeauthority.gov.au/sites/default/files/CCA_CFIStudyPublicReportChapter4.pdf>.

1.3 How much CDR do we need?

Under all net zero scenarios, significant and additional CDR will be essential, globally and in Australia.

The precise level of global and Australian CDR required will depend on a range of factors, including the current and future costs of abatement, available CDR approaches and their near-term adoption, the pace and extent of emissions reduction efforts, as well as the availability and development of low-emissions technologies.[25]

Most global estimates, including those from the IPCC,[26] agree that billions of tonnes of CO_2 must be removed annually worldwide. For example, the 2024 State of CDR report suggested 7–9 Gt of CO_2 per year ($GtCO_2$/y) would need to be removed from the atmosphere.[27] The report also estimated that 260 $GtCO_2$ would need to be cumulatively removed between 2020 and the time of net zero emissions, based on many IPCC scenarios that aim to limit warming below 2°C.[28] However, in other sustainable development scenarios,[29] a lower amount of 170 Gt of CO_2 would need to be cumulatively removed, reflecting a more responsible and sustainable pathway for CDR deployment.[30]

On average, around 2 Gt of CO_2 is being removed through CDR globally, predominantly through conventional CDR activities such as afforestation and reforestation.[31] As of July 2025, the data sharing project CDR.fyi reported that credits for 37 megatonnes (Mt) of novel CDR have been sold on carbon markets and are committed to be removed, of which 2.2% have actually been removed and durably stored.[32]

In Australia, the Climate Change Authority (CCA) has estimated that the country will need at least 133 Mt of CO_2 removals by 2050 to achieve its national net zero targets.[33] Figure 4 illustrates possible emissions reduction pathways under two selected CCA scenarios. Under these scenarios, Australia will require anywhere between 133 and 200 Mt of CO_2 removals in 2050, depending on the emissions reduction rate.[34] However, the exact level of CDR and mix of conventional and novel CDR required is difficult to determine and highly sensitive to the modelling assumptions used. Another recent study,[35] with different underpinning assumptions, estimated a similar overall level of CDR required but at a greater reliance on novel CDR in its "Net-zero Emissions by 2050" scenario.

The Australian Government, in its response to the CCA's 2023 Annual Climate Change Statement, acknowledges the need to incentivise the development of novel CDR by supporting research, development and demonstration (RD&D) through carbon markets or other financial instruments, as well as by helping to reduce the domestic and international regulatory barriers limiting its uptake.[36] By supporting key CCA recommendations, the government is recognising the role novel CDR can play in achieving net zero.

25 Bergman A, Rinberg A (2021) The case for carbon dioxide removal: from science to justice. In Carbon Dioxide Removal Primer. <https://cdrprimer.org/read/chapter-1>.

26 The review study, Fuss et al., finds that models estimate between 1.3 and 29 $GtCO_2$/y will be needed by 2050, with the most likely amount being between 5 and 15 $GtCO_2$y. See; Fuss S, Lamb WF, Callaghan MW, Hilaire J, Creutzig F, Amann T, Beringer T, de Oliveira Garcia W, Hartmann J, Khanna T, Luderer G, Nemet GF, Rogelj J, Smith P, Vicente JL, Wilcox J, Zamora Dominguez MM, Minx JC (2018) Negative emissions—Part 2: Costs, potentials and side effects. Environmental Research Letters 13(6), 063002. <https://doi.org/10.1088/1748-9326/aabf9f>; Minx JC, Lamb WF, Callaghan MW, Fuss S, Hilaire J, Creutzig F, Amann T, Beringer T, de Oliveira Garcia W, Hartmann J, Khanna T, Lenzi D, Luderer G, Nemet GF, Rogelj J, Smith P, Torvanger A, Waller L, Weber E, Wilcox J (2018) Negative Emissions Technologies and Reliable Sequestration: A Research Agenda. <https://pubmed.ncbi.nlm.nih.gov/31120708/>;

27 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>.

28 Smith SM et al., (2024) The State of Carbon Dioxide Removal 2024 – 2nd Edition. <DOI:10.17605/OSF.IO/F85QJ>.

29 Scenarios refer to scientifically modelled storylines of a plausible future, based on many assumptions about the future evolution of demographics, economic growth and technological progress, among others. IPCC scenarios are scenarios that are based primarily on IPCC temperature classifications and outcomes. Sustainable development scenarios are a subset of scenarios that consider additional social and environmental sustainability criteria while also limit global warming.

30 Smith SM et al., (2024) The State of Carbon Dioxide Removal 2024 – 2nd Edition. <DOI:10.17605/OSF.IO/F85QJ>.

31 Smith SM et al., (2024) The State of Carbon Dioxide Removal 2024 – 2nd Edition. <DOI:10.17605/OSF.IO/F85QJ>.

32 CDR.fyi (n.d.) <https://www.cdr.fyi/>.

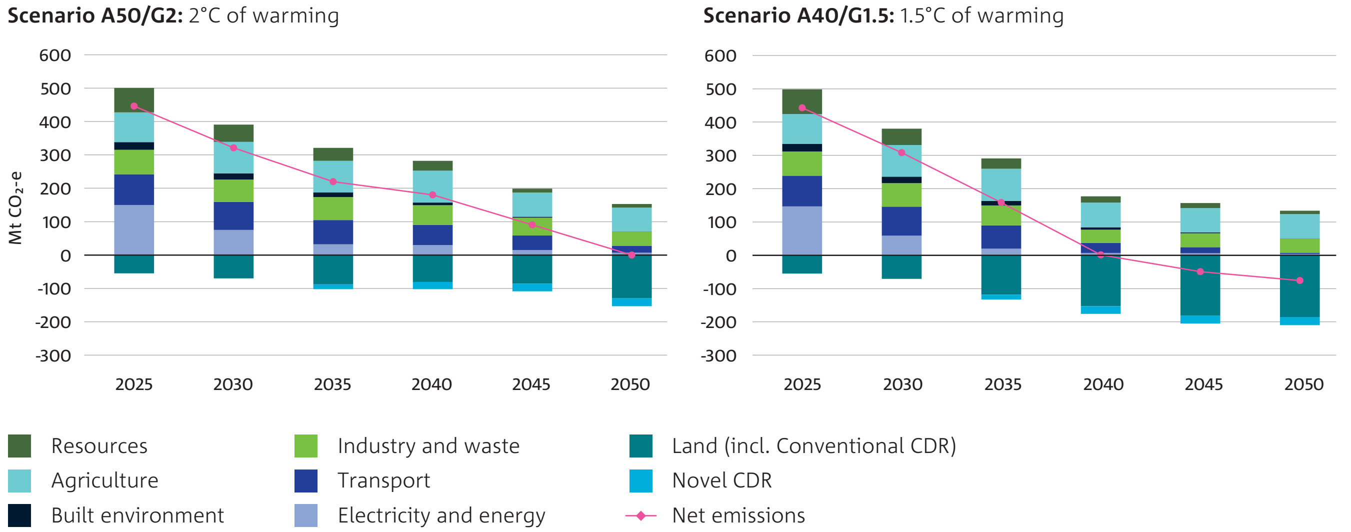
33 Climate Change Authority (2024) Sector Pathways Review 2024. Commonwealth of Australia, Canberra. <https://www.climatechangeauthority.gov.au/sites/default/files/documents/2024-09/2024SectorPathwaysReview.pdf>.

34 Climate Change Authority (2024) Sector Pathways Review 2024. Commonwealth of Australia, Canberra. <https://www.climatechangeauthority.gov.au/sites/default/files/documents/2024-09/2024SectorPathwaysReview.pdf>; Climate Change Authority (2025) 2035 Targets Advice Report. Climate Change Authority, Canberra, ACT. <https://www.climatechangeauthority.gov.au/sites/default/files/documents/2025-09/2035%20Targets%20Advice%20Report.pdf>

35 Nong D, Verikios G, Whitten S, et al. (2025) Early transition to near-zero emissions electricity and carbon dioxide removal is essential to achieve net-zero emissions at a low cost in Australia. Communications Earth & Environment 6, 653. <https://doi.org/10.1038/s43247-025-02615-4>.

36 Department of Climate Change, Energy, the Environment and Water (2023) Annual Climate Change Statement 2023. <https://www.dcceew.gov.au/sites/default/files/documents/annual-climate-change-statement-2023.pdf>.

Figure 4: Modelling of emissions reductions and CDR under two net zero scenarios.



The gross emissions (Mt CO_2-e) of seven sectors (land, electricity and energy, transport, industry and waste, built environment, agriculture and resources) and carbon removals through novel CDR approaches together achieve net zero emissions by 2050 under two chosen scenarios. Scenario A50/G2 aligns with Australia's current targets, a 43% emissions reduction from 2005 levels by 2030 and net zero by 2050 in a world tracking towards 2°C of warming, and Scenario A40/G1.5 aligns with faster emissions reductions in a world tracking towards 1.5°C of warming. Sourced from CSIRO modelling in AusTIMES, commissioned by the Climate Change Authority (2024).[37]

37 Climate Change Authority (2024) Sector Pathways Review 2024. Commonwealth of Australia, Canberra. <https://www.climatechangeauthority.gov.au/sites/default/files/documents/2024-09/2024SectorPathwaysReview.pdf>.

1.4 Why do we need a portfolio approach?

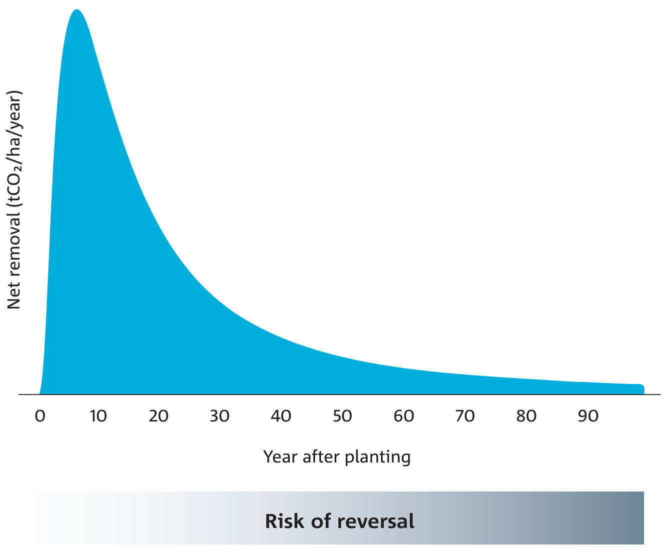
No single CDR approach can achieve the required scale for Australia to reach net zero by 2050. While it is expected that conventional CDR will continue to provide near-term benefits, novel CDR approaches are anticipated to be favoured in the long term to achieve net zero and beyond.

Both conventional and novel CDR approaches face limitations and are exposed to risks, underscoring that no single approach can achieve the large-scale deployment necessary to limit global warming below 2°C.

Conventional approaches, such as afforestation and reforestation, are cost-effective in the near term, with a global average cost of A$18–24 per tCO_2 removed.[38] However, their storage potential saturates over time (as shown in Figure 5), are land-intensive, and their CO_2 removal capacity is inherently constrained by land availability and competition with other primary industries, such as agriculture and the production of low-carbon fuels.[39]

The profile in Figure 5 suggests additional land would be required each year to maintain a constant rate of conventional CDR over time, putting upward pressure on land prices and costs. Similarly, it shows how conventional CDR approaches tend to rely on storage in carbon stocks that have a risk of reversal.[40] According to Australia's 2025 National Climate Risk Assessment Report,[41] land-based mitigation options are increasingly compromised by climate change and extreme events (e.g. bushfires, floods, droughts, pests) or human-related activities (e.g. logging, land-use change, urban area expansion).[42]

Figure 5: Stylised annual CO_2 removal profile for conventional CDR per hectare of land.[43]



In contrast, novel CDR approaches offer durable storage over much longer timescales, potentially exceeding 10,000 years. This is because novel CDR approaches store CO_2 in less easily reversible forms, such as in geological storage formations (see Section 5) or as stable carbonates (see Section 7). However, novel CDR approaches are still emerging and come with significant energy and resource requirements, as well as high costs, especially in the near term.[44]

For example, this Roadmap estimates that CDR via a first-of-a-kind direct air capture and storage facility will cost in excess of ~A$1,000 per tCO_2 in 2025 (see Section 9). While costs are projected to significantly fall in the future, this can only be realised with technological advancements, as well as the support of market-related, cross-cutting enablers to direct capital, enable cost-effective integration with existing infrastructure, and build social acceptance (see Section 14).

38 Smith SM et al., (2024) The State of Carbon Dioxide Removal 2024 – 2nd Edition. <DOI:10.17605/OSF.IO/F85QJ>.

39 IPCC (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. <https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_FullReport.pdf>.

40 Caldecott B, Johnstone I (2024) The carbon removal budget: theory and practice. Journal of Environmental Policy & Planning 15(1), Article 2374515. <https://doi.org/10.1080/17583004.2024.2374515>.

41 Australian Climate Service (2025) Australia's National Climate Risk Assessment. Australian Climate Service, Canberra, ACT. <https://www.acs.gov.au/pages/national-climate-risk-assessment>.

42 Mota-Nieto J (2024) Carbon Dioxide Removal (CDR): A Key Pillar of Carbon Management and Sustainability. Energy Insight: 158. Oxford Institute for Energy Studies, Oxford, UK. <https://www.oxfordenergy.org/wpcms/wp-content/uploads/2024/11/Insight-158-Carbon-Dioxide-Removals.pdf>.

43 Profile based on average annual sequestration profile for mallee monoculture plantings from FullCAM. See: Department of Climate Change, Energy, the Environment and Water (DCCEEW) (2024) Full Carbon Accounting Model (FullCAM). Commonwealth of Australia, Canberra. <https://www.dcceew.gov.au/climate-change/publications/full-carbon-accounting-model-fullcam>.

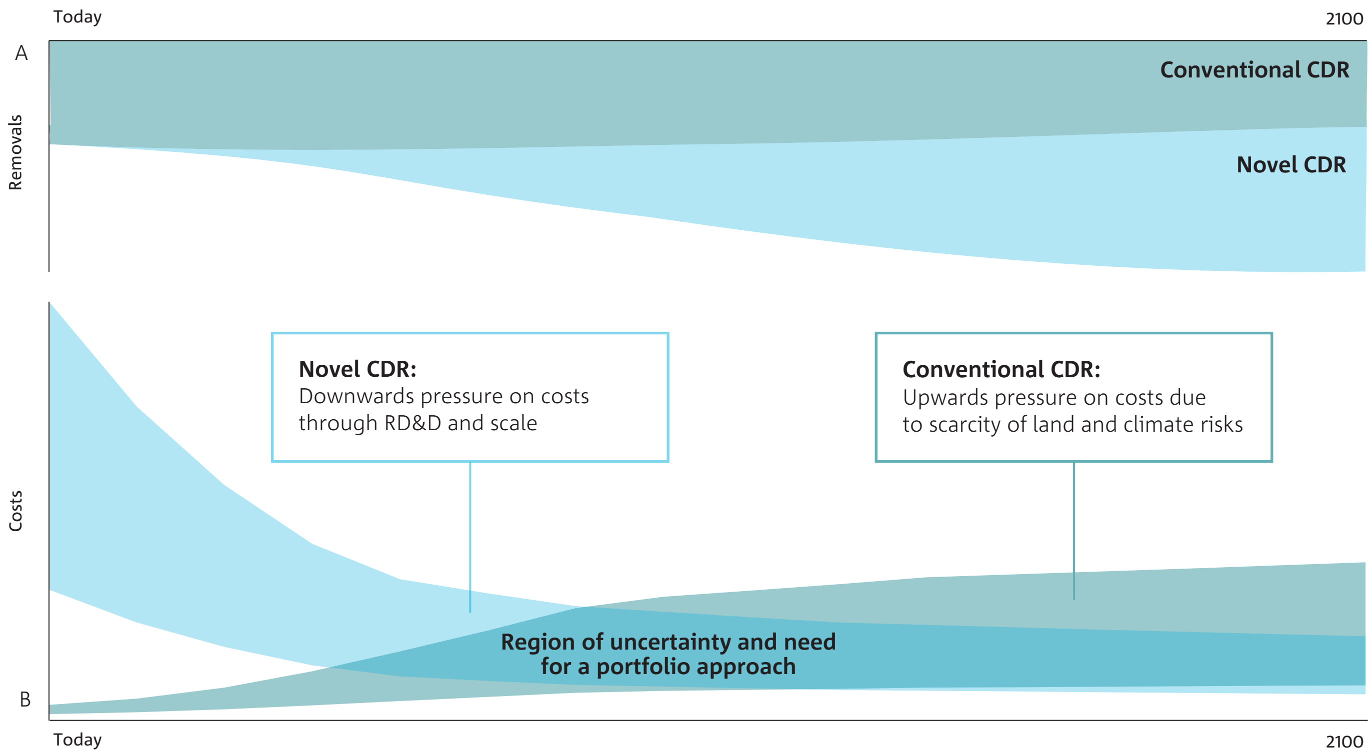
44 Smith SM et al., (2024) The State of Carbon Dioxide Removal 2024 – 2nd Edition. <DOI:10.17605/OSF.IO/F85QJ>.

Figure 6 illustrates how a portfolio approach could be required to manage risk and create future CDR optionality. Figure 6 (A) provides a stylised removal profile for conventional and novel CDR pathways, demonstrating the discussed saturation that is expected with conventional CDR over time. Figure 6 (B) depicts the cost-competitiveness of conventional and novel removals over time. While future cost trajectories cannot be predicted with certainty, the near-term costs reflect the current market, while mid-century costs are informed by CSIRO's 2024 Multi-Sectoral Modelling report[45] (for conventional CDR) and this Roadmap (for novel CDR).

These estimates do not explicitly account for durability differences between conventional and novel approaches, which will place additional value in a portfolio approach.

When viewed together, the capacity and cost profiles in Figure 6 (A) and (B) highlight that a diverse mix of CDR approaches will be essential. It will be important to optimise the use of cheap and available conventional CDR in the near term while supporting RD&D of novel CDR approaches to reduce their costs and improve their scalability.

Figure 6: (A) Stylised removal profile for conventional and novel CDR pathways. (B) Stylised CDR cost ranges over time (2025–2100), anchored in the near term by market prices and in the mid-century by cost modelling from CSIRO's 2024 Multi-sectoral Modelling report[46] and this report.



45 Green DL, Reedman LJ, Kanudia A, Murugesan M, Dollman R, West S, Dioguardi E, Grant A, Nolan M, Singha D, Maxwell R, Li M, Havas L (2025) Multi-sectoral modelling 2024. CSIRO, Australia. <https://www.aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2024/2025-iasr-scenarios/csiro-2024-multi-sectoral-modelling-report.pdf>.

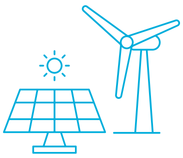
46 Green DL, et al., (2025) Multi-sectoral modelling 2024. CSIRO, Australia. <https://www.aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2024/2025-iasr-scenarios/csiro-2024-multi-sectoral-modelling-report.pdf>.

1.5 Australia's resource potential

Australia's rich natural and energy assets offer a globally unique platform to scale up both conventional and novel CDR.

Australia is endowed with natural assets, including abundant land and mineral resources, high-durability geological basins and their significant CO_2 storage capacities, a vast marine estate, and low-emission energy opportunities. Together, these endowments position Australia and create the opportunity for it to be an early mover in global CDR markets, which are projected to expand into a multi-billion to trillion-dollar industry by 2050,[47] encompassing both compliance and voluntary markets. Combined with stable institutions and a highly skilled engineering and natural resource industry workforce, these advantages enable the near-term deployment of cost-effective conventional CDR, while supporting development and scale-up of novel approaches to reduce their costs and resource requirements over time. The breadth of these advantages is illustrated in Figure 7 and explored further in Part III of the report.

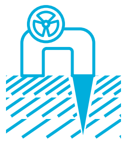
Figure 7: A summary of Australia's resource potential, including natural assets, land and mineral resources, geological basins, marine estate and low-emission energy potential.



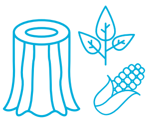
Globally competitive **renewable energy potential**.

8.5 million km² exclusive economic zone, **the 3rd** largest in the world.

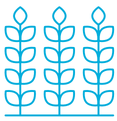
Extensive mafic and ultramafic rock reserves with additional potential for reuse of mining residues.



Internationally recognised geological storage potential.



Significant waste and residue **biomass resources**.



650,000 km² of pasture, cropping and horticultural land.

47 Harrison K (2024) Carbon credits face biggest test yet, could reach $238/ton in 2050, according to BloombergNEF report. BloombergNEF, New York and London. <https://about.bnef.com/insights/commodities/carbon-credits-face-biggest-test-yet-could-reach-238-ton-in-2050-according-to-bloombergnef-report/>.

1.6 Report overview

This Roadmap aims to quantify Australia's potential to durably remove CO_2 from the atmosphere, helping Australia develop a portfolio of solutions for carbon removal. It provides an objective assessment of the cost, scalability, measurement, reporting and verification (MRV) requirements needed to support the deployment of novel CDR approaches.

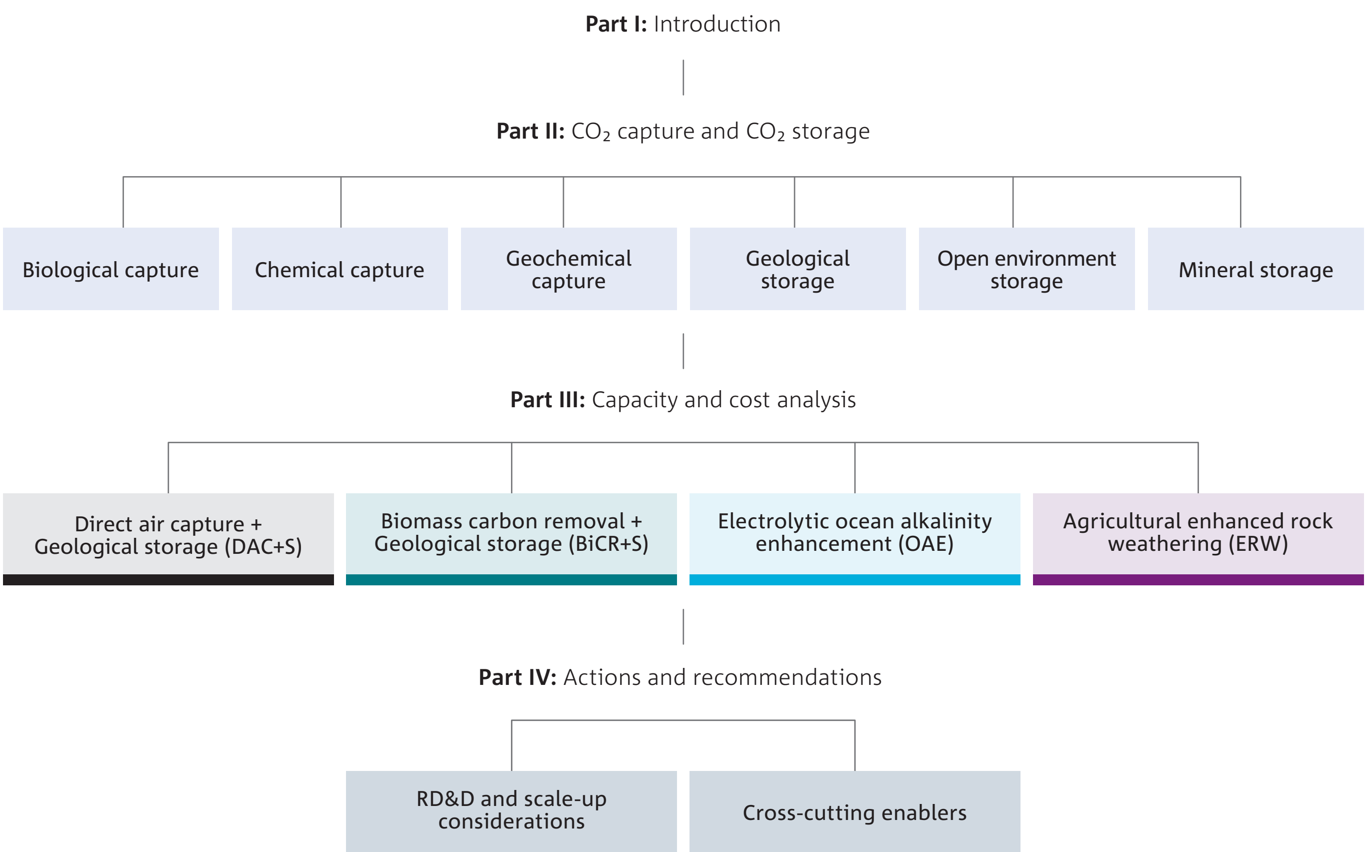
With conventional CDR already contributing to Australia's climate goals, this Roadmap builds an evidence base for the potential to use novel CDR through transparent, objective and proportionate economic analysis. It also looks to identify the key actions required to scale up novel CDR in Australia, across various approaches and RD&D timelines, as well as cross-cutting enablers such as finance, policy, markets, infrastructure and social and environmental engagement.

This Roadmap consists of four parts, as shown in Figure 8. Part II explores CO_2 capture and CO_2 storage separately, given the range of possible CDR combinations available (see Figure 3). The section also aims to provide a foundation for the cost and capacity analysis to follow. Part III outlines the methodology used to assess Australia's potential for novel CDR and presents results for four representative CDR approaches:

- Direct air capture and geological storage (DAC+S).
- Biological carbon removal and geological storage (BiCR+S).
- Electrolytic ocean alkalinity enhancement (OAE).
- Agricultural enhanced rock weathering (ERW).

The Roadmap concludes with Part IV, which presents actions and recommendations for the RD&D and scale-up strategy for the four CDR approaches analysed, as well as the cross-cutting enablers for the novel CDR industry in Australia.

Figure 8: This Roadmap consists of four parts (Introduction, CO_2 capture and CO_2 storage, Capacity and cost analysis, and Actions and recommendations).



Climeworks' Mammoth plant © OZZO Photography.

Part II: CO_2 capture and CO_2 storage

This part of the Roadmap examines processes that capture and durably store CO_2, recognising that the integration of both is required to create durable CDR approaches. Figure 9 presents the taxonomy used to structure the analysis, focusing solely on CDR-specific capture and storage processes, which form a non-exhaustive selection of CDR approaches. These approaches represent a subset of broader carbon management approaches, which also include CCS and CCU (see Figure 3, Section 1.2).

This Roadmap considers three forms of capture: biological CO_2 capture (Section 2), geochemical CO_2 capture (Section 3) and chemical CO_2 capture (Section 4) and three CO_2 storage processes: geological storage (Section 5), open environment storage (Section 6), mineral CO_2 storage (Section 7). For each of the capture and storage processes considered, this section provides an overview of the process or system, focusing specifically on the approaches analysed in this Roadmap (see Figure 9), and their current state of development globally and in Australia. As a result, this section is not considered an exhaustive discussion of all CO_2 storage processes relevant to the CDR landscape. While out of scope for this Roadmap, information on conventional CDR has been provided for completeness.

Figure 9: A summary of CDR approaches considered in this section of the Roadmap, including their durability.

CO_2 CAPTURE		CO_2 STORAGE			
		Geological storage	Mineral storage		Open environments
		CO_2 injection deep underground	Above-ground mineral	Below-ground solid	
Biologically captured during biomass growth	Via carbon sequestration in biomass				Conventional CDR 10–100 years
	Via biomass conversion	BiCR+S – fast pyrolysis to H_2, combustion >1,000 years	BiCR+S (ex-situ mineral carbonation) >1,000 years	BiCR+S (in-situ mineral carbonation) >1,000 years	BiCR+S – slow pyrolysis to biochar 100–1,000 years
Geochemically bound in minerals			Ex-situ mineral carbonation >1,000 years		ERW >1,000 years OAE >1,000 years
Chemically captured as gas	From the air	DAC+S (geological storage) >1,000 years	DAC+S (ex-situ mineral carbonation) >1,000 years	DAC+S (in-situ mineral carbonation) >1,000 years	

2 Biological capture

Biological CO_2 capture refers to the process of capturing CO_2 during the growth of biomass. This section begins with an exploration of biological capture used for conventional CDR, followed by biomass carbon removal (BiCR). Conventional biological capture describes the well-established approaches that remove CO_2 from the atmosphere through biological processes (i.e. photosynthesis). However, these biological processes do not always result in the durable removal of CO_2, for example, due to natural decomposition. In contrast, BiCR is a novel capture process that converts biomass into long-lived products and/or high-purity CO_2 for durable geological and mineral storage (see Section 5–7).

2.1 Conventional biological capture

Biological capture, or primary productivity, describes well-established, human-induced approaches to increase the rate of CO_2 capture from the atmosphere through biological processes (i.e. photosynthesis). This CO_2 is then stored in plants, biomass and soil (see Section 6).[48] Biological capture approaches underpin conventional CDR and are currently deployed at scale globally as part of land-use, land-use change, and forestry activities.[49] This section provides an overview of common biological capture approaches and their state of development, as well as the MRV considerations for carbon accounting.

2.1.1 Overview

Conventional biological capture approaches include, but are not limited to, afforestation, reforestation and agroforestry.[50] Table 1 provides a high-level overview of these approaches.

Table 1: Common conventional CDR approaches.[51]

APPROACH	DESCRIPTION
Afforestation	Conversion to forest of land that was not previously forested.
Reforestation	Conversion to forest of land that was previously deforested.
Agroforestry	Growing trees on agricultural land while maintaining agricultural production systems.

Biological capture projects must consider the local context, such as soil conditions and ecosystems, climate, land ownership, and the project's scale, establishment, and maintenance. Any activities associated with agricultural production also need to adapt to existing agricultural practices, balancing between carbon capture and maintaining agricultural productivity.[52]

Well-planned biological capture activities can yield numerous environmental co-benefits, such as improving soil health and quality, biodiversity, system resilience, as well as enhanced forest and agricultural productivity. They can also provide additional employment for local communities, supporting local economies,[53] although the net employment impact will depend on the previous land use.

48 Smith SM, Geden O, Gidden MJ, Lamb WF, Nemet GF, Minx JC, Powis C, Bellamy R, Callaghan M, Cowie A, Cox E, Fuss S, Gasser T, Grassi G, Greene J, Lueck S, Mohan A, Müller-Hansen F, Peters G, Pratama Y, Repke T, Riahi K, Schenuit F, Steinhauser J, Strefler J, Valenzuela JM, Minx J (Eds) (2023) The State of Carbon Dioxide Removal – 1st Edition. <DOI: 10.17605/OSF.IO/W3B4Z>.

49 Smith SM et al., (2024) The State of Carbon Dioxide Removal 2024 – 2nd Edition. <DOI:10.17605/OSF.IO/F85QJ>.

50 Smith SM et al., (2024) The State of Carbon Dioxide Removal 2024 – 2nd Edition. <DOI:10.17605/OSF.IO/F85QJ>.

51 Smith SM et al., (2024) The State of Carbon Dioxide Removal 2024 – 2nd Edition. <DOI:10.17605/OSF.IO/F85QJ>.; IPCC (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. <https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_FullReport.pdf>.

52 IPCC (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. <https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_FullReport.pdf>.

53 IPCC (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. <https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_FullReport.pdf>.

State of development

Biological capture approaches are mature (TRL 8–9) and widely adopted, with many companies operating at commercial scales in Australia and globally. This maturity provides a potential near-term pathway for Australia and the world to reach their net zero targets. At the same time, broader decarbonisation is taking place and novel capture approaches are being developed and scaled up.

Over the period between 2010 and 2020 in Australia, biological capture activities had helped to remove a substantial amount of CO_2 from the atmosphere, with human-induced regeneration of native forests delivering the highest average sequestration rate of 20 Mt of CO_2 per year ($MtCO_2$/y), followed by plantation and farm forestry at 11.5 $MtCO_2$/y.[54] By 2050, biological capture activities have the potential to remove 74–130 $MtCO_2$/y in Australia, according to CCA's model of a Paris-aligned net zero pathway for Australia.[55] Globally, biological capture activities are projected to remove 5.7 gigatons (Gt) of CO_2 by 2050, according to the 2024 State of Carbon Dioxide Removal report.[56]

Globally, approximately 2.2 Gt of CO_2 were removed from the atmosphere in 2022, the majority of which came from biological capture activities, with less than 0.1% (i.e. 1.35 Mt of CO_2) coming from novel capture processes.[57] Afforestation and reforestation account for the majority of global conventional CDR activities, most actively driven by China, the collective European Union countries, the US, Brazil, and the Russian Federation.[58]

2.1.2 MRV capture and storage

While many MRV protocols have been developed for biological capture approaches globally, continued RD&D will help strengthen methodologies for quantifying the amount of CO_2 removed, enhance the consistency between different protocols, and integrate advanced technologies to improve MRV efficiency and reduce costs. As of 2024, 34 protocols had been developed for afforestation, reforestation, agroforestry, and forest management.[59] Different instruments (e.g. eddy covariance or chamber systems), techniques (e.g. field sampling, remote sensing), models (e.g. the Full Carbon Accounting Model, or FullCAM, developed by the Australian Government Department of Climate Change, Energy, the Environment and Water, or DCCEEW[60]) and emission factors can be used together to measure and quantify the total CO_2 removal of biological capture activities.[61]

For the MRV of afforestation, reforestation and agroforestry, challenges and uncertainties remain in quantifying the CO_2 fluxes (i.e., emissions and removals) from land use, land-use change, and forestry activities.[62] There are also inconsistencies across different protocols and countries in the distinction between natural and anthropogenic CO_2 fluxes.[63] Both factors have contributed to general concerns from the public around the quality of the carbon credits issued for these activities.[64] Some MRV approaches apply discounts to generated credits to account for these uncertainties.

54 Fitch P, Battaglia M, Lenton A, Feron P, Gao L, Mei Y, Hortle A, Macdonald L, Pearce M, Occhipinti S, Roxburgh S, Steven A (2022) Australia's sequestration potential. CSIRO.

55 Climate Change Authority (2024) Sector Pathways Review 2024. Commonwealth of Australia, Canberra. <https://www.climatechangeauthority.gov.au/sites/default/files/documents/2024-09/2024SectorPathwaysReview.pdf>.

56 Smith SM et al., (2024) The State of Carbon Dioxide Removal 2024 – 2nd Edition. <DOI:10.17605/OSF.IO/F85QJ>.

57 Smith SM et al., (2024) The State of Carbon Dioxide Removal 2024 – 2nd Edition. <DOI:10.17605/OSF.IO/F85QJ>.

58 Smith SM et al., (2024) The State of Carbon Dioxide Removal 2024 – 2nd Edition. <DOI:10.17605/OSF.IO/F85QJ>.

59 Smith SM et al., (2024) The State of Carbon Dioxide Removal 2024 – 2nd Edition. <DOI:10.17605/OSF.IO/F85QJ>.

60 Department of Climate Change, Energy, the Environment and Water (DCCEEW) (2024) Full Carbon Accounting Model (FullCAM). Commonwealth of Australia, Canberra. <https://www.dcceew.gov.au/climate-change/publications/full-carbon-accounting-model-fullcam>.

61 Smith SM et al., (2024) The State of Carbon Dioxide Removal 2024 – 2nd Edition. <DOI:10.17605/OSF.IO/F85QJ>.

62 Smith SM et al., (2024) The State of Carbon Dioxide Removal 2024 – 2nd Edition. <DOI:10.17605/OSF.IO/F85QJ>.

63 Smith SM et al., (2024) The State of Carbon Dioxide Removal 2024 – 2nd Edition. <DOI:10.17605/OSF.IO/F85QJ>.

64 Smith SM et al., (2024) The State of Carbon Dioxide Removal 2024 – 2nd Edition. <DOI:10.17605/OSF.IO/F85QJ>.

2.2 Biomass carbon removal (BiCR)

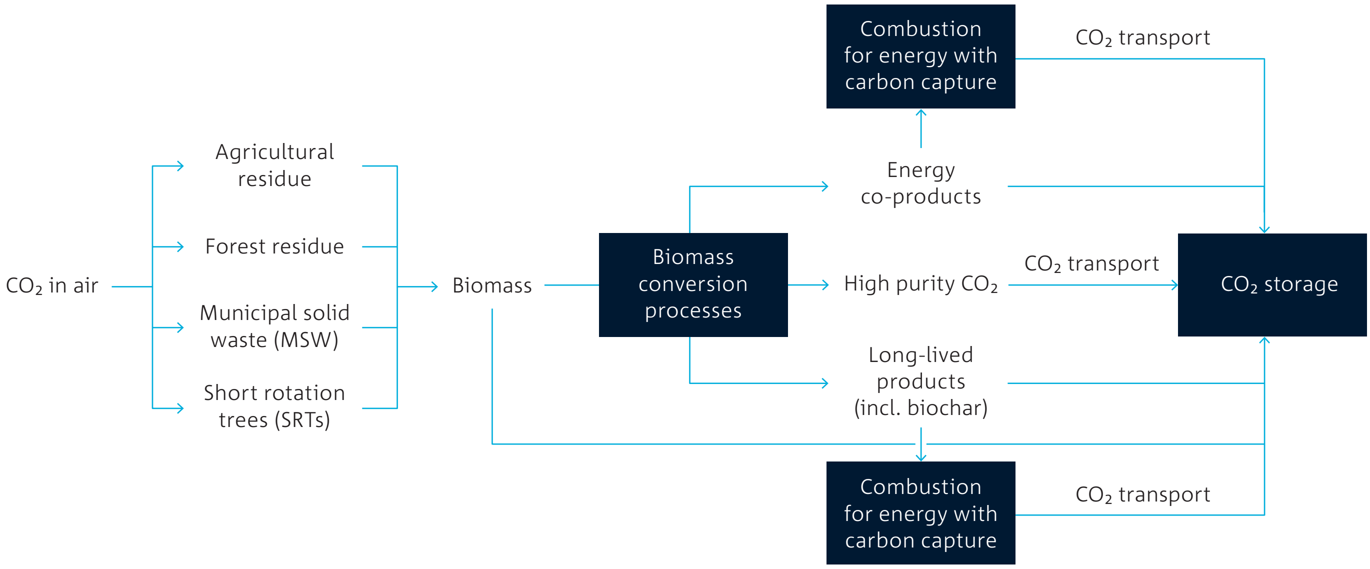
BiCR is a novel capture approach that builds upon conventional biological CO_2 capture, enhancing the durability of the stored carbon. Specifically, BiCR goes further by converting biomass into high-purity CO_2 and durably storing it in geological (see Section 5) or mineral (see Section 7) storage, or converting biomass into long-lived products. This approach addresses the limitations of conventional biological capture, which is vulnerable to reversal through decomposition or disturbance, and aims to secure carbon removal over much longer timescales.

Biomass conversion can co-produce energy products (e.g. bioenergy, sustainable aviation fuel, other low-carbon liquid fuels) and long-lived carbon products (e.g. biochar). These products can be combusted and/or utilised for energy generation, representing a CCU approach.

Alternatively, they can be stored in geological storage (in the case of bio-oil) or in land-based open environments (in the case of biochar, see Section 6), representing a CDR approach (i.e. BiCR+S). Figure 10 summarises the possible pathways of the BiCR+S approach, including those that produce energy products, representing a combination of CCU and CDR.

Biomass plays an important and cross-cutting role in the global pathway to net zero emissions, supporting both emissions reduction and CDR efforts. The use of biomass to support CDR must be carefully managed to ensure Australia's biomass resources are used to maximise benefits across communities, industries, and the environment (see Box 2).

Figure 10: Overview of the BiCR+S approach.



Box 2: Australia's biomass resources.

Australia has abundant biomass resources[65] that could be leveraged for CDR. The types of biomass feedstocks considered in this Roadmap include:

- **Agricultural biomass**, including byproducts from farming, such as crop residues (e.g. crop stubbles and grasses) and processing wastes (e.g. sugarcane bagasse).
- **Forest residues**, including unused residues from primary and secondary mills, small-diameter trees and logging residues from existing plantations.
- **Municipal solid waste (MSW)**, including organic waste generated by households, commercial activities and industrial activities, with examples including paper and cardboard, food wastes, and wood wastes.
- **Biomass from short rotation trees (SRTs)**, such as native perennial plants. SRTs can be grown to supply additional biomass for CDR or integrated into conventional farming and forestry systems.

The use of biomass feedstocks involves trade-offs and must be carefully managed to avoid conflict with existing land use, competing feedstock applications, and water resource constraints. Feedstocks can be used in various high-value applications that are often underappreciated. For example, sugarcane bagasse is commonly burned at sugar mills to generate onsite energy, so diverting it for other uses would require alternative energy solutions.[66]

Biomass can also be used as a feedstock in the production of sustainable aviation fuel and other low-carbon liquid fuels. Agricultural residues are often left on fields to maintain soil health (i.e. nutrients, moisture, structure) or used as animal feed.[67] Similarly, retaining a manageable amount of forestry residues in plantations is crucial for supporting the local carbon cycle and biodiversity.[68] Further details on the biomass feedstocks and their specific considerations can be found in the *Australian CDR Roadmap – Modelling Appendix*.

All of the biomass considered in this Roadmap is waste or residue material, except SRT biomass. While strategic planting could provide benefits to agricultural productivity in terms of shelter and salinity,[69] there are also valid concerns about food security when agricultural land is diverted to grow SRT crops.

While risks can potentially be mitigated, developing a deeper understanding of Australia's biomass feedstock landscape is essential to unlock the country's resource potential and guide strategic decisions on the most effective and sustainable uses of biomass resources. Additionally, inputs from landowners, Traditional Owners and producers are important in determining the best use for their available biomass feedstocks based on market demand, policy incentives, and local conditions.

65 Crawford DF, O'Connor MH, Jovanovic T, Herr A, Raison RJ, O'Connell DA, Baynes T (2015) A spatial assessment of potential biomass for bioenergy in Australia in 2010, and possible expansion by 2030 and 2050. GCB Bioenergy 8(4), 707–722. <https://doi.org/10.1111/gcbb.12295>.

66 CSIRO (2023) Sustainable Aviation Fuel Roadmap.

67 CSIRO (2023) Sustainable Aviation Fuel Roadmap.

68 CSIRO (2023) Sustainable Aviation Fuel Roadmap.

69 Crawford DF, O'Connor MH, Jovanovic T, Herr A, Raison RJ, O'Connell DA, Baynes T (2015) A spatial assessment of potential biomass for bioenergy in Australia in 2010, and possible expansion by 2030 and 2050. GCB Bioenergy 8(4), 707–722. <https://doi.org/10.1111/gcbb.12295>.

2.2.1 Overview

BiCR processes involve the conversion of biomass and can be based on thermochemical or biological mechanisms. This section provides a high-level explanation and state of development discussion of three mature (high TRLs) thermochemical BiCR processes, including:

- **Slow pyrolysis to biochar**, which operates at lower temperatures over longer durations to produce biochar, a stable form of carbon storage, along with a syngas byproduct.
- **Fast pyrolysis to hydrogen (H_2)**, which uses higher temperatures over short timescales to yield bio-oil and some biochar, along with a syngas byproduct containing CO_2 that is captured and durably stored.
- **Combustion to electricity**, which combusts biomass to generate electricity while capturing CO_2 for storage.

This is followed by a high-level overview of emerging and alternative BiCR processes that have the potential to lower energy costs, optimise the use of biomass resources, and better align with region-specific needs.

Slow pyrolysis to biochar

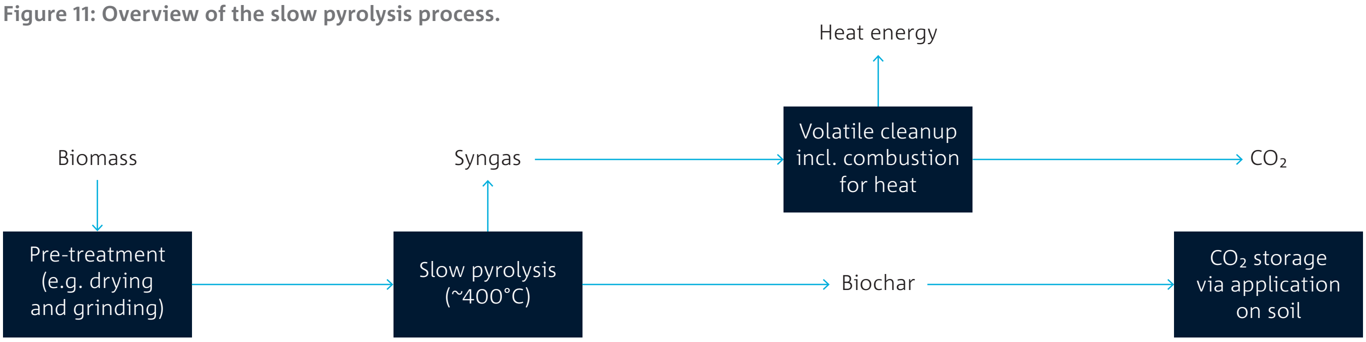
The slow pyrolysis process applies heat at around 400°C to the biomass in the absence of oxygen (O_2) and over a timescale of minutes to days, producing predominantly biochar (Figure 11).[70] Biochar is a porous carbon product made up of typically 12–25% of the total biomass's carbon, depending on the feedstock.[71] Biochar can be applied to soil as a long-lived carbon product, allowing CO_2 to be durably stored (see Section 6.1.2: Organic carbon, Biochar). The syngas byproduct of the slow pyrolysis process can be combusted for heat, releasing CO_2 gas that may or may not be captured depending on the scale of the operation and the economic viability of integrating carbon capture and storage processes. The state of development of CDR operations using biochar can be found in Section 6.1.2: Organic carbon, Biochar.

Fast pyrolysis to H_2

The fast pyrolysis process requires temperatures of 500–650°C and a reaction timescale of seconds to produce high bio-oil yields and a small amount of biochar.[72] The high yields of bio-oil enable subsequent upgrading pathways into H_2, liquid fuels (i.e. gasoline and diesel), or bio-asphalt (Figure 12).[73]

Depending on the bio-oil upgrading pathway, fast pyrolysis processes can achieve a CDR potential exceeding 1.6 tCO_2 per dry tonne of biomass.[74] The pathway producing H_2 has the highest CDR rate (i.e. up to 100% of carbon in biomass can be captured and stored), followed by the pathway producing liquid fuels (i.e. 67% of carbon in biomass can be captured and stored), and lastly, the pathway producing bio-asphalt (i.e. 57–74% of carbon in biomass can be captured and stored).[75] In general, the fast pyrolysis processes shown in Figure 12 capture a greater proportion of the carbon content of biomass than the slow pyrolysis to biochar process shown in Figure 11.

Figure 11: Overview of the slow pyrolysis process.



Note: Suitable biomass includes low-moisture, low-ash agricultural and forestry residues and MSW; carbon crop biomass.

70 Al-Rumaihi A, Shahbaz M, Mckay G, Mackey H, Al-Ansari T (2022) A review of pyrolysis technologies and feedstock: A blending approach for plastic and biomass towards optimum biochar yield. Renewable and Sustainable Energy Reviews 167, 112715. <https://doi.org/10.1016/j.rser.2022.112715>.

71 Pett-Ridge J, Kuebbing S, Mayer AC, Hovorka S, Pilorgé H, Baker SE, et al. (2023) Roads to Removal: Options for Carbon Dioxide Removal in the United States. Report No. LLNL-TR-852901. Lawrence Livermore National Laboratory (LLNL), Livermore, CA, United States. <https://www.osti.gov/biblio/2301853>.

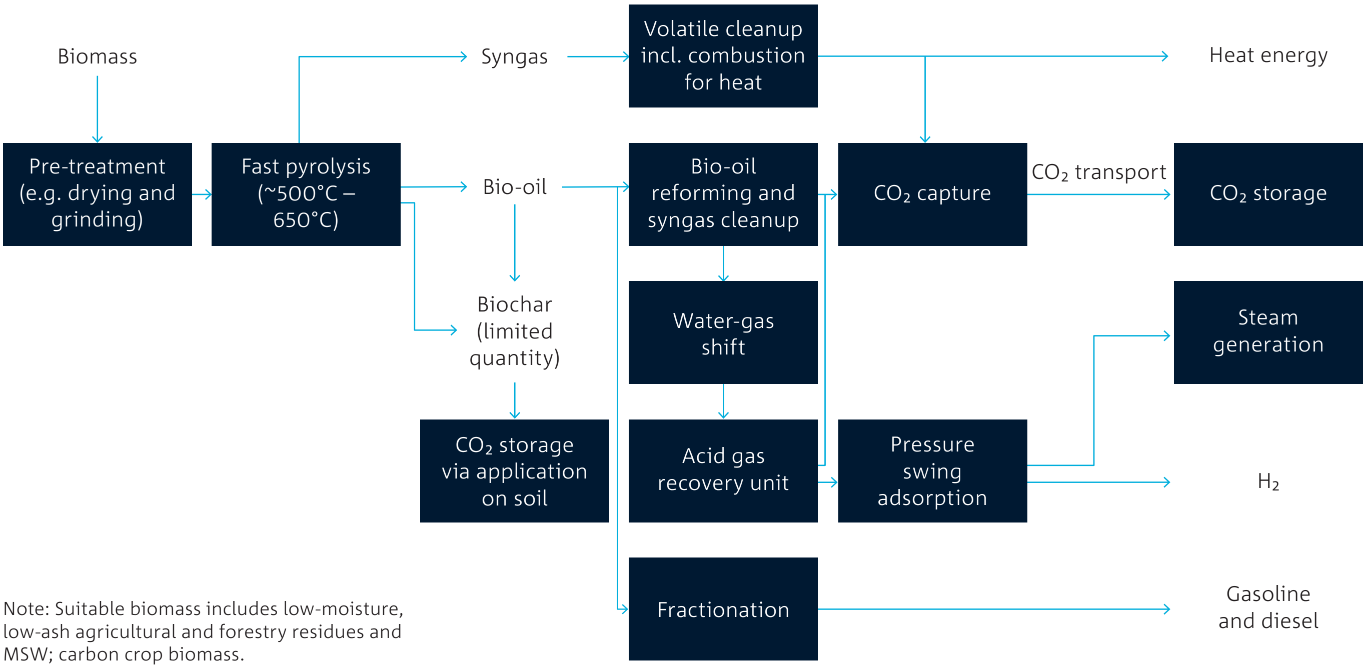
72 Al-Rumaihi A, et al (2022) A review of pyrolysis technologies and feedstock: A blending approach for plastic and biomass towards optimum biochar yield. <https://doi.org/10.1016/j.rser.2022.112715>.

73 Pett-Ridge et al. (2023) Roads to removal: options for carbon dioxide removal in the United States. Lawrence Livermore National Laboratory. <https://www.osti.gov/biblio/2301853>.

74 Pett-Ridge et al. (2023) Roads to removal: options for carbon dioxide removal in the United States. Lawrence Livermore National Laboratory. <https://www.osti.gov/biblio/2301853>.

75 Pett-Ridge et al. (2023) Roads to removal: options for carbon dioxide removal in the United States. Lawrence Livermore National Laboratory. <https://www.osti.gov/biblio/2301853>.

Figure 12: Overview of the fast pyrolysis process.[76]



Note: Suitable biomass includes low-moisture, low-ash agricultural and forestry residues and MSW; carbon crop biomass.

State of development

There have been increasing efforts to demonstrate and scale up fast pyrolysis in industry globally, and emerging attention to its potential for CDR purposes.[77] An example of a commercial fast pyrolysis operator with a CDR focus is Charm Industrial (US). The company has developed a fast pyrolysis process for agricultural and forestry wastes and residues to produce bio-oil that is injected and durably stored underground, as well as biochar.[78]

In 2024, Charm Industrial commissioned eight pyrolysers, each capable of producing 0.5 tonnes of bio-oil and 0.2 tonnes of biochar from one tonne of biomass, equivalent to capturing one tonne of CO_2.[79] In May 2023, Charm Industrial had its first offtake agreement with advanced market commitment Frontier to remove 112,000 tCO_2 via bio-oil between 2024 and 2030.[80] In January 2025, the company signed an agreement with Google to remove 100,000 tCO_2 through 2030 via biochar.[81] Charm Industrial also actively drives MRV advancements, working in partnership with Isometric to develop high-quality standards and practices and an open digital MRV system for transparency and knowledge sharing.[82]

Combustion to electricity

Combustion is a single-step heating process that produces steam and electricity alongside CO_2 (Figure 13).[83] The combustion process involves fewer and less complex steps than that of fast pyrolysis to H_2, and consequently has lower capital investment requirements and less process risk.

76 Smart S, Ashman P, Scholes C, Tabatabaei M, Hosseini T, Yee R, McConnachie M, Sheil A, Jackson T, Beiraghi J (2023) Technoeconomic Modelling of Future Fuel Production Pathways: Summary Report. Future Fuels CRC, RP1.2-02, The University of Queensland, The University of Adelaide, The University of Melbourne, Australia. <https://www.futurefuelscrc.com/wp-content/uploads/FFCRC_RP1.2-02_SummaryReport_Open-access.pdf>.

77 Hrbek J (2022) Status Report on Thermal Gasification of Biomass and Waste 2021. IEA Bioenergy Task 33, University of Natural Resources and Life Sciences Vienna (BOKU), Austria. <https://www.ieabioenergy.com/wp-content/uploads/2022/03/Status-Report2021_final.pdf>.

78 Charm Industrial (n.d.) FAQ and Protocols for Bio-oil Sequestration. <https://www.charmindustrial.com/faq>.

79 Reinhardt P (2024) The Charm Underground: 2024 Year in Review. Charm Industrial. <https://charmindustrial.com/blog/the-charm-underground-2024-year-in-review>.

80 Frontier Climate (2023) First Offtake: Frontier buyers sign $53M in agreements with Charm Industrial. <https://frontierclimate.com/writing/first-offtake>.

81 Cohn H (2024) The Charm duo: Charm bio-oil and Charm biochar. Charm Industrial. <https://charmindustrial.com/blog/charm-duo>.

82 Cohn H (2024) Charm delivers first-ever Isometric verified carbon removals to Stripe, Shopify, JP Morgan Chase. <https://charmindustrial.com/blog/charm-delivers-first-ever-isometric-verified-carbon-removals-to-stripe-shopify-jp-morgan-chase>; Charm Industrial (n.d.) <https://charmindustrial.com/ledger>; Charm Industrial (2024) Introducing Ledger: A system for reliably monitoring & reporting biomass carbon removal at scale. <https://charmindustrial.com/blog/introducing-ledger%3A-a-system-for-reliably-monitoring-reporting-biomass-carbon-removal-at-scale>.

83 Pett-Ridge et al. (2023) Roads to removal: options for carbon dioxide removal in the United States. Lawrence Livermore National Laboratory. <https://www.osti.gov/biblio/2301853>.

However, the steam and electricity products are commodities that can be produced by a range of other low-cost processes.[84] Relatively high CDR potential of 1.6 tCO_2 per dry tonne of biomass can be achieved through this process.[85]

State of development

The ability to convert conventional power plants powered by fossil fuel combustion to those powered by biomass combustion, along with the flexibility towards different biomass feedstocks, are two driving factors enabling biomass combustion processes to be adopted and scaled up globally.

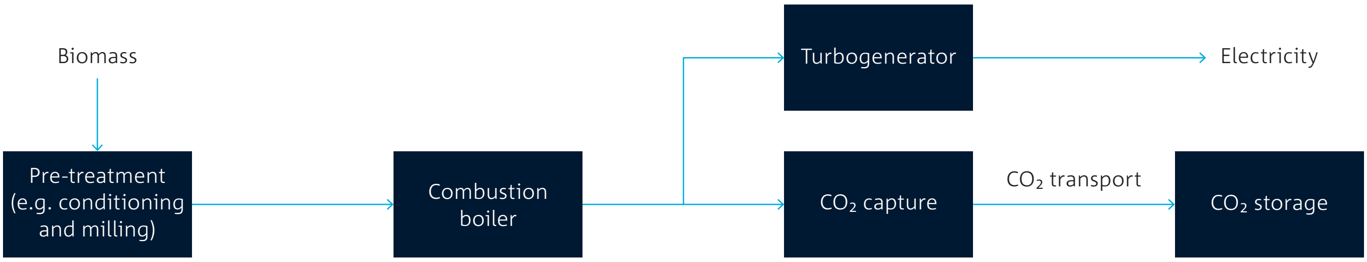
In March 2025, Stockholm Exergi (Sweden) announced the decision to build one of the world's largest biomass combustion facilities with CCS processes integrated, building on the operation of a test facility since 2019 which was used to demonstrate and prove its capture process. The commercial-scale facility is expected to be operational in 2028, with a capacity to capture and durably store 800,000 tonnes of CO_2 per year (tCO_2/y) from the atmosphere.[86]

The Danish Government has been investing heavily in projects to help reduce Denmark's annual CO_2 emissions by 2.3 Mt from 2030.[87] In 2023, Ørsted Bioenergy was awarded the first contract under the public funding scheme to integrate CO_2 capture processes into its straw- and woodchip-fired power plants. The refurbished power plants are expected to be operational by 2026, capturing 430,000 tCO_2/y from the atmosphere and delivering 3.67 Mt of certified carbon removal for Microsoft.[88]

Similarly, Drax (United Kingdom, or UK) has been piloting and scaling up CO_2 capture and storage processes to integrate into its existing biomass power plant, which combusts byproducts and wastes from timber and forest industries. Drax plans to convert two operating units at its Power Station for CO_2 capture purposes, with the capacity to remove 8 $MtCO_2$/y once operational in 2030.[89]

Toshiba Energy Systems and Solutions (ESS) Corporation (Japan) has also integrated CO_2 capture and storage processes into its Mikawa Power Plant, powered by palm kernel shells. The commercial-scale facility commenced operation in 2020, capturing 500 tCO_2 per day. The captured CO_2 is planned to be liquified and stored at an offsite CO_2 storage, with ongoing RD&D since 2021.[90] In 2016, the company also operated a pilot facility at a municipal waste incineration plant, capturing 10 tCO_2 per day and utilising end CO_2 products for crop cultivation and algaculture.[91]

Figure 13: Overview of the combustion to electricity process.[92]



Note: Suitable biomass includes low-moisture, low-ash agricultural and forestry residues and MSW; carbon crop biomass.

84 Pett-Ridge et al. (2023) Roads to removal: options for carbon dioxide removal in the United States. Lawrence Livermore National Laboratory. <https://www.osti.gov/biblio/2301853>.

85 Pett-Ridge et al. (2023) Roads to removal: options for carbon dioxide removal in the United States. Lawrence Livermore National Laboratory. <https://www.osti.gov/biblio/2301853>.

86 Stockholm Exergi (2025) Stockholm Exergi to build one of the world's largest facilities for removing carbon dioxide from the atmosphere. <https://beccs.se/news/stockholm-exergi-to-build-one-of-the-worlds-largest-facilities-for-removing-carbon-dioxide-from-the-atmosphere/>.

87 Danish Energy Agency (2024) Danish Energy Agency presses the start button for billion-dollar tendering procedure for carbon capture and storage. <https://ens.dk/en/press/danish-energy-agency-presses-start-button-billion-dollar-tendering-procedure-carbon-capture>.

88 Ørsted (n.d.) Carbon capture and storage. <https://orsted.com/en/what-we-do/renewable-energy-solutions/bioenergy/carbon-capture-and-storage>.

89 Baringa Partners LLP (2025) Value for Money Assessment of the Low-Carbon Dispatchable CfD for Drax Power Station. Drax Group, Selby, UK. <https://www.drax.com/wp-content/uploads/2025/02/Baringa_Report_February_2025.pdf>; Drax Group (n.d.) BECCS at Drax: the process. <https://www.drax.com/beccs-at-drax-the-process/>.

90 Kitamura H, Iwasa K, Fujita K, Muraoka D (2022) CO_2 Capture Project Integrated with Mikawa Biomass Power Plant: Case Study. Toshiba Energy Systems & Solutions Corporation, Yokohama, Japan. <https://www.toshiba.com/taes/cms_files/Carbon_Capture_Mikawa_CaseStudy.pdf>.

91 Toshiba Energy Systems & Solutions Corporation (n.d.) Efforts for CO_2 emission reduction – CO_2 capture technology. <https://www.global.toshiba/ww/products-solutions/thermal/products-technical-services/zero-emissions.html>.

92 Pett-Ridge et al. (2023) Roads to removal: options for carbon dioxide removal in the United States. Lawrence Livermore National Laboratory. <https://www.osti.gov/biblio/2301853>.

2.2.2 Emerging and alternative BiCR processes

There are many emerging and alternative BiCR processes based on less advanced thermochemical, biological and other mechanisms, with the potential to lower energy costs, optimise the use of biogenic resources, and better align with region-specific needs. Some of these processes require further RD&D and scale-up support (see Table 2). The summary has been developed based on the US Roads to Removal report.

Table 2: Overview of emerging and alternative BiCR processes.[93]

PROCESS	DESCRIPTION	KEY RD&D CHALLENGES
Gasification	Gasification is the process of decomposing biomass into syngas, which comprises carbon monoxide, H_2, CO_2 and a small amount of methane. Syngas can be further upgraded into liquid fuels (e.g. sustainable aviation fuel, gasoline, and diesel), H_2, or renewable natural gas.[94] Of the syngas upgrading pathways, up to 100% of carbon in biomass can be captured and stored if H_2 is produced, equivalent to the CDR potential of approximately 1.50–1.85 tCO_2 per dry tonne of biomass. Pathways that produce liquid fuels and renewable natural gas can convert 26–36% of the carbon in biomass into fuels, with the remaining proportion (64–74% of the carbon in biomass) potentially being captured and stored.[95] Gasification has been developed and demonstrated in industry for both CDR and CCU purposes. An example gasification operator is UK-based Kew Technology, which has constructed a commercial-scale gasification facility with integrated carbon capture. The facility consists of many high-pressure, modular units, each of which can process 15,000 tonnes of feedstock per year, generate 4 megawatts (MW) of energy output as H_2 product (at a rate of 120 kg per hour), and remove 20,000 tCO_2/y from the atmosphere.[96]	Complex and expensive post-gasification clean up; requirement for consistent feedstock and centralised processing requirement.[97]
Hydrothermal liquefaction	Hydrothermal liquefaction is a thermochemical process that converts biomass into liquid fuels at moderate temperatures (250–375°C) and operating pressures of 4–22 MPa. It has the advantage of being able to process high-moisture biomass such as manure and food waste. CO_2 can be captured from the off-gas generated during the hydrothermal liquefaction process, and from the off-gas produced during the steam methane reforming step to produce H_2.	Limited efficiency in capturing and storing all the carbon in biomass that is not converted into chemicals, fuels, or energy; high-pressure requirement; low-durability char produced compared to biochar.
Biological processes	Biological processes utilise microorganisms and/or enzymes to convert biomass into fuels or renewable natural gas. Notable processes include fermentation and anaerobic digestion.	Fermentation: Sustaining economic viability, high capital and operating costs. Anaerobic digestion: Limited CDR efficiency per unit biomass feedstock.

93 Pett-Ridge et al. (2023) Roads to removal: options for carbon dioxide removal in the United States. Lawrence Livermore National Laboratory. <https://www.osti.gov/biblio/2301853>.

94 Pett-Ridge et al. (2023) Roads to removal: options for carbon dioxide removal in the United States. Lawrence Livermore National Laboratory. <https://www.osti.gov/biblio/2301853>.

95 Pett-Ridge et al. (2023) Roads to removal: options for carbon dioxide removal in the United States. Lawrence Livermore National Laboratory. <https://www.osti.gov/biblio/2301853>.

96 KEW Technology Ltd (2022) Direct Air Capture Programme: CCH_2 – Carbon Capture and Hydrogen. Department for Business, Energy and Industrial Strategy, London, UK. <https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1075298/kew-dacs-ggr-programme-ccH₂.pdf>; KEW Technology Ltd (n.d.) Our technology. <https://kew-tech.com/our-technology/>.

97 CSIRO (2023) Sustainable Aviation Fuel Roadmap.

2.2.3 MRV capture and storage

Several MRV protocols have been developed to allow CDR via BiCR+S to be sold through voluntary carbon markets. Isometric, a carbon removal registry, has developed the Biogenic Carbon Capture and Storage protocol, which applies to the BiCR processes covered by the scope of this analysis.[98] This section draws primarily on the Isometric protocol to illustrate MRV requirements for BiCR+S, and all MRV-related insights presented here are based on this protocol unless otherwise specified. The decision to primarily draw on Isometric protocols, rather than those of other organisations, for BiCR+S and other novel CDR approaches in scope is due to Isometric being a highly regarded global expert in MRV for CDR and having developed a wide range of protocols. This enables a simple but consistent structure to present how net CO_2 removal is calculated and to illustrate the MRV nuances between different novel CDR approaches.

Using the Isometric protocol, the net CO_2 removal is calculated based on the total CO_2 removed from the atmosphere and durably stored as biogenic carbon, excluding the amount of counterfactual CO_2 and any direct CO_2 emissions from the project.

The total amount of CO_2 removed from the atmosphere and durably stored as biogenic carbon can be measured and calculated depending on the selected storage method for CO_2, such as geological storage or ex-situ or in-situ mineral carbonation (see Section 5–7).

Calculations of counterfactual CO_2 account for the CO_2 stored in the biomass feedstock that would have remained durably stored in the biomass in the absence of the project, as biomass feedstock is a CO_2 storage medium on its own, despite the limited durability.

Direct CO_2 emissions from the project are associated with its establishment and operation (including energy use), end-of-life activities such as MRV, embodied emissions in the production and transportation of feedstock, equipment, and materials to the facility, and any leakage emissions. Leakage emissions represent increased emissions that occur when feedstock production increases in response to increased demand or additional activities are required to replace current feedstock uses.

The Isometric protocol requires the project to consider unique elements of BiCR+S, including the additionality of CDR and the non-additionality of co-product production facilities, as well as the emissions related to reagent use and disposal, and the purity and concentration of CO_2. Uncertainties associated with the MRV of BiCR+S also need to be considered and accounted for, including the measurement error related to fuel combustion, the production of capture materials, and the production and processing of biomass feedstocks.[99]

98 Isometric (n.d.) Biogenic Capture and Storage Protocol v1.1. <https://registry.isometric.com/protocol/biogenic-capture-and-storage/1.1#project-design-document>; Isometric (n.d.) Biomass Feedstock Accounting Module v1.3. <https://registry.isometric.com/Module/biomass-feedstock-accounting>.

99 Verra (2025) *CO_2 Capture from Bioenergy: VCS Module VMD0059*. Verified Carbon Standard Program, Washington, DC, USA. <https://www.verra.org/wp-content/uploads/2025/04/VMD0059-CO_2-Capture-from-Bioenergy-final-publication.pdf>.

3 Geochemical capture

Geochemical CO_2 capture removes CO_2 from the atmosphere through interactions with Earth's natural carbon cycle, including land and ocean sinks. This section focuses on two groups of human-induced capture processes that increase the natural rate of geochemical CO_2 capture. The first group of processes accelerates the natural marine carbon cycle by enhancing the ocean's capacity to absorb additional atmospheric CO_2,[100] forming the basis of the ocean alkalinity enhancement (OAE) approach. The second group of processes, known as enhanced rock weathering (ERW), accelerates the reaction between atmospheric CO_2 dissolved in rainwater as carbonic acid and calcium- and magnesium-rich silicate rocks, by crushing and deliberately dispersing these rocks on large areas of land.[101]

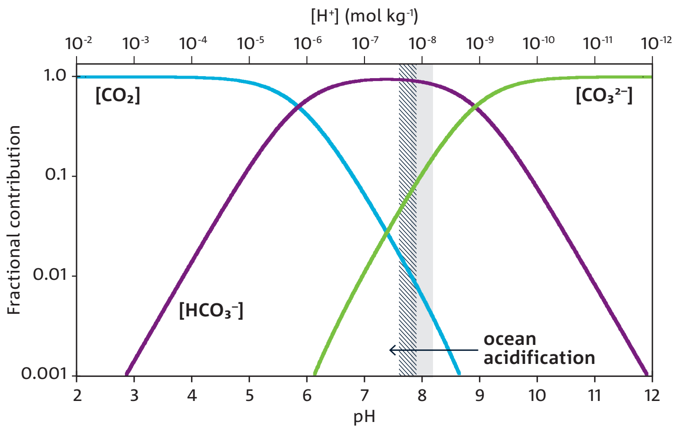
3.1 Ocean alkalinity enhancement (OAE)

The ocean currently removes approximately 26% of the annual anthropogenic emissions of CO_2 from the atmosphere, acting as a carbon sink.[102] The exchange of CO_2 between the ocean and the atmosphere is controlled by a combination of physical, chemical, biological and geological processes.[103] When CO_2 reacts with seawater, a small amount (~1%) remains as aqueous CO_2, while the remaining portion is converted to dissolved inorganic carbon in the form of bicarbonate ions (HCO_3^-) and carbonate ions (CO_3^{2-}),[104] both of which are durable forms of CO_2 storage[105] (see Section 6).

The amount stored in each form of CO_2 is a function of the seawater pH (Figure 14), with the carbonate system acting as a natural buffer for the seawater pH.[106] For example, if a source of acidity is added to seawater, bicarbonate and carbonate ions are converted into CO_2, and some of this CO_2 is released back to the atmosphere, minimising the change in seawater pH. When a source of alkalinity is added, the opposite reaction takes place, in which dissolved CO_2 is converted into bicarbonate and carbonate ions, leading to the drawdown of additional CO_2 from the atmosphere.

OAE approaches take advantage of this interaction between different forms of CO_2 and seawater pH to enhance the ocean's capacity to absorb additional atmospheric CO_2 and durably store it as carbonate and bicarbonate ions.[107] This section provides an overview of different OAE approaches with a focus on a closed-loop electrolytic OAE approach in more detail. It is recognised that separating OAE into distinct CO_2 capture and storage components is challenging, due to the inherent chemistry and dynamics of the ocean system. For this section, CO_2 capture refers to the increased capacity of seawater to absorb CO_2.

Figure 14: Relationship between ocean carbonate chemistry and pH.[108]



Note: Bjerrum plot shows the relative proportions of [HCO_3^-], [CO_3^{2-}] and [CO_2] to dissolved inorganic carbon in seawater at temperature T = 25°C, salinity S = 35%, and pressure P = 0 bar. The shaded region reflects the annual average pH range of the ocean surface, while the hashed region reflects the ocean surface pH range from the global ocean geochemistry model projections of Turley et al. (2010).

100 GESAMP (2019) High level review of a wide range of proposed marine geoengineering techniques. (Eds. PW Boyd, CMG Vivian). IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UN Environment/UNDP/ISA Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection, Rep. Stud. GESAMP No. 98. <http://www.gesamp.org/publications/high-level-review-of-a-wide-range-of-proposed-marine-geoengineering-techniques>.

101 Holden FJ, Davies K, Bird MI, Hume R, Green H, Beerling DJ, Nelson PN (2024) In-field carbon dioxide removal via weathering of crushed basalt applied to acidic tropical agricultural soil. Science of the Total Environment 955, 176568. <https://doi.org/10.1016/j.scitotenv.2024.176568>.

102 Friedlingstein P et al (2025) Global Carbon Budget 2024. Earth System Science Data 17, 965–1039. <https://doi.org/10.5194/essd-17-965-2025>.

103 Gruber N, Bakker DCE, DeVries T, Gregor L, Hauck J, Landschützer P, McKinley GA, Müller JD (2023) Trends and variability in the ocean carbon sink. Nature Reviews Earth & Environment 4, 119–134. <https://doi.org/10.1038/s43017-022-00381-x>.

104 Dickson AG (2010) The carbon dioxide system in seawater: equilibrium chemistry and measurements. In Guide to best practices for ocean acidification research and data reporting. (Eds. U Riebesell, VJ Fabry, L Hansson, J-P Gattuso) 17–40. Publications Office of the European Union, Luxembourg. <https://www.pmel.noaa.gov/CO₂/files/dickson_thecarbondioxidesysteminseawater_equilibriumchemistryandmeasurementspp17-40.pdf>.

105 IPCC (2005) IPCC special report on carbon dioxide capture and storage. <https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_wholereport-1.pdf>.

106 Zeebe RE, Wolf-Gladrow DA (2001) CO_2 in seawater: equilibrium, kinetics, isotopes. In *CO_2 in Seawater: Equilibrium, Kinetics, Isotopes.* Chapter 1. Elsevier Oceanography Series, Amsterdam, The Netherlands. <https://sseh.uchicago.edu/doc/Zeebe_CO₂_In_Seawater_Ch_1.pdf>.

107 GESAMP (2019) High level review of a wide range of proposed marine geoengineering techniques. (Eds. PW Boyd, CMG Vivian). IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UN Environment/UNDP/ISA Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection, Rep. Stud. GESAMP No. 98. <http://www.gesamp.org/publications/high-level-review-of-a-wide-range-of-proposed-marine-geoengineering-techniques>.

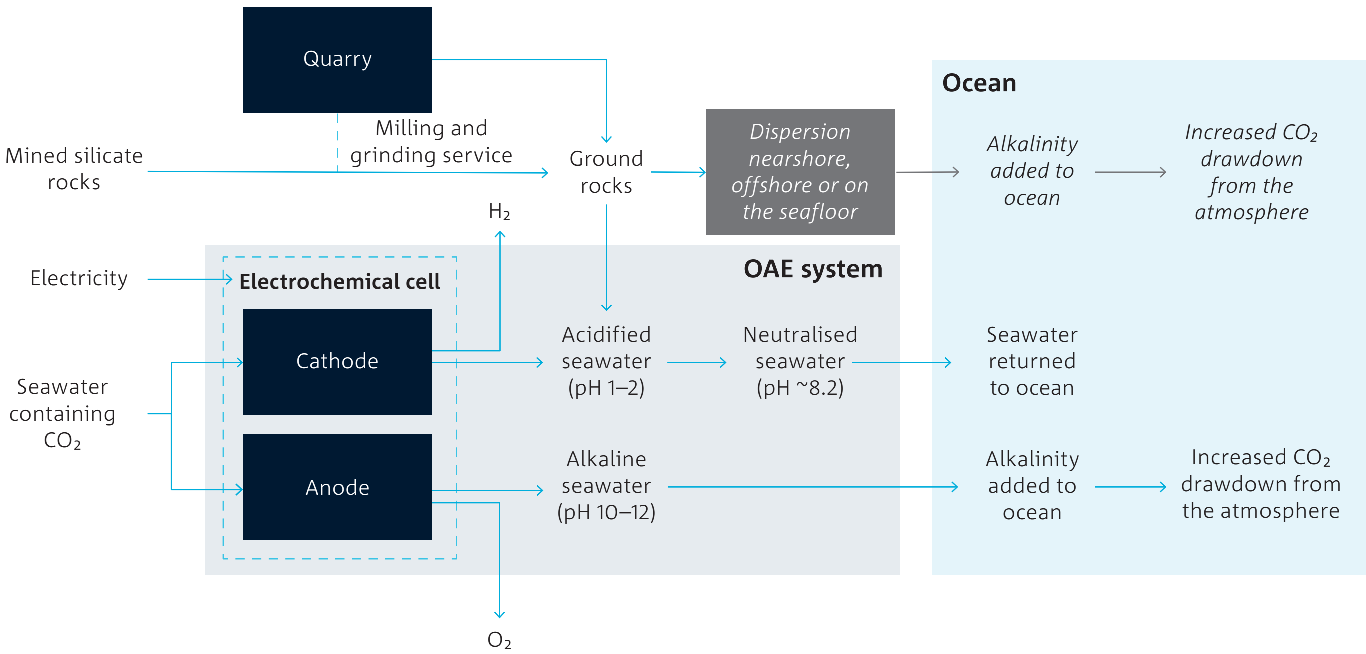
108 Barker S, Ridgwell A (2012) Ocean acidification. Nature Education Knowledge 3(10), 21. <https://www.nature.com/scitable/knowledge/library/ocean-acidification-25822734/>.

3.1.1 Overview

There are two broad categories of OAE approaches: electrochemical approaches and mineral addition approaches (Figure 15).[109] Electrochemical OAE approaches work by separating seawater into basic (e.g. sodium hydroxide, NaOH) and acidic (e.g. hydrochloric acid, HCl) components using electrochemistry, with methods varying based on the type of electrochemical cell used and whether the primary medium for carbon removal is through the basic or acidic stream.[110] In contrast, mineral addition OAE approaches involve adding alkaline rocks and materials into the ocean, which elevates seawater pH and allows additional atmospheric CO_2 to be taken up by the ocean.

This section focuses on one electrochemical OAE approach, specifically electrolytic OAE, given that it has a relatively high TRL[111] and does not directly add solid material to the ocean, which can lead to a potential perturbation of the marine ecosystem.[112] While beyond the scope of this Roadmap, a high-level overview of promising alternative OAE approaches and their RD&D challenges, including for mineral addition OAE, has been provided at the end of this section.

Figure 15: Overview of OAE approaches.



Pathway not prioritised in quantitative analysis for this approach.
Note: Chlorine is not produced due to the use of oxygen selective electrodes.

109 Eisaman MD, Geilert S, Renforth P, Bastianini L, Campbell J, Dale AW, Foteinis S, Grasse P, Hawrot O, Löscher CR, Rau GH, Rønning J (2023) Assessing the technical aspects of ocean-alkalinity-enhancement approaches. In Guide to Best Practices in Ocean Alkalinity Enhancement Research. (Eds. A Oschlies, A Stevenson, LT Bach, K Fennel, REM Rickaby, T Satterfield, R Webb, J-P Gattuso) Chapter 3. Copernicus Publications, State Planet. <https://doi.org/10.5194/sp-2-oae2023-3-2023>; Karunarathne S, Andrenacci S, Carranza-Abaid A, Jayarathna C, Maelum M, Skagestad R, Haugen HA (2024) Review on CO_2 removal from ocean with an emphasis on direct ocean capture (DOC) technologies. Separation and Purification Technology 350, 128598. <https://doi.org/10.1016/j.seppur.2024.128598>.

110 Eisaman MD et al (2023) Assessing the technical aspects of ocean-alkalinity-enhancement approaches. In Guide to Best Practices in Ocean Alkalinity Enhancement Research. <https://doi.org/10.5194/sp-2-oae2023-3-2023>; Karunarathne S et al (2024) Review on CO_2 removal from ocean with an emphasis on direct ocean capture (DOC) technologies. <https://doi.org/10.1016/j.seppur.2024.128598>

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

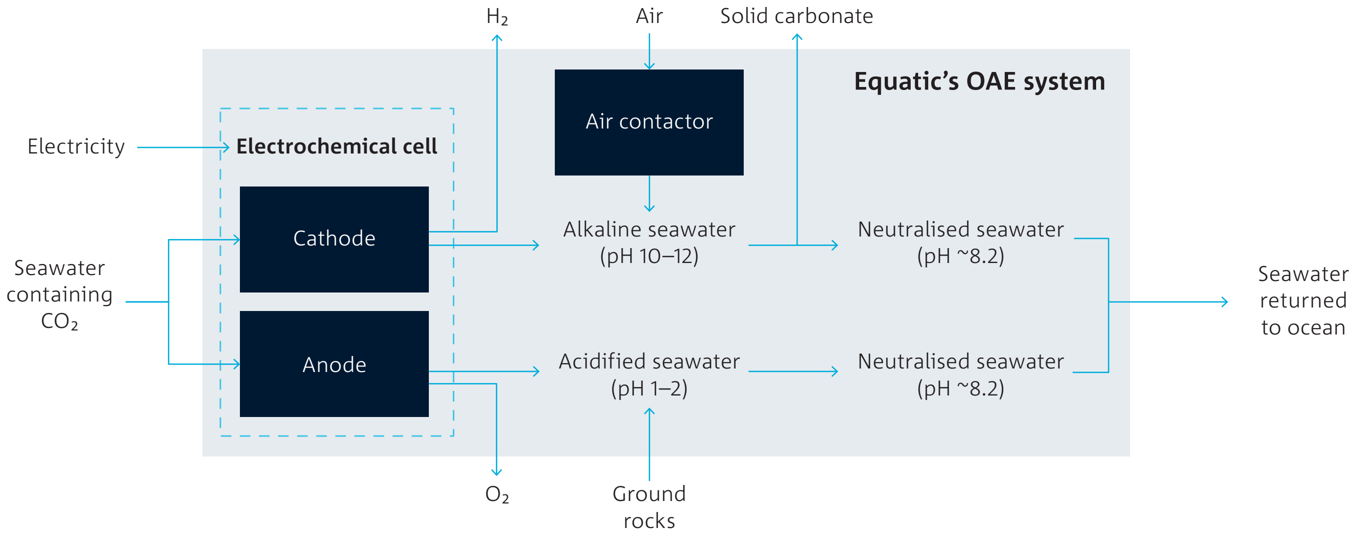
112 Lenton A, Matear RJ, Keller DP, Scott V, Vaughan NE (2018) Assessing carbon dioxide removal through global and regional ocean alkalinization under high and low emission pathways. Earth System Dynamics 9, 339–357. <https://doi.org/10.5194/esd-9-339-2018>.

Electrolytic OAE

In the electrolytic OAE approach, seawater is electrolysed and separated into basic and acidic components. The separated basic component can be discharged at an appropriate pH and returned to the ocean, where it captures atmospheric CO_2. The acidic component may be sold as a byproduct but is typically neutralised with solid materials (e.g. alkaline rocks) before being returned to the ocean. Other byproducts of the seawater electrolysis process can include O_2 and chlorine gas (Cl_2), as well as H_2, which can be captured and sold as byproducts, subsidising the cost of the OAE process.[113] One OAE facility may process a volume of seawater that is up to 147 times smaller than the volume of air required by a direct air capture facility to remove the same amount of CO_2 from the atmosphere.[114] It does, however, require a significant amount of electricity, primarily to power the electrolysis process.

Equatic, a US-based company specialising in OAE, has modified this process to create a closed-loop CDR approach (Figure 16).[115] Rather than returning the basic component to the ocean, an on-land air contactor is used to remove CO_2 directly from the atmosphere. Atmospheric CO_2 reacts with the basic component to neutralise it while also forming stable carbonate and bicarbonate ions. This enables the direct measurement of the amount of CO_2 removed, thereby improving the robustness of MRV for this approach.[116] The resulting neutralised seawater containing carbonate and bicarbonate ions can be returned to the ocean. A byproduct of the reaction is solid calcium carbonate ($CaCO_3$), which can be separated and sold as an additive for construction materials.[117] Equatic's closed loop OAE process is used as the representative process for the quantitative analysis of OAE capacity and cost in Section 11 of this Roadmap.

Figure 16: Overview of Equatic's OAE process.[118]



Note: Chlorine is not produced due to the use of oxygen selective electrodes.

113 Eisaman MD et al (2023) Assessing the technical aspects of ocean-alkalinity-enhancement approaches. In Guide to Best Practices in Ocean Alkalinity Enhancement Research. <https://doi.org/10.5194/sp-2-oae2023-3-2023>; Karunarathne S et al (2024) Review on CO_2 removal from ocean with an emphasis on direct ocean capture (DOC) technologies. <https://doi.org/10.1016/j.seppur.2024.128598>

114 Karunarathne S et al (2024) Review on CO_2 removal from ocean with an emphasis on direct ocean capture (DOC) technologies. <https://doi.org/10.1016/j.seppur.2024.128598>

115 La Plante EC, Simonetti DA, Wang J, Al-Turki A, Chen X, Jassby D, Sant GN (2021) Saline water-based mineralization pathway for gigatonne-scale CO_2 management. ACS Sustainable Chemistry & Engineering 9, 1073–1089. <https://pubs.acs.org/doi/pdf/10.1021/acssuschemeng.0c08561>.

116 La Plante EC, Chen X, Bustillos S, Bouissonnie A, Traynor T, Jassby D, Corsini L, Simonetti DA, Sant GN (2023) Electrolytic seawater mineralization and the mass balances that demonstrate carbon dioxide removal. ACS Environmental Science & Technology Engineering 3, 955–968. <https://pubs.acs.org/doi/pdf/10.1021/acsestengg.3c00004>.

117 Equatic, EcoEngineers (2023) Equatic's measurement, reporting, and verification methodology. White paper prepared in consultation with EcoEngineers, August 2023. <https://assets-global.website-files.com/63b2d261224d1f4f233c389b/64db74185f73d23d6ff4e945_Equatic-EcoEngineers-White%20Paper%20MRV.pdf>.

118 La Plante EC et al (2021) Saline water-based mineralization pathway for gigatonne-scale CO_2 management. ACS Sustainable Chemistry & Engineering 9, 1073–1089. <https://pubs.acs.org/doi/pdf/10.1021/acssuschemeng.0c08561>.

3.1.2 Emerging and alternative OAE approaches

Several emerging and alternative OAE approaches at medium-high TRLs show promise for scaling and improving energy efficiency, though further RD&D are needed. While not covered in detail in this Roadmap, approaches such as CO_2 stripping, electrodialytic OAE, and mineral addition OAE are highlighted in Table 3 for their potential.

Table 3: Emerging and alternative OAE approaches.

APPROACH	DESCRIPTION	KEY RD&D CHALLENGES
CO_2 stripping (also known as direct ocean capture)	After the electrochemical separation of seawater, the acidic component is used to acidify input seawater, catalysing the conversion of aqueous bicarbonate in seawater into CO_2 gas, which can be captured using a vacuum pump and durably stored in geological or mineral storage (see Section 5–7). The decarbonised, acidified seawater is combined with the alkaline component and returned to the ocean with a slightly higher pH level, thereby enhancing the ocean's capacity to absorb additional CO_2 from the atmosphere.[119] Mobile (ship-mounted) versions of this approach are also being considered.[120] Captura (US) has been leading the RD&D efforts for the CO_2 stripping process, currently operating a third pilot project in Hawaii with the capacity to capture 1,000 tCO_2/y, building on two previous pilot projects in California.[121] In March 2025, Captura secured an offtake agreement to deliver 30,000 carbon removal credits for Mitsui O.S.K. Lines (Japan).[122]	Medium TRL (TRL 6 as of November 2023), high energy requirement, understanding and managing the environmental impacts in the short- and long-term.[123]
Electrodialytic OAE	Electrodialytic OAE refers to the electrochemical separation of seawater to produce low-concentration sodium hydroxide, hydrochloric acid and negligible amounts of H_2 and O_2.[124] Ebb Carbon (US) has been leading the RD&D efforts for the electrodialytic OAE process. The company is scaling up a pilot project in Washington, increasing the CDR capacity from 100 to 1,000 tCO_2/y.[125] In 2024, Ebb Carbon signed an agreement with Microsoft to remove up to 350,000 tCO_2 over the next 10 years.[126]	Neutralisation of acidic component (i.e. hydrochloric acid) at scale.[127]
Mineral addition OAE	Alkaline solid materials such as lime (CaO or $Ca(OH)_2$), brucite ($Mg(OH)_2$) and sodium carbonate (Na_2CO_3) are dispersed into the ocean. Mineral addition OAE increases seawater pH, allowing the ocean to take up additional atmospheric CO_2. CO_2 reacts with seawater to form stable (bi)carbonate ions, which can be stored for 10,000 to 100,000 years (see Section 6).[128]	High uncertainty on the environmental impacts, efficiency and MRV for this approach.[129]

119 Eisaman MD et al (2023) Assessing the technical aspects of ocean-alkalinity-enhancement approaches. In Guide to Best Practices in Ocean Alkalinity Enhancement Research. <https://doi.org/10.5194/sp-2-oae2023-3-2023>

120 Aleta P, Refaie A, Afshari M, Hassan A, Rahimi M (2023) Direct ocean capture: the emergence of electrochemical processes for oceanic carbon removal. Energy & Environmental Science 16, 4944–4967. <https://doi.org/10.1039/D3EE01471A>.

121 Captura (n.d.) Technology: Direct Ocean Capture. <https://capturacorp.com/technology/>.

122 Captura (2025) Captura announces sale of carbon removal credits and strategic partnership with Mitsui O.S.K. Lines. <https://capturacorp.com/sale-of-carbon-credits-and-partnership-with-mol/>.

123 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/>.

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

125 Ebb Carbon (n.d.) Electrochemical ocean alkalinity enhancement for carbon dioxide removal. <https://www.ebbcarbon.com/solution>; Ebb Carbon (2024) Project Macoma secures first-of-a-kind permit for marine carbon dioxide removal. <https://www.ebbcarbon.com/post/ebb-carbon-s-project-macoma-secures-first-of-a-kind-permit>; Ebb Carbon (n.d.) Sequim PNNL site: ocean carbon dioxide removal system deployment. <https://www.ebbcarbon.com/site-sequim-pnnl>.

126 Ebb Carbon (2024) Ebb Carbon signs deal with Microsoft for CO_2 removal. <https://www.businesswire.com/news/home/20241024346899/en/Ebb-Carbon-Signs-Deal-With-Microsoft-for-CO2-Removal/>.

127 Eisaman MD et al (2023) Assessing the technical aspects of ocean-alkalinity-enhancement approaches. In Guide to Best Practices in Ocean Alkalinity Enhancement Research. <https://doi.org/10.5194/sp-2-oae2023-3-2023>

128 Eisaman MD et al (2023) Assessing the technical aspects of ocean-alkalinity-enhancement approaches. In Guide to Best Practices in Ocean Alkalinity Enhancement Research. <https://doi.org/10.5194/sp-2-oae2023-3-2023>

129 Karunarathne S et al (2024) Review on CO_2 removal from ocean with an emphasis on direct ocean capture (DOC) technologies. <https://doi.org/10.1016/j.seppur.2024.128598>; Eisaman MD et al (2023) Assessing the technical aspects of ocean-alkalinity-enhancement approaches. In Guide to Best Practices in Ocean Alkalinity Enhancement Research. <https://doi.org/10.5194/sp-2-oae2023-3-2023>.

3.1.3 MRV capture and storage

In June 2024, Isometric published the world's first protocol for OAE, called Ocean Alkalinity Enhancement from Coastal Outfalls.[130] This section draws primarily on the Isometric protocol to illustrate MRV requirements for OAE, and all MRV-related insights presented here are based on this protocol unless otherwise specified. The decision to primarily draw on MRV protocols from Isometric, rather than those of other organisations, for OAE and other novel CDR approaches in scope is due to Isometric being a highly regarded global expert in MRV for CDR and having developed a wide range of protocols. This enables a simple but consistent structure to present how net CO_2 removal is calculated and to illustrate the MRV nuances between different novel CDR approaches.

In the MRV of OAE processes, the net CO_2 removal refers to the total CO_2 removed from the atmosphere and stored, excluding the amount of counterfactual CO_2 captured and stored, as well as any direct CO_2 emissions from the project. The total CO_2 removed from the atmosphere and stored is based on the amount of increased alkalinity in the ocean, determined through measurements taken at the project site, as well as the quantification of additional carbon drawdown into the ocean using ocean models. Counterfactual CO_2 is the amount of CO_2 that would have been removed from the atmosphere by the natural carbon cycle of the ocean, including the interactions associated with sediments.[131]

Direct CO_2 emissions from the project are associated with the establishment and operation of the project (including energy use), end-of-life activities such as MRV, embodied emissions in the production and transportation of feedstock, equipment and materials to the facility, as well as any leakage emissions. Leakage emissions represent increased emissions that occur when materials are diverted from other uses, causing increased emissions elsewhere. In the case of OAE, leakage emissions can be associated with feedstocks (e.g. renewable electricity, rocks for neutralisation) or consumables (e.g. electrolyser components).[132]

There has been progress in the development of MRV protocols and methodologies for OAE approaches, combining direct measurements and quantification using ocean models. However, RD&D is still needed to account for the challenges of operating in open environments, thereby improving the robustness and scalability of the MRV process for other OAE approaches.

Two leading companies in OAE approaches, Equatic and Ebb Carbon, have also developed their own MRV methodologies.

Equatic's MRV methodology is based on Isometric's Electrolytic Seawater Mineralisation protocol,[133] first released in March 2025, and is catered to closed-loop electrolytic OAE processes (Figure 16). In their methodology, CO_2 is measured in multiple locations, including dissolved CO_2 in the incoming seawater to the facility, gaseous CO_2 entering the facility to react with the basic component, and solid carbonates and aqueous bicarbonates formed after the basic component reacts with gaseous CO_2. Equatic uses on-stream, real-time and off-line sensors to gather measurements of alkalinity, pH, temperature, and salinity of the seawater and processed solutions, all of which are entered in a model (i.e. CO_2SYS) to estimate the CO_2 concentrations (i.e. carbonate ions, bicarbonate ions, dissolved CO_2) in the system. Although minimal, Equatic also considers the risk of reversal, especially the localised secondary carbonate precipitation. Sources of CO_2 emissions in Equatic's operations include electricity to power the facility, energy for grinding and transporting rocks to the facility (for acidic component neutralisation), and the construction of the facility.[134]

Ebb Carbon's publicly available MRV methodology includes additional comprehensive details in the calculation of the total amount of CO_2 removal. For example, it accounts for factors leading to OAE efficiency losses, such as alkalinity subduction, secondary precipitation, potential acid leaks, and/or biogeochemical feedback. It also utilises regional ocean models and biogeochemical modules, in addition to physical measurements of seawater parameters, to calculate the amount of CO_2 captured and stored.[135]

130 Isometric (2023) Ocean alkalinity enhancement protocol v1.0: requirements and procedures for net CO_2e removal via coastal outfalls. <https://registry.isometric.com/protocol/ocean-alkalinity-enhancement/1.0>.

131 Isometric (2023) Ocean alkalinity enhancement protocol v1.0: requirements and procedures for net CO_2e removal via coastal outfalls. <https://registry.isometric.com/protocol/ocean-alkalinity-enhancement/1.0>.

132 Isometric (2023) Ocean alkalinity enhancement protocol v1.0: requirements and procedures for net CO_2e removal via coastal outfalls. <https://registry.isometric.com/protocol/ocean-alkalinity-enhancement/1.0>.

133 Isometric (2023) Electrolytic seawater mineralization protocol v1.0: MRV and best practices for high-quality carbon dioxide removal. <https://registry.isometric.com/protocol/electrolytic-seawater-mineralization/1.0>.

134 Equatic, EcoEngineers (2023) Equatic's measurement, reporting, and verification methodology. White paper prepared in consultation with EcoEngineers, August 2023. <https://assets-global.website-files.com/63b2d261224d1f4f233c389b/64db74185f73d23d6ff4e945_Equatic-EcoEngineers-White%20Paper%20MRV.pdf>.; La Plante EC, Chen X, Bustillos S, Bouissonnie A, Traynor T, Jassby D, Corsini L, Simonetti DA, Sant GN (2023) Electrolytic seawater mineralization and the mass balances that demonstrate carbon dioxide removal. ACS Environmental Science & Technology Engineering 3, 955–968. <https://pubs.acs.org/doi/pdf/10.1021/acsestengg.3c00004>.

135 Ebb Carbon (2023) Electrochemical Ocean Alkalinity Enhancement: Measurement, reporting and verification (MRV) for Safe and Effective Carbon Dioxide Removal. <https://www.ebbcarbon.com/_files/ugd/d1a3e5_dc35ab01aa5c4a1fa8c069b00aca0e9f.pdf>.

3.2 Enhanced rock weathering (ERW)

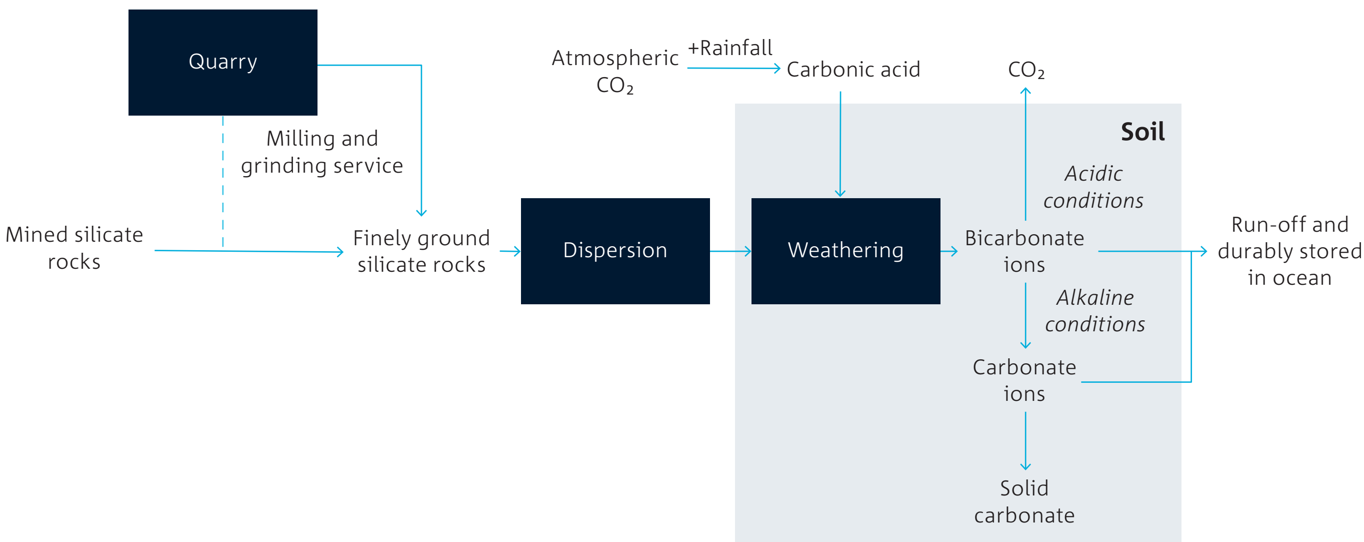
The natural weathering of calcium- and magnesium-rich silicate rocks plays an important role in the global carbon cycle over geological timescales.[136] The process begins when CO_2 in the atmosphere is dissolved in rainwater, forming a dilute carbonic acid. When this carbonic acid comes into contact with calcium- and magnesium-rich silicate rocks, the dissociation of carbonic acid forms bicarbonate (HCO_3^-) and hydrogen (H^+) ions. The acid (H^+) reacts with the silicate minerals, releasing cations (e.g. Ca^{2+} and Mg^{2+}) and bicarbonate ions in the soil.[137] Under alkaline conditions, these soluble bicarbonate ions can be precipitated into (and accumulated as) solid carbonates in soil (see Section 6, land-based storage), or transferred through the soil system into runoffs, feeding into rivers and oceans, where they are durably stored (see Section 6, Ocean-based storage).[138] Under acidic soil conditions, bicarbonates and carbonates in soil can be converted back into CO_2.

3.2.1 Overview

ERW approaches involve deliberately dispersing finely crushed rocks on land at scale,[139] consequently increasing the rate at which atmospheric CO_2 in the form of carbonic acid is captured (Figure 17). By matching rock types with appropriate soil characteristics, local climate and farming practices that promote alkaline conditions, ERW aims to accelerate natural weathering. These finely crushed rocks have an increased surface area due to comminution which involves crushing, grinding and milling at quarries, and therefore have a higher weathering rate compared to naturally occurring rocks. Depending on the size of the crushed rocks, the weathering timescale of ERW approaches can be decreased to years or decades as opposed to geological timescales.[140]

ERW approaches offer flexibility in terms of the applicable feedstocks (i.e. a range of rock types and industrial byproducts) and a range of open environments for implementation. This section focuses on ERW approaches for agricultural land using rocks that are purpose-mined and ground or utilised from existing quarries, providing an overview of the approach and its state of development.

Figure 17: Overview of the ERW process.



136 Tao F, Houlton BZ (2024) Inorganic and organic synergies in enhanced weathering to promote carbon dioxide removal. Global Change Biology 30, e17132. <https://doi.org/10.1111/gcb.17132>.

137 Holden FJ, Davies K, Bird MI, Hume R, Green H, Beerling DJ, Nelson PN (2024) In-field carbon dioxide removal via weathering of crushed basalt applied to acidic tropical agricultural soil. Science of the Total Environment 955, 176568. <https://doi.org/10.1016/j.scitotenv.2024.176568>.

138 Holden FJ et al (2024) In-field carbon dioxide removal via weathering of crushed basalt applied to acidic tropical agricultural soil. Science of the Total Environment 955, 176568. <https://doi.org/10.1016/j.scitotenv.2024.176568>; IPCC (2005) IPCC special report on carbon dioxide capture and storage. <https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_wholereport-1.pdf>.

139 Holden FJ et al (2024) In-field carbon dioxide removal via weathering of crushed basalt applied to acidic tropical agricultural soil. Science of the Total Environment 955, 176568. <https://doi.org/10.1016/j.scitotenv.2024.176568>.

140 Buss W, Hasemer H, Ferguson S, Borevitz J (2024) Stabilisation of soil organic matter with rock dust partially counteracted by plants. Global Change Biology 30, e17052. <https://doi.org/10.1111/gcb.17052>.

This is followed by a high-level overview of alternative ERW approaches that have the potential to enhance the weathering efficiency, improve mining sustainability through byproduct utilisation, and more closely align with regional needs.

In addition to the main purpose of facilitating CDR, agricultural ERW can deliver co-benefits for soil health and productivity. By increasing soil alkalinity, implementing ERW represents a complementary solution to potentially enhance and accelerate the mitigation of soil acidification, supporting other existing agricultural practices such as applying crushed limestone on soil (i.e. agricultural liming) or reducing the use of acidifying fertilisers. The weathering of calcium- and magnesium-rich silicate rocks also supplies nutrients to the soil, supporting plant growth and the broader soil ecosystem.[141]

Agricultural ERW

Implementing ERW on agricultural land is a relevant approach for Australia due to the prevalence of agricultural land in proximity to suitable rock sources and the incentive of co-benefits for soil health and agricultural production, which could build support from farmers and landowners.

While various calcium- and magnesium-rich silicate rocks and byproduct materials can be used in the ERW process, basalt has high potential as a candidate for the agricultural ERW approach in Australia. This is due to its abundance, low concentration of potentially toxic elements, and availability as a finely crushed byproduct of the quarrying industry, enabling the bypassing of some capital and operating costs associated with comminution.[142] Basalt is composed of minerals that can be weathered at a faster rate than other felsic or sedimentary rocks, and can provide vital nutrients for plant growth, such as magnesium, calcium, iron, potassium and phosphorus.[143] Agricultural land also typically does not have high alkalinity (i.e. pH < 7) at the surface level, which is an important condition for basalt to begin weathering.[144]

3.2.2 Emerging and alternative ERW processes

There are emerging and alternative ERW approaches at low TRLs that have the potential to enhance the weathering efficiency, improve mining sustainability through waste utilisation, and better align with region-specific circumstances; however, further RD&D is needed. While not covered in detail in this project, approaches that are deployed at other natural environments, such as rivers and coastlines, are highlighted in Table 4 for their potential. Supporting RD&D in overcoming environmental and economic uncertainties and advancing MRV methods is important for creating a pathway to scale up emerging and alternative ERW approaches.

Table 4: Overview of emerging and alternative ERW approaches.

APPROACH	DESCRIPTION	KEY RD&D CHALLENGES
Coastal ERW[145]	Dispersion of finely ground alkaline rocks onto beaches and coastal shelves to react with dissolved CO_2 in seawater to form bicarbonate ions.	Low TRL and uncertainties in the MRV process and the impact on coastal and ocean environments.
River alkalinity enhancement[146]	In rivers with favourable conditions, dispersion of finely ground alkaline feedstocks (e.g. limestone) to react with dissolved CO_2 in riverine water to form bicarbonate ions.[147] River alkalinity enhancement overlaps with the 'Mineral addition OAE' approach.	Low TRL and uncertainties in the MRV process and the impact on riverine, coastal, and ocean environments.

141 Common Capital Pty Ltd (2023) Scaling atmospheric carbon dioxide removal in New South Wales. Report prepared for the NSW Office of Energy and Climate Change. <https://www.energy.nsw.gov.au/sites/default/files/2024-02/Common_Capital_Scaling_atmospheric_CDR_in_NSW_Final.pdf>.

142 Lewis AL, Sarkar B, Wade P, Kemp SJ, Hodson ME, Taylor LL, Yeong KL, Davies K, Nelson PN, Bird MI, Kantola IB, Masters MD, DeLucia E, Leake JR, Banwart SA, Beerling DJ (2021) Effects of mineralogy, chemistry and physical properties of basalts on carbon capture potential and plant-nutrient element release via enhanced weathering. Applied Geochemistry 132, 105023. <https://doi.org/10.1016/j.apgeochem.2021.105023>; Holden FJ, Davies K, Bird MI, Hume R, Green H, Beerling DJ, Nelson PN (2024) In-field carbon dioxide removal via weathering of crushed basalt applied to acidic tropical agricultural soil. Science of the Total Environment 955, 176568. <https://doi.org/10.1016/j.scitotenv.2024.176568>. <https://www.sciencedirect.com/science/article/pii/S004896972406724X?via%3Dihub - s0005>.

143 Lewis AL et al (2021) Effects of mineralogy, chemistry and physical properties of basalts on carbon capture potential and plant-nutrient element release via enhanced weathering. Applied Geochemistry 132, 105023. <https://doi.org/10.1016/j.apgeochem.2021.105023>.

144 Consultation insights.

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

146 Isometric HQ Ltd. (2025) River Alkalinity Enhancement Protocol v1.0. Isometric, London, UK. <https://registry.isometric.com/protocol/river-alkalinity-enhancement/1.0/ctn_1JQ8ZCFJY1S0ZWXH>.

147 CarbonRun (n.d.) Healthy Rivers. Healthy Planet. <https://www.carbonrun.io/#science>.

3.2.3 MRV capture and storage

Isometric has developed and updated the Enhanced Weathering in Agriculture protocol, which applies to agricultural ERW approaches.[148] This section draws primarily on the Isometric protocol to illustrate MRV requirements for ERW, and all MRV-related insights presented here are based on this protocol unless otherwise specified. The decision to primarily draw on MRV protocols from Isometric, rather than those of other organisations, for ERW and other novel CDR approaches in scope is due to Isometric being a highly regarded global expert in MRV for CDR and having developed a wide range of protocols. This enables a simple but consistent structure to present how net CO_2 removal is calculated and to illustrate the MRV nuances between different novel CDR approaches.

In the MRV of agricultural ERW approaches, the net CO_2 removal is the total CO_2 removed from the atmosphere and stored as solid or aqueous inorganic carbon in the deployment site, excluding the amount of counterfactual CO_2 captured and stored and any direct CO_2 emissions from the project.

At a high level, the total CO_2 removed from the atmosphere and stored can be quantified by measuring the amount of cations (e.g. Ca^{2+} and Mg^{2+}) released from the weathering, or the amount of bicarbonate and carbonate ions formed.[149] After the measurements are collected, they need to be adjusted by the amount of ions temporarily or durably lost through (bio)geochemical processes in the soil or the amount of CO_2 released back to the atmosphere in downstream river systems and oceans.[150] Examples of such (bio)geochemical processes in the soil include plant uptake, clay formation, reactions of cations with acids in the soil and carbonate mineral formation.[151]

Counterfactual CO_2 is the amount of CO_2 that would have been removed from the atmosphere as a result of natural weathering or pre-existing land practices. For example, any CDR achieved through the common agricultural practice of applying limestone (i.e. calcium carbonate) must be separated from the CDR achieved through agricultural ERW using basalt. To quantify the amount of counterfactual CO_2, measurements from the ERW site need to be compared against those from a control plot, which needs to be established and maintained separately with no additional ERW practices.[152]

Direct CO_2 emissions from the project are associated with the establishment and operation of the project, as well as end-of-life activities such as MRV and any leakage emissions. Leakage emissions represent increased emissions when materials (i.e. rocks) are diverted from other uses, causing increased emissions elsewhere.[153]

Verification of CDR by agricultural ERW requires life cycle and total environmental footprint analyses using a combination of solid, liquid and gas phase analysis methods, with key considerations including:[154]

- Types of feedstocks used.
- Location of ERW implementation and the surrounding open system (including spatial and temporal changes).
- Emissions associated with the project establishment, operation, and end-of-life activities.
- Changes in organic and inorganic carbon.
- Accurate baseline assessment, ensuring the CDR calculations of ERW activities are additional.
- Medium-term climate changes and impacts.
- Environmental and social risks.

148 Isometric HQ Ltd. (2025) Enhanced Weathering in Agriculture Protocol v1.1. Isometric, London, UK. <https://registry.isometric.com/protocol/enhanced-weathering-agriculture/1.1/ctn_1JBF3A2JY1S0Z7MA#systems-boundary--ghg-emission-scope>.

149 Common Capital Pty Ltd (2023) Scaling atmospheric carbon dioxide removal in New South Wales. Report prepared for the NSW Office of Energy and Climate Change. <https://www.energy.nsw.gov.au/sites/default/files/2024-02/Common_Capital_Scaling_atmospheric_CDR_in_NSW_Final.pdf>.

150 Hasemer H, Borevitz J, Buss W (2024) Measuring enhanced weathering: inorganic carbon-based approaches may be required to complement cation-based approaches. Frontiers in Climate 6, 1352825. <https://www.frontiersin.org/journals/climate/articles/10.3389/fclim.2024.1352825/full>.

151 Isometric HQ Ltd. (2025) Enhanced Weathering in Agriculture Protocol v1.1. Isometric, London, UK. <https://registry.isometric.com/protocol/enhanced-weathering-agriculture/1.1/ctn_1JBF3A2JY1S0Z7MA#systems-boundary--ghg-emission-scope>.

152 Isometric HQ Ltd. (2025) Enhanced Weathering in Agriculture Protocol v1.1. Isometric, London, UK. <https://registry.isometric.com/protocol/enhanced-weathering-agriculture/1.1/ctn_1JBF3A2JY1S0Z7MA#systems-boundary--ghg-emission-scope>.

153 Isometric HQ Ltd. (2025) Enhanced Weathering in Agriculture Protocol v1.1. Isometric, London, UK. <https://registry.isometric.com/protocol/enhanced-weathering-agriculture/1.1/ctn_1JBF3A2JY1S0Z7MA#systems-boundary--ghg-emission-scope>.

154 Mission Innovation Carbon Dioxide Removal (CDR) Mission (2024) Measurement, Reporting and Verification (MRV) for Carbon Dioxide Removal: Issues and Opportunities for International Harmonization of National Governments' CDR MRV Methodologies. Mission Innovation, London, UK. <https://www.mission-innovation.net/wp-content/uploads/2024/12/2024-12_CDR-Mission-MRV-Report.pdf>; Isometric HQ Ltd. (2025) Enhanced Weathering in Agriculture Protocol v1.1. Isometric, London, UK. <https://registry.isometric.com/protocol/enhanced-weathering-agriculture/1.1/ctn_1JBF3A2JY1S0Z7MA#systems-boundary--ghg-emission-scope>.

Additionally, the analysis and verification process could include the co-benefits of agricultural ERW for farm productivity to increase buy-in from farmers and landowners.[155]

The MRV process for ERW approaches is challenging due to the operation in open environments, requiring significant RD&D to reduce costs and improve scalability. Measurement is the most challenging step as cations, bicarbonate, and carbonate ions often exist in low concentrations and vary spatially, requiring extensive sample collection, which can be time and labour-intensive, and not guaranteeing accurate results.[156] To overcome this, further RD&D can be focused on improving soil carbon measurement technologies and simulation models, and integrating them into the MRV process to improve the CDR quantification.[157]

Despite the technical challenges with MRV, in early 2025, the global industry's first certified carbon credits in ERW were delivered by startup InPlanet (Brazil, Germany), with verification from Isometric's Enhanced Weathering Protocol. The transparent data and underlying information behind each credit can be used as evidence and guidance for future ERW operators and CDR buyers, enabling the scaling up of ERW projects and increasing the uptake of ERW carbon credits in the carbon market.[158]

155 Mission Innovation Carbon Dioxide Removal (CDR) Mission (2024) Measurement, Reporting and Verification (MRV) for Carbon Dioxide Removal: Issues and Opportunities for International Harmonization of National Governments' CDR MRV Methodologies. Mission Innovation, London, UK. <https://www.mission-innovation.net/wp-content/uploads/2024/12/2024-12_CDR-Mission-MRV-Report.pdf>.

156 Dietzen C, Rosing MT (2023) Quantification of CO_2 uptake by enhanced weathering of silicate minerals applied to acidic soils. International Journal of Greenhouse Gas Control 125, 103872. <https://doi.org/10.1016/j.ijggc.2023.103872>.

157 Tao F, Houlton BZ (2024) Inorganic and organic synergies in enhanced weathering to promote carbon dioxide removal. Global Change Biology 30(2), e17132. <https://doi.org/10.1111/gcb.17132>.

158 InPlanet (2025) World's first enhanced rock weathering carbon removal credits issued. InPlanet, Brazil. <https://inplanet.earth/press/worlds-first-enhanced-rock-weathering-carbon-removal-credits-issued/>; Isometric HQ Ltd. (2025) Enhanced Weathering in Agriculture Protocol v1.1. Isometric, London, UK. <https://registry.isometric.com/protocol/enhanced-weathering-agriculture/1.1#co-benefits-and-opportunities>; Isometric HQ Ltd. (2025) Project profile: Enhanced Weathering in Agriculture. Isometric, London, UK. <https://registry.isometric.com/project/prj_1J7NQMR9V1S04P0D

4 Chemical capture

Chemical CO_2 capture refers to the process of capturing CO_2 from the atmosphere using specific chemical processes. This section focuses on a group of chemical CO_2 capture processes known as direct air capture (DAC).

4.1 Direct air capture (DAC)

Direct air capture (DAC) refers to a group of chemical processes to separate and concentrate CO_2 from the atmosphere, facilitated in two stages. First, CO_2 is captured from the atmosphere using a selective chemical or material. Once the material is close to saturation, it undergoes a regeneration process to release the CO_2 for storage, allowing the material to be restored to its original state for reuse.[159] To be considered a CDR approach, DAC processes need to be combined with CO_2 storage, which could be geological (see Section 5) or mineral storage (see Section 7), allowing CO_2 to be stored for 10,000–100,000 years.[160]

4.1.1 Overview

The two main types of DAC processes considered in this Roadmap are based on the adsorption of CO_2 to a solid material (i.e. solid adsorbent DAC) and the absorption of CO_2 to a liquid solution (i.e. liquid absorbent DAC).

The differences between the processes of adsorption and absorption are explained in Box 3. The section explains the solid adsorbent and liquid absorbent DAC process, along with their current state of development. It is followed by an overview of emerging DAC processes that have the potential to reduce energy costs and support region-specific requirements. Lastly, the section provides an overview of the MRV process for the DAC+S approach, presenting the calculation method for net CO_2 removal and key MRV considerations. Further information on the MRV process and considerations associated with CO_2 storage can be found in Section 5 (for geological storage) and Section 7 (for mineral storage).

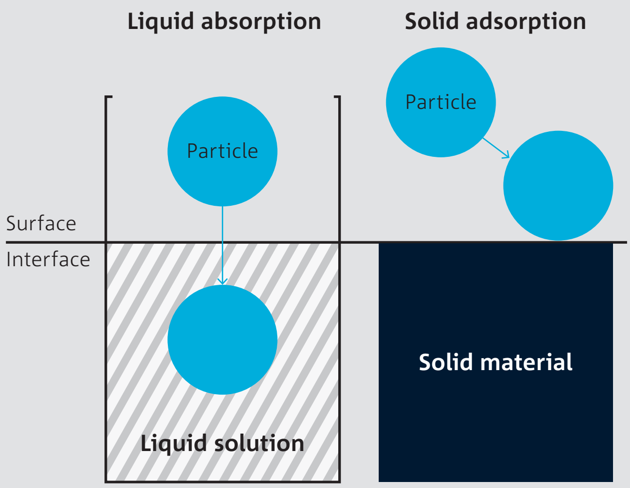
Solid adsorbent DAC

Solid adsorbent DAC represents a group of processes that use a solid material to capture CO_2 from the atmosphere. This analysis focuses on processes that utilise amine-based physical adsorbents and low-temperature heat regeneration due to their advanced development (high TRLs), potential for energy efficiency, and the opportunity to learn from and leverage existing demonstration and commercial projects domestically and globally.

Box 3: Adsorption vs absorption – differences and examples.

Adsorption and absorption are processes through which one substance attaches to another.
Adsorption is the adhesion of a substance onto the surface of another substance. In contrast, absorption is the incorporation of a substance throughout another substance. While adsorption and absorption can happen at different phases of two substances (gas, solid, liquid), the two key DAC processes considered in this Roadmap are the adsorption of CO_2 to a solid material (i.e. solid adsorbent DAC) and the absorption of CO_2 to a liquid solution (i.e. liquid absorbent DAC).

Figure 18: Liquid absorption vs solid adsorption mechanisms.



159 Pett-Ridge et al. (2023) Roads to removal: options for carbon dioxide removal in the United States. Lawrence Livermore National Laboratory. <https://www.osti.gov/biblio/2301853>; Carbon Dioxide Removal Mission (2022) Carbon dioxide removal technology roadmap: innovation gaps and landscape analysis.

160 IPCC (2005) IPCC special report on carbon dioxide capture and storage. <https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_wholereport-1.pdf>.

161 RMI (2023) The applied innovation roadmap for CDR. <https://rmi.org/insight/the-applied-innovation-roadmap-for-cdr/>; Pett-Ridge et al. (2023) Roads to removal: options for carbon dioxide removal in the United States. Lawrence Livermore National Laboratory. <https://www.osti.gov/biblio/2301853>.

In the solid adsorbent DAC process, amine-based materials are fixed to filters inside contactor modules, capturing atmospheric CO_2 from the air as it passes through the contactors. The contactors are then heated to 80–120°C in a semi-vacuum environment using low-grade heat such as steam to release high-purity CO_2 and regenerate the amine-based materials.[161] Figure 19 illustrates the complete DAC+S CDR approach via the solid adsorbent DAC process.

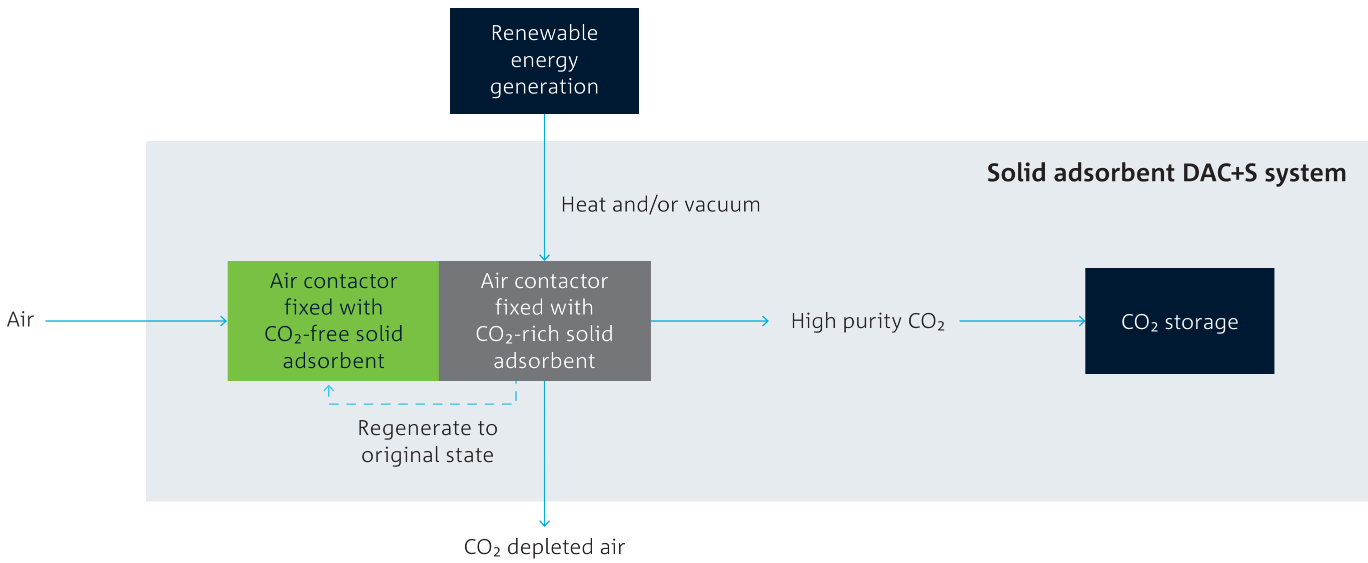
State of development

Solid adsorbent DAC using amine-based materials is one of the leading processes for DAC globally, with many facilities operating at pilot or early commercial scale. As of November 2023, solid adsorbent DAC using amine-based materials had reached a TRL range between 7 and 9.[162]

The most advanced solid adsorbent DAC project using amine-based materials globally is operated by Climeworks (Switzerland). Climeworks's first commercial-scale DAC+S facility in Iceland commenced operation in 2021, with an annual capture capacity of 4,000 tCO_2/y, supported by Carbfix (Iceland) in the storage technology.[163] Their second facility in Iceland commenced operation in 2024 with a maximum capture capacity of 36,000 tCO_2/y.[164] Other notable companies conducting pilots and demonstrations of solid adsorbent DAC using amine-based materials include Zero Carbon Systems (US, formerly Global Thermostat),[165] Octavia Carbon (Kenya),[166] Hydrocell and Soletair Power (Finland).[167]

In Australia, CSIRO has developed an innovative hybrid solid/liquid sorbent-based process with high selectivity for CO_2 in the atmosphere. The process is being piloted at Santos' Moomba operations in South Australia (SA), with a capture capacity of 90 tCO_2/y. There are also plans to install a second unit with an increased capacity of 365 tCO_2/y.[168]

Figure 19: Overview of the DAC+S CDR approach via the solid adsorbent DAC process.



162 Stakeholder consultation; RMI (2023) The applied innovation roadmap for CDR. <https://rmi.org/insight/the-applied-innovation-roadmap-for-cdr/>.

163 Climeworks AG (2021) Orca: the world's first large-scale direct air capture and storage plant. Climeworks, Zurich, Switzerland. <https://climeworks.com/plant-orca>.

164 Climeworks AG (2024) Mammoth: our newest direct air capture and storage facility. Climeworks, Zurich, Switzerland. <https://climeworks.com/plant-mammoth>.

165 Zero Carbon Systems (2024) Zero Carbon Systems intends to own and operate a 2,500-ton demonstration plant, a 50,000-ton commercial plant, and a million-ton scale plant by around 2030. Zero Carbon Systems, New York, USA. <https://www.zerocarbonsystems.com/news>.

166 Njanja A (2024) Kenya's Octavia gets $3.9M seed to remove carbon from air. TechCrunch, 16 October. <https://techcrunch.com/2024/10/16/octavia-gets-backing-to-remove-carbon-from-air/>; however, this article says the plant capacity is 1000 tpa – Payton B (2023) Kenya gears up for direct air capture push in the Great Carbon Valley. Reuters, 13 November. <https://www.reuters.com/sustainability/climate-energy/kenya-gears-up-direct-air-capture-push-great-carbon-valley-2023-11-13/>; pilot is mentioned in Applied Innovation Roadmap; Octavia Carbon (2023) Response to the Article 6.4 Supervisory Body's Information Note on Removal Activities. UNFCCC, Bonn, Germany. <https://unfccc.int/sites/default/files/resource/OctaviaCarbon.pdf>.

167 Soletair Power (n.d.) Building Carbon Capture Technology. Soletair Power, Finland. <https://www.soletairpower.fi/technology/>.

168 Walker S, Dawkins R (2023) Direct air captures the path to emissions targets. CSIRO, Canberra, Australia. <https://www.csiro.au/en/news/All/Articles/2023/June/Direct-air-capture>.

Liquid absorbent DAC

Liquid absorbent DAC approaches use a liquid to capture CO_2 from the atmosphere. This analysis primarily focuses on the hydroxide absorbent DAC process, chosen for its relatively advanced development stage, characterised by medium to high TRLs.[169]

The hydroxide absorbent DAC process is a continuous process where atmospheric CO_2 is reacted with a hydroxide solution to form a solid carbonate product. The solid carbonate product is then calcined at 700–900°C in a calciner to release high-purity CO_2, which is subsequently captured and transported to a geological storage or mineral carbonation facility (see Section 5 and 7). A solid oxide product is also formed, which can be mixed with water to regenerate the hydroxide solution, allowing it to be reused in multiple cycles.[170] Figure 20 illustrates the complete DAC+S CDR approach via the liquid absorbent DAC process.

State of development

The hydroxide absorbent DAC+S approach is relatively advanced and is being scaled up globally. As of November 2023, the hydroxide absorbent DAC process had reached a TRL range between 7 and 9.[171]

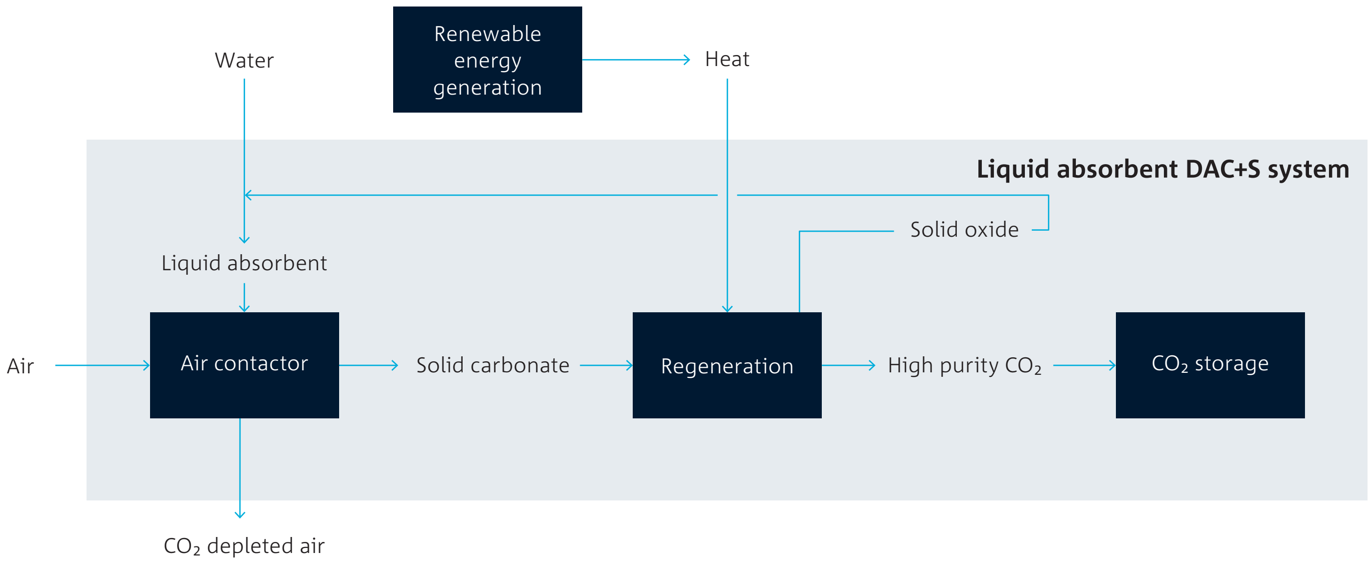
The process has been developed by Carbon Engineering (Canada), with a commercial-scale facility being constructed in Texas since 2023 in partnership with Worley and 1PointFive. The DAC facility, STRATOS, is expected to have the capacity to capture up to 500,000 tCO_2/y.[172]

In Australia, CSIRO has developed a representative approach of the liquid absorbent DAC process, which uses amino acid solutions (see Section 4.1.2), expected to be demonstrated in 2026.[173]

4.1.2 Emerging and alternative DAC processes

Emerging, lower-TRL DAC processes offer promising pathways to reduce both cost and energy consumption. Innovations such as alternative adsorbent and absorbent materials, along with non-thermal regeneration processes (see Table 5), are at the forefront of this progress. While these processes require further RD&D and scale-up efforts, they represent valuable opportunities for improving DAC outcomes.

Figure 20: Overview of the DAC+S approach via the liquid absorbent DAC process.



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

170 RMI (2023) The applied innovation roadmap for CDR. https://rmi.org/insight/the-applied-innovation-roadmap-for-cdr/; Pett-Ridge et al. (2023) Roads to removal: options for carbon dioxide removal in the United States. Lawrence Livermore National Laboratory. <https://www.osti.gov/biblio/2301853>.

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

172 Carbon Engineering Ltd. (n.d.) Our Technology: Direct Air Capture. Carbon Engineering, British Columbia, Canada. <https://carbonengineering.com/our-technology/>; 1PointFive (2025) STRATOS: Direct Air Capture Facility in Ector County, Texas. 1PointFive, Houston, TX. <https://www.1pointfive.com/projects/ector-county-tx>.

173 Walker S, Dawkins R (2023) Direct air captures the path to emissions targets. CSIRO, Canberra, Australia. <https://www.csiro.au/en/news/All/Articles/2023/June/Direct-air-capture>.

Table 5: Emerging and alternative DAC processes

PROCESS	DESCRIPTION	KEY RD&D CHALLENGES
Amino acid liquid DAC	Amino acid liquid DAC uses an amino acid solution to absorb atmospheric CO_2, forming a carbamate compound or a bicarbonate compound in aqueous solutions.[174] The CO_2-rich solution containing carbamate or bicarbonate compound is then heated to 120°C using low-grade heat such as steam to release high-purity CO_2 for storage and regenerate the amino acid solution.[175] Compared to the hydroxide absorbent DAC process, the amino acid liquid DAC process has lower energy requirements and a simpler process design (i.e. fewer and less complex units of operation), resulting in potentially lower capital and operating costs.[176]	Corrosivity of some amines, thermal degradation and loss of amino acid solution.[177]
Membrane DAC	Membrane DAC uses polymeric membranes to capture CO_2 from the atmosphere.[178]	Low capture efficiency.[179]
Cryogenic DAC	Cryogenic DAC uses very low temperatures to transform CO_2 from gaseous to solid state (i.e. dry ice) for capture.[180]	High energy requirement for cooling.[181]
Mineral-based solid adsorbent DAC	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).[182]	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.[183]
Electrode-based DAC	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.[184]	Uncertainty in material cost and durability, adsorption and regeneration kinetics, and overall energy efficiency.[185]
Moisture-swing solid adsorbent DAC	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.[186]	Potential high-water requirement if deployed in hot and dry climates.[187] The co-production of CO_2 and water requires separation and purification systems and anti-corrosion materials which can increase capital costs.[188] Suitable solid adsorbents for this process currently have high costs.[189]

174 Hack J, Maeda N and Meier DM (2022) Review on CO_2 capture using amine-functionalized materials. ACS Omega.

175 Dutcher B, Fan M and Russell AG (2015) Amine-based CO_2 capture technology development from the beginning of 2013 – a review. ACS Applied Materials & Interfaces; RMI (2023) The applied innovation roadmap for CDR. <https://rmi.org/insight/the-applied-innovation-roadmap-for-cdr/>.

176 Stakeholder consultation.

177 Momeni A, McQuillan RV, Alivand MS, Zavabeti A, Stevens GW, Mumford KA (2024) Direct air capture of CO_2 using green amino acid salts. Chemical Engineering Journal 480, Article 147934. <https://doi.org/10.1016/j.cej.2023.147934>; Bera N, Sardar P, Hazra R, Samanta AN, Sarkar N (2024) Direct air capture of CO_2 by amino acid-functionalized ionic liquid-based deep eutectic solvents. ACS Sustainable Chemistry & Engineering 12(38), 14288–14295. <https://doi.org/10.1021/acssuschemeng.4c05090>.

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

179 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/>.

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

181 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/>.

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

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

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

185 Pett-Ridge et al. (2023) Roads to removal: options for carbon dioxide removal in the United States. Lawrence Livermore National Laboratory. <https://www.osti.gov/biblio/2301853>.

186 Shindel B, Hegarty J, Estradioto JD, Barsoum ML, Yang M, Farha OK, Dravid VP (2025) Platform materials for moisture-swing carbon capture. Environmental Science & Technology 59(9), 12345–12356. <https://doi.org/10.1021/acs.est.4c11308>.

187 Pett-Ridge et al. (2023) Roads to removal: options for carbon dioxide removal in the United States. Lawrence Livermore National Laboratory. <https://www.osti.gov/biblio/2301853>.

188 Stakeholder consultation.

189 Stakeholder consultation.

4.1.3 MRV capture and storage

Several MRV protocols have been developed to allow CDR via DAC+S to be sold through voluntary marketplaces. Isometric, a carbon removal registry, has developed the Direct Air Capture protocol which applies to a broad range of currently mature and emerging DAC processes.[190] This section draws primarily on the Isometric protocol to illustrate MRV requirements for DAC+S, and all MRV-related insights presented here are based on this protocol unless otherwise specified. The decision to primarily draw on MRV protocols from Isometric, rather than that of other organisations, for DAC+S and other novel CDR approaches in scope is due to Isometric being a highly regarded global expert in MRV for CDR and having developed a wide range of protocols. This enables a simple but consistent structure to present how net CO_2 removal is calculated and to illustrate the MRV nuances between different novel CDR approaches.

The Isometric protocol requires management and documentation of emissions associated with the liquid absorbents and solid adsorbents used. While there might be multiple parties involved in different steps of a DAC+S operation, the Isometric protocol requires one party to be nominated for the entire project when applying for credits, reducing the risk of double counting of CO_2 removal.

The system boundaries of a DAC+S project include four components:

- DAC process, covering all activities associated with capturing atmospheric CO_2.
- CO_2 transportation, covering all activities associated with transporting CO_2 from the DAC facility to the storage location.
- CO_2 storage, covering all activities associated with the durable storage of CO_2 at the storage location (see Section 5 and 7 for further details).
- CO_2 monitoring, covering all activities related to monitoring CO_2 storage (see Section 5 and 7 for further details).

The net CO_2 removal for the Isometric protocol is calculated based on the total CO_2 stored in geological storage or the subsurface for mineral carbonate formations, excluding the amount of counterfactual CO_2 storage and any direct CO_2 emissions from the project.

The total amount of CO_2 captured and stored can be directly measured using a mass flow meter or calculated using the volume and density measurements. The density of CO_2 can be directly measured using a calibrated density meter or calculated using pressure and temperature measurement. These measurement systems are readily available off-the-shelf and can be integrated into the DAC facility design to streamline the MRV process.

Counterfactual CO_2 is the amount of CO_2 removed from the atmosphere by another DAC project and durably stored, which is typically zero since DAC projects don’t have competing inputs with each other or with other industries (i.e. atmospheric CO_2).

Using the Isometric protocol, direct CO_2 emissions from the project are associated with the system boundaries of the project (e.g. energy use, transportation, and embodied emissions), as well as any leakage emissions. Leakage emissions represent increased emissions when materials are diverted from other uses (e.g. if a DAC project uses grid energy) or when production activity is indirectly increased or incentivised.

The direct capture of atmospheric CO_2, the closed loop process and the requirement for additional renewable energy sources allow the MRV of DAC processes to be relatively simpler than other CDR processes.

In 2023, Climeworks and Carbfix partnered with CDR crediting platform Puro.Earth to develop an MRV methodology for DAC+S.[191] In May 2024, Climeworks received third-party, internationally recognised certification from Puro.Earth for its commercial facility in Iceland, the first company in the DAC industry, establishing new standards in the global CDR industry and enhancing transparency and trust in the voluntary carbon market.[192]

190 Isometric HQ Ltd. (2025) Direct Air Capture Protocol v1.2. Isometric, London, UK. <https://registry.isometric.com/protocol/direct-air-capture#calculation-of-coe-4>.

191 Puro.earth (2023) Climeworks selects Puro.earth to work toward certification under the Puro Standard, in collaboration with storage partner Carbfix. Puro.earth, Helsinki, Finland. <https://puro.earth/our-blog/climeworks-selects-puro-earth-to-work-toward-certification-under-the-puro-standard-in-collaboration-with-storage-partner-carbfix>.

192 Climeworks (2024) Climeworks first DAC company to be certified under Puro Standard. <https://climeworks.com/press-release/climeworks-first-dac-company-certified-under-puro-standard>.

5 Geological storage

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.[193] The durability of geological CO_2 storage systems is dictated by physical trapping mechanisms. In the context of this Roadmap, only CO_2 that is captured from the atmosphere for geological storage in underground geological formations is considered. This section outlines geological storage, reviewing it in the global and Australian context and providing a discussion on MRV requirements.

5.1 Geological CO_2 storage

The most common geological storage formations applicable for Australia are saline aquifers and depleted oil and gas fields.[194] Saline aquifers are deep, porous rocks saturated with brackish to saline water where CO_2 can be securely stored in the pore spaces between rock grains. Depleted oil and gas fields are also porous rock reservoirs, similar to saline aquifers, but that have previously held hydrocarbons. They are both being used in commercial CCS projects, because of their potential to provide reliable and inexpensive CO_2 storage. This is largely due to their proven ability to contain CO_2 and the potential for reuse of existing infrastructure (e.g. wells, pipelines).

Storage of CO_2 in saline aquifers and depleted oil and gas fields is at TRL 9,[195] with the Gorgon CCS project in Western Australia (WA) and Moomba CCS project in SA being notable Australian examples.[196] Both geological storage formations are typically located 1–3 km below the surface, onshore or offshore, where CO_2 remains in a dense, supercritical state (behaving like a gas but with the density of a liquid). The durability of geological CO_2 storage systems is dictated by physical and chemical trapping mechanisms. As a result of these processes, CO_2 can be durably stored in geological formations for over 10,000 years.[197] As shown in Figure 9 (matrix diagram), geological storage is typically used to store CO_2 captured from DAC and BiCR facilities.

5.1.1 Global state of play

There is significant global potential for geological storage to support global CDR needs. For example, the Oil and Gas Climate Initiative's (OGCI) 2024 CO_2 Storage Resource Catalogue (CSRC) assessed 1,272 sites across 54 countries for the potential capacity of geological formations to durably store captured CO_2 using the Society of Petroleum Engineers (SPE) Storage Resources Management System (SRMS) classification system (see Box 4).[198] Results from this assessment indicated over 14,000 Gt of potential geological CO_2 storage capacity worldwide. Of this, 0.052 Gt was stored, 1.7 Gt was commercial, 625 Gt was sub-commercial, and 13,434 Gt remained prospective/undiscovered.[199]

Despite the global potential for geological CO_2 storage, the commercial readiness of geological storage resources is low. As of 2024 and excluding CO_2-Enhanced Oil Recovery projects, only Australia, Canada, Norway and the US had commercial geological storage capacity.[200] Challenges include lack of supporting regulatory frameworks, limited resources for site identification and a lack of financial incentives to undertake the activity.[201]

With growing global recognition of the role of geological CO_2 storage in achieving net zero targets, countries are taking action to overcome barriers. This is reflected in the strong growth the number of CCS projects under development, as of the end of 2024 total number of CCS facilities in the development pipeline was 628, an increase of over 60% on the previous year.[202] This momentum bodes well for CDR, as many removal approaches rely on the same storage infrastructure, regulatory frameworks, and expertise as CCS. Expansion of CCS capacity and capability reduces costs, builds confidence, and lays the groundwork for scaling up CDR deployment.

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

194 Fitch P, Battaglia M, Lenton A, Feron P, Gao L, Mei Y, Hortle A, Macdonald L, Pearce M, Occhipinti S, Roxburgh S, Steven A (2022) Australia's sequestration potential, CSIRO.

195 There are 9 ongoing projects; Fitch P et al (2022) Australia's sequestration potential, CSIRO.

196 Gorgon see: Chevron Australia (n.d.) Gorgon Project: carbon capture and storage. <https://australia.chevron.com/what-we-do/gorgon-project/carbon-capture-and-storage>; Moomba Santos commissioned its 1.7 Mt CO_2 per year depleted gas field storage project, the world's third-largest dedicated storage project in Australia in 2024, and ENI NI started capture and injection of 25 000 t CO_2 per year in a depleted gas field offshore Italy with as part of the Ravenna CCS project in Italy in 2024. See: Fitch P et al (2022) Australia's sequestration potential, CSIRO.

197 IPCC (2005) IPCC special report on carbon dioxide capture and storage. <https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_wholereport-1.pdf>.

198 OGCI (2024) CO_2 storage resource catalogue – Cycle 4: main report. <https://www.ogci.com/wp-content/uploads/2024/12/CSRC_Cycle_4_Main_Report_November_2024.pdf>.

199 The CSRC classifies the resource maturity of published storage resource sites using the Society of Petroleum Engineers (SPE) Storage Resources Management System (SRMS). The CSRC SPE SRMS methodology can be found here: OGCI (2024) CO_2 storage resource catalogue – Cycle 4: main report. <https://www.ogci.com/wp-content/uploads/2024/12/CSRC_Cycle_4_Main_Report_November_2024.pdf>.

200 Characterised, discovered geological sites with active injection projects, regulatory permits, and credible commercial plans.

201 Kelemen P, Benson SM, Pilorgé H, Psarras P, Wilcox J (2019) An overview of the status and challenges of CO_2 storage in minerals and geological formations. Frontiers in Climate 1, 9. <https://doi.org/10.3389/fclim.2019.00009>.

202 Global CCS Institute (2024) Global status of CCS: 2024 report. <https://www.globalccsinstitute.com/wp-content/uploads/2024/11/Global-Status-Report-6-November.pdf>.

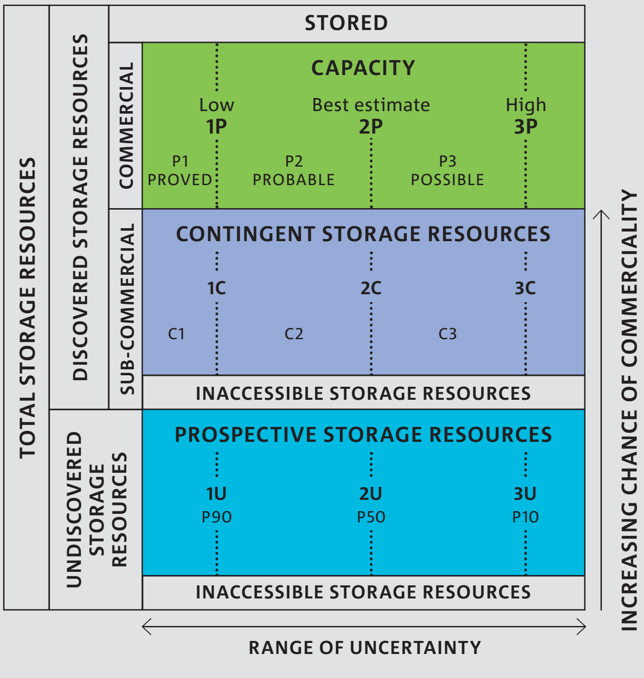
Box 4: Determining geological resources and reserves.

Planning and implementing large-scale geological CO_2 storage requires a clear understanding of the total volume theoretically available in a geological formation and the portion of that potential that can be realistically utilised.

CO_2 storage capacity is typically classified using resource and reserve concepts, whereby valuation and investment require carefully considered and standardised reporting. Correct nomenclature reports "Resources" as the estimated quantity of a commodity over a given time and "Reserves" as the confirmed quantities of a commodity. Characterising the capacity of a geological CO_2 storage site from a theoretical resource through to a commercially viable operation, matures as more data is gathered to reduce uncertainty and prove the techno-economic feasibility of injection at a specific location. Therefore, it is widely accepted that commercial confidence in CO_2 storage capacity is directly related to the scale of the capacity estimation (basin-wide or site-specific), the level of knowledge of the sub-surface (data availability and quality), and the stage of development of a given site (Pre-feasibility to operational). For example, while in the early basin screening stage, the theoretical capacity of geological CO_2 storage is often orders of magnitude larger than the practicable storage. When considerations such as drilling costs, injectivity requirements (including volume and rate), infrastructure access, resource competition, and social acceptance are factored in, the final capacity may end up significantly smaller.[203]

CO_2 storage capacity can be classified using the SPE-SRMS (see Figure 21). This classification system provides a structured understanding of the relationship between uncertainty, commercial maturity, and reported CO_2 storage capacity, and explains how storage capacity may be contingent upon other factors. This framework uses a horizontal range of uncertainty to reflect the likelihood of varying storage capacities and the chance of commerciality on the vertical axis to indicate the likelihood of a project reaching commercialisation. It categorises *total storage* resources as the estimated quantity in geological formations, with *stored values* representing CO_2 already injected into defined sites, *commercial (capacity)* values indicating accessible storage under specified conditions, *sub-commercial (contingent)* values reflecting storage potential not yet viable for commercial use, and *undiscovered (prospective)* values representing potential storage capacity in unexplored formations.

Figure 21: Resource classification framework based on the SPE-SRMS.[204]



203 Bashir A, Ali M, Patil S, Aljawad MS, Mahmoud M, Al-Shehri D, Hoteit H, Kamal MS (2023) Comprehensive review of CO_2 geological storage: exploring principles, mechanisms, and prospects. Petroleum Science 20, 1028–1063. <https://link.springer.com/article/10.1007/s12182-019-0340-8>.

204 Bachu S, Bonijoly D, Bradshaw J, Burruss R, Holloway S, Christensen NP, Mathiassen OM (2007) CO_2 storage capacity estimation: methodology and gaps. International Journal of Greenhouse Gas Control 1(4), 430–443. <https://doi.org/10.1016/S1750-5836(07)00086-2>; Other classification systems also exist, including the Techno-Economic Resource–Reserve Pyramid. See: Clean Air Task Force (2023) Unlocking Europe's CO_2 storage potential: analysis of optimal CO_2 storage in Europe. <https://www.catf.us/resource/unlocking-europes-CO2-storage-potential-analysis-optimal-CO2-storage-europe/>.

5.1.2 Australia state of play

Australia has significant discovered and undiscovered geological CO_2 storage resources to support CDR using depleted hydrocarbon fields and saline aquifers. As of 2024, analysis from the OGCI's CSRC assessed that Australia had 9 Mt of stored CO_2, 111 Mt of commercial capacity, 31 Gt of sub-commercial capacity and 471 Gt of undiscovered CO_2 storage resources.[205] Australia's stored capacity is the second-highest of the 54 countries assessed in the 2024 CSRC.[206]

For Commonwealth waters, regulations governing geological CO_2 storage are among the most advanced globally and were enacted under the Offshore Petroleum and Greenhouse Gas Storage Act 2006. These regulations are being reviewed and updated to reflect developments in Australia's understanding of geological CO_2 storage. Onshore CO_2 storage regulations have been enacted in SA, Victoria, and Queensland, are being enacted in WA and are being considered for the Northern Territory (NT). Five GHG storage exploration permits were awarded under the 2021 Offshore Greenhouse Gas Storage Acreage Release, and another 10 were recently released for bidding in 2023.[207] The Australian Government's commitment to realising Australia's geological CO_2 storage capacity is reflected in its May 2024 Future Gas Strategy, which includes a key action to "promote geological storage of CO_2 and support our region's transition to net zero".[208]

As of 2025, there were 18 geological CO_2 storage projects in various stages of development across Australia, highlighting the increasing technical capabilities and support from industry and government.[209] Australia's CO_2 storage projects are associated with the production of natural gas and liquified natural gas, H_2 and ammonia, industrial emission sources and DAC. The majority of these CO_2 storage projects have sufficient capacities to accept third-party CO_2 volumes. The Gorgon Project offshore WA was Australia's first commercially operating project. It has stored 11 Mt of CO_2 (as of May 2025).[210] Another notable project is the Santos' Moomba facility in the Cooper Basin of SA. Commencing operations in October 2024, by June 2025, it had already stored 800,000 tCO_2-e.[211]

5.1.3 MRV storage

MRV methodologies for geological CO_2 storage are critical to providing assurance of durability for CDR projects. MRV methodologies are available for all stages of operation (pre-injection, operation, and post-injection). The pre-injection phase collects baseline geological and geochemical data on the storage site to reduce uncertainty and derisk the storage location. This information is also used to build dynamic models that simulate CO_2 injection and storage behaviour. During the injection phase, CO_2 injection flow rates, pressure, and plume movement are closely monitored. After injection, the focus shifts to monitoring CO_2 migration and preventing any CO_2 leakage.[212]

Each stage of operation uses different MRV methods, but a key purpose of monitoring the storage site during and following injection is to verify the geological containment of CO_2, demonstrate regulatory compliance and improve the confidence of CDR investors and public sentiment.[213] A range of tools and techniques (typically developed in the oil and gas industry) has been demonstrated for geological CO_2 storage.[214]

205 As of 2025 the Gorgon Project in WA has stored >11Mt to date and the Santos Moomba project is approaching 1 Mt, bring Australia's total stored capacity estimate to 12Mt. See: Chevron Australia (n.d.) Gorgon Project: carbon capture and storage. <https://australia.chevron.com/what-we-do/gorgon-project/carbon-capture-and-storage>; Santos (n.d.) Moomba carbon capture and storage. <https://www.santos.com/moombaccs/>.

206 Language aligned to SRMS maturity classification (see section 2.2). *Stored values* represent CO_2 already injected into defined sites. OGCI (2024) CO_2 storage resource catalogue – Cycle 4: main report. <https://www.ogci.com/wp-content/uploads/2024/12/CSRC_Cycle_4_Main_Report_November_2024.pdf>.

207 Geoscience Australia (2024) Carbon capture and storage. <https://www.ga.gov.au/aecr2024/carbon-capture-and-storage>.

208 Department of Industry, Science and Resources (2024) Future gas strategy. <https://www.industry.gov.au/publications/future-gas-strategy>.

209 Geoscience Australia (2024) Carbon capture and storage. <https://www.ga.gov.au/aecr2024/carbon-capture-and-storage>.

210 Chevron Australia (2025) Gorgon carbon capture and storage fact sheet. <https://australia.chevron.com/-/media/australia/publications/documents/gorgon-CCS--fact-sheet.pdf>.

211 Santos (2025) Moomba carbon capture and storage wins international industry recognition. <https://www.santos.com/news/santos-moomba-carbon-capture-and-storage-wins-international-industry-recognition/>.

212 IEAGHG (2024) Measurement, reporting and verification (MRV) and accounting for carbon dioxide removal (CDR) in the context of both project based approaches and national greenhouse gas inventories (NGHGI). <https://publications.ieaghg.org/technicalreports/2024-09%20Measurement,%20reporting%20and%20verification%20of%20CDR.pdf>.

213 IEAGHG (2024) Measurement, reporting and verification (MRV) and accounting for carbon dioxide removal (CDR) in the context of both project based approaches and national greenhouse gas inventories (NGHGI). <https://publications.ieaghg.org/technicalreports/2024-09%20Measurement,%20reporting%20and%20verification%20of%20CDR.pdf>.

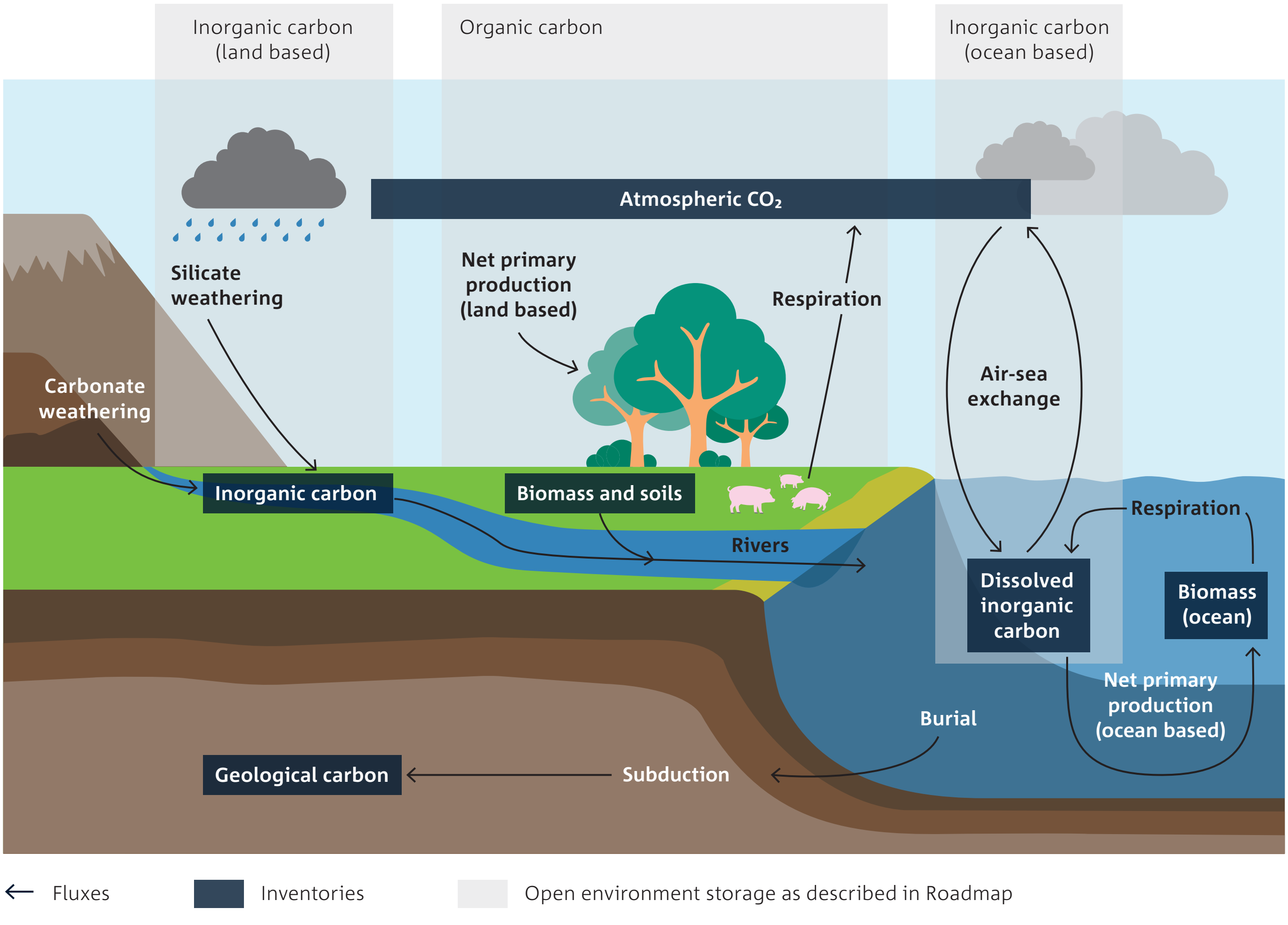
214 Fitch P, Battaglia M, Lenton A, Feron P, Gao L, Mei Y, Hortle A, Macdonald L, Pearce M, Occhipinti S, Roxburgh S, Steven A (2022) Australia's sequestration potential, CSIRO.

6 Open environment storage

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.[215] Carbon can be stored inorganically as carbonate or bicarbonate ions, or organically as living biomass, soil carbon, or biochar, with different levels of durability. In the context of this Roadmap, ERW, OAE and BiCR (i.e. slow pyrolysis to biochar) approaches store carbon in open environments (see Figure 9, matrix diagram), accelerating geochemical and biological processes that are part of the natural carbon cycle (see Figure 22).

This section outlines the storage of inorganic carbon (on land and in the ocean) and organic carbon, along with the MRV requirements for each. Because open environment storage is inherently interlinked with biological and geochemical CO_2 capture, a discussion of the global and Australian state of development is provided in this section for three CDR approaches, namely agricultural ERW (i.e. ERW capture + land-based storage), electrolytic OAE (i.e. OAE capture + ocean-based storage) and BiCR (i.e. slow pyrolysis to biochar capture and storage).

Figure 22: Overview of the carbon cycle.[216]



Note: this is a simplified diagram and does not show all aspects of natural carbon cycles. It is intended to highlight the open environment carbon storage pathways utilised by novel CDR approaches discussed in the Roadmap.

215 IEA (2025) The State of Energy Innovation. International Energy Agency, Paris. <https://iea.blob.core.windows.net/assets/6ff289bd-xxxx-xxxx-xxxx-xxxxc2b9deab/Thestateofenergyinnovation.pdf> (accessed 22 October 2025)

216 Rønning JB (2024) Ocean alkalinity enhancement: tool to mitigate climate change. Ph.D. thesis. Syddansk Universitet. Det Naturvidenskabelige Fakultet. https://doi.org/10.21996/p2f3-rp88

6.1 Inorganic and organic carbon

6.1.1 Inorganic carbon

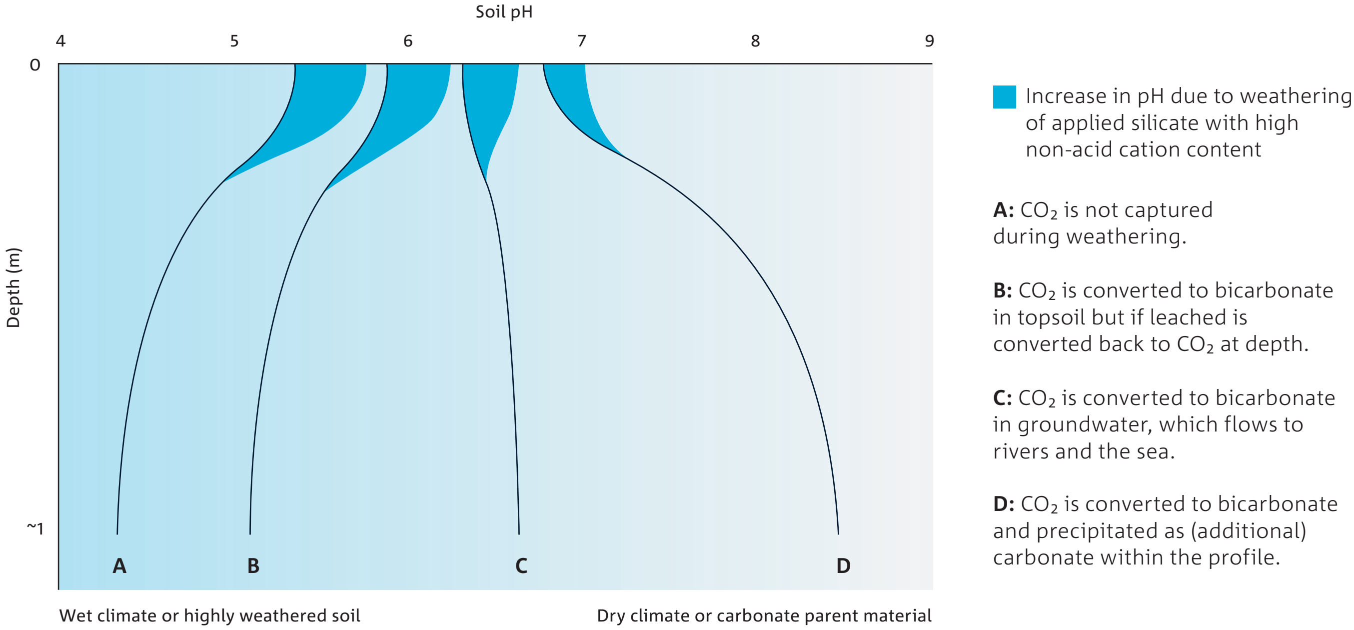
Land-based storage

CO_2 in the atmosphere (dissolved in rainwater as carbonic acid) can be captured and durably stored in land-based storage (i.e. soil) as bicarbonate ions.[217] Depending on the soil pH, structure and water availability, these soluble bicarbonate ions can be precipitated into (and accumulated as) solid carbonates.[218] Under alkaline and stable conditions, bicarbonates and carbonates can be naturally stored in soil for thousands to millions of years.[219] However, under acidic and unstable conditions, they can be reversed back to CO_2. An example of this is intensive agricultural systems that increase soil acidity.[220] Figure 23 illustrates the various pathways of soil carbon sequestration as the rock weathers, based on soil pH, structure, and water availability.

State of development

The ERW capture process (see Section 3.2.1) and land-based CO_2 storage can be combined to form the agricultural ERW approach for CDR. Agricultural ERW has been actively researched and commercially pursued in Australia and globally in recent years. As of November 2023, agricultural ERW had reached a TRL of 7.[221]

Figure 23: Generalised pathways of soil carbon based on soil pH, structure and water availability.[222]



217 In-field carbon dioxide removal via weathering of crushed basalt applied to acidic tropical agricultural soil. Science of the Total Environment 955, 176568. <https://doi.org/10.1016/j.scitotenv.2024.176568>; Carbon Dioxide Removal Mission (2022) Carbon dioxide removal technology roadmap: innovation gaps and landscape analysis; IPCC (2005) IPCC special report on carbon dioxide capture and storage. <https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_wholereport-1.pdf>.

218 In-field carbon dioxide removal via weathering of crushed basalt applied to acidic tropical agricultural soil. Science of the Total Environment 955, 176568. <https://doi.org/10.1016/j.scitotenv.2024.176568>https://www.sciencedirect.com/science/article/pii/S004896972406724X?via%3Dihub - s0005; Carbon Dioxide Removal Mission (2022) Carbon dioxide removal technology roadmap: innovation gaps and landscape analysis; IPCC (2005) IPCC special report on carbon dioxide capture and storage. <https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_wholereport-1.pdf>.

219 IPCC (2005) IPCC special report on carbon dioxide capture and storage. <https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_wholereport-1.pdf>.

220 Zamanian K, Zhou J, Kuzyakov Y (2021) Soil carbonates: the unaccounted, irrecoverable carbon source. Geoderma 384, 114817. <https://doi.org/10.1016/j.geoderma.2020.114817>. https://www.sciencedirect.com/science/article/pii/S004896972406724X?via%3Dihub - s0005>.

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

In Australia, the agricultural ERW approach has been studied and trialled, with the Australian National University having conducted a 16-week laboratory study and James Cook University having conducted a five-year field trial in Queensland.[223] Across various incubation and field experiments as part of the two projects, the amount of CDR achieved ranged between 0.02 and more than 10 tCO_2 per hectare, varying based on the rock and soil types, environmental conditions, application rates and methods, duration, and measurement techniques.[224]

In 2023, the New South Wales (NSW) government funded a study to model the State's CDR potential via the agricultural ERW approach. It was found that approximately 0.07 and 0.31 $MtCO_2$/y could be removed via the agricultural ERW process in NSW, at a minimum cost of A$267 to A$1,186 per tCO_2.[225]

An example of commercial operators in the global context includes the US company Lithos Carbon, which utilises ultra-fine volcanic basalt rock dust as feedstock for agricultural ERW. Since its founding in 2022, the company has partnered with farmers across the US to demonstrate its process and collect soil samples to develop MRV processes. Lithos Carbon has signed agreements with the advanced market commitment Frontier to remove 154,240 tCO_2 between 2024 and 2028, and separately with Microsoft to remove 11,400 tCO_2 between 2024 and 2027.[226]

UNDO (UK) and Eion (US) are other startups that have partnered with Microsoft in 2024 to support the company's CDR carbon-negative commitment by 2030. UNDO dispersed 111,000 tonnes of basalt and wollastonite over 9,000 hectares of agricultural land in 2024, adding to its cumulative estimated carbon capture total of 63,136 tCO_2. UNDO's partnership with Microsoft aims to remove 15,000 tCO_2 by expanding operations in the UK, Canada and Scotland.[227]

Eion uses olivine imported from Norway to disperse on agricultural land across the US. After accounting for the emissions associated with rock extraction, comminution, transport, spreading and natural system loss (i.e. CO_2 re-emissions from soil), Eion's process claims a net removal of 84.42%, as of August 2023. Eion's partnership with Microsoft aims to remove 8,000 tCO_2.[228] In 2025, Eion signed an agreement with Frontier to remove 78,707 tCO_2 between 2027 and 2030.[229]

Ocean-based storage

The ocean is a vast and ongoing carbon reservoir, storing approximately 38,000–40,000 Gt of inorganic carbon.[230] As explained in Section 3.1, atmospheric CO_2 is captured and stored in seawater negligibly as aqueous CO_2 and predominantly as dissolved inorganic carbon in the forms of bicarbonate ions (HCO_3^-, ~90%) and carbonate ions (CO_3^{2-}, ~10%). Both bicarbonate and carbonate ions can be durably stored in the ocean over very long timescales, ranging from 10,000 to 100,000 years.[231]

222 In-field carbon dioxide removal via weathering of crushed basalt applied to acidic tropical agricultural soil. Science of the Total Environment 955, 176568. <https://doi.org/10.1016/j.scitotenv.2024.176568>

223 Hasemer H, Borevitz J, Buss W (2024) Measuring enhanced weathering: inorganic carbon-based approaches may be required to complement cation-based approaches. Frontiers in Climate 6, 1352825. <https://doi.org/10.3389/fclim.2024.1352825>; Holden FJ, Davies K, Bird MI, Hume R, Green H, Beerling DJ, Nelson PN (2024) In-field carbon dioxide removal via weathering of crushed basalt applied to acidic tropical agricultural soil. Biogeochemistry 167, 989–1005. <https://doi.org/10.1007/s10533-024-01160-0> < https://www.sciencedirect.com/science/article/pii/S004896972406724X?via%3Dihub - s0005>.

224 Nelson P (2024) Spreading crushed rock over farmland can remove CO_2 from the atmosphere – if we do it right. <https://theconversation.com/spreading-crushed-rock-over-farmland-can-remove-co-from-the-atmosphere-if-we-do-it-right-240303>.

225 Common Capital Pty Ltd (2023) Scaling atmospheric carbon dioxide removal in New South Wales. Report prepared for the NSW Office of Energy and Climate Change. <https://www.energy.nsw.gov.au/sites/default/files/2024-02/Common_Capital_Scaling_atmospheric_CDR_in_NSW_Final.pdf>.

226 Lithos Carbon (n.d.) Permanent carbon capture on farms. <https://www.lithoscarbon.com/>; Frontier Climate (2023) Lithos: enhancing weathering for permanent carbon removal. <https://frontierclimate.com/writing/lithos>; Lithos Carbon (2024) Lithos Carbon researching carbon removal using enhanced rock weathering for Microsoft. <https://www.businesswire.com/news/home/20240925479345/en/Lithos-Carbon-Researching-Carbon-Removal-using-Enhanced-Rock-Weathering-for-Microsoft>.

227 The public announcement of the partnership did not disclose the period over which ERW needs to be done and CDR achieved. See: UNDO Carbon (n.d.) Enhanced rock weathering. <https://un-do.com/enhanced-weathering/>; UNDO Carbon (2024) 2024 in review: progress, partnerships, and pioneering carbon removal solutions. <https://un-do.com/resources/blog/2024-in-review-progress-partnerships-and-pioneering-carbon-removal-solutions/>; UNDO Carbon (2024) UNDO signs follow-on enhanced rock weathering carbon removal deal with Microsoft. <https://un-do.com/resources/blog/undo-signs-follow-on-enhanced-rock-weathering-carbon-removal-deal-with-microsoft/>.

228 The public announcement of the partnership did not disclose the period over which ERW needs to be done and CDR achieved. See: Eion Carbon (2024) Calculating Eion's carbon impact: our life cycle assessment. <https://eioncarbon.com/blog/life-cycle-assessment/>; Eion Carbon (2024) Eion signs deal to deliver carbon removal credits to Microsoft. <https://www.businesswire.com/news/home/20240924835529/en/>.

229 Frontier Climate (2025) Frontier buyers sign $33M in offtake agreements with Eion. <https://frontierclimate.com/writing/eion>.

230 Shadwick E, Rohr T, Richardson A (2023) Oceans absorb 30% of our emissions, driven by a huge carbon pump. CSIRO. <https://www.csiro.au/en/news/All/Articles/2023/June/oceans-absorb-emissions>.

The amount stored in each form of CO_2 is a function of the seawater pH (Figure 14). The increase in CO_2 in the ocean since the preindustrial period has resulted in a decline in ocean pH (ocean acidification), along with a decrease in the concentration of carbonate ions.[232] However, on much longer timescales, the natural weathering of silicate rocks is believed to have led to an increase in pH through the addition of soluble bicarbonate ions via run-off, which in turn reduced atmospheric CO_2 levels and increased the amount of CO_2 stored in the ocean. This is termed ocean alkalinisation.

State of development

The electrolytic capture process (see Section 3.1.1) and ocean-based CO_2 storage can be combined to form the electrolytic OAE approach for CDR. Electrolytic OAE is rapidly advancing globally, with growing efforts predominantly from US companies to demonstrate and scale up processes. As of November 2023, electrolytic OAE had reached a TRL of 6.[233]

Globally, Equatic (US) has been leading the RD&D and scaling up of electrolytic OAE.[234] In early 2024, it began constructing the world's largest ocean-based demonstration facility in Singapore with a removal capacity of 3,650 tCO_2/y, leveraging the learnings and some built infrastructure from two previous pilot projects in Singapore and Los Angeles. In mid-2024, Equatic partnered with CDR project developer Deep Sky (Canada) to commence engineering for North America's first commercial-scale OAE facility in Quebec.[235] The facility is expected to remove 109,500 tCO_2 from the atmosphere and produce 3,600 tonnes of green H_2 per year once operational, targeting a pathway to achieve CDR at less than US$100 per tonne by 2030.[236]

In Australia, CSIRO's CarbonLock is developing a flexible, mobile, modular testbed system to explore a range of OAE approaches. The research project combines modelling and observations to evaluate sites, optimise the process, assess impacts on surrounding environments, and support the development of an MRV framework.[237]

6.1.2 Organic carbon

Forest and soil carbon (conventional CDR)

Australia's forests contain a substantial amount of carbon in above-ground and below-ground carbon pools. As of 2021, a total stock of 19,147 Mt was estimated to be stored in native forests (98.9%), plantations (1.0%) and other forests (0.1%).[238] One of the most important carbon pools in forests is living plant tissue. Plants store most of their carbon in woody plant tissues like tree trunks, roots and large branches. A portion of the carbon in living tissues will accumulate as leaf litter and coarse woody debris, eventually decaying and either feeding the forest soil-carbon pool or returning to the atmosphere (see Figure 22).

While increasing the long-term storage of carbon in forests and soils can contribute to reducing atmospheric concentrations of CO_2, this type of storage has low durability (10–100 years) and a high risk of reversal. Forest and soil carbon pools are increasingly vulnerable to climate change, extreme weather events and human-related activities that cause disturbances and release CO_2 back into the atmosphere.[239]

231 IPCC (2005) IPCC special report on carbon dioxide capture and storage. <https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_wholereport-1.pdf>.

232 Hurd, Catriona; Lenton, AA; Tilbrook, B; Boyd, Philip (2018) Current understanding and challenges for oceans in a higher-CO_2 world. University of Tasmania. Journal contribution. <https://hdl.handle.net/102.100.100/531061>.

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

234 Equatic (n.d.) The Equatic process. <https://www.equatic.tech/the-equatic-process>.

235 Equatic (2024) Equatic unveils plans for the world's largest ocean-based carbon removal plant. <https://www.equatic.tech/articles/equatic-unveils-plans-for-the-worlds-largest-ocean-based-carbon-removal-plant>.

236 Equatic (2024) Equatic to build North America's first commercial-scale ocean-based carbon removal facility. <https://www.equatic.tech/articles/equatic-to-build-north-americas-first-commercial-scale-ocean-based-carbon-removal-facility>;<https://www.equatic.tech/articles/equatic-to-build-north-americas-first-commercial-scale-ocean-based-carbon-removal-facility>; Deep Sky (2024) Equatic to build North America's first commercial-scale ocean-based carbon removal facility. <https://www.deepskyclimate.com/blog/equatic-to-build-north-americas-first-commercial-scale-ocean-based-carbon-removal-facility>.

237 CSIRO (2023) Enhancing alkalinity for ocean-based carbon dioxide removal. <https://research.csiro.au/carbonlock/enhancing-alkalinity-for-ocean-based-cdr/>.

238 Montreal Process Implementation Group for Australia (MIG) and National Forest Inventory Steering Committee (NFISC) (2024) Indicator 5.1a: Contribution of forest ecosystems and forest industries to the global greenhouse gas balance. Australia's State of the Forests Report. Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra. <https://www.agriculture.gov.au/sites/default/files/documents/Indicator_5_1a_carbon_cycle_2024.pdf>.

239 Montreal Process Implementation Group for Australia (MIG) and National Forest Inventory Steering Committee (NFISC) (2024) Indicator 5.1a: Contribution of forest ecosystems and forest industries to the global greenhouse gas balance. Australia's State of the Forests Report. Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra. <https://www.agriculture.gov.au/sites/default/files/documents/Indicator_5_1a_carbon_cycle_2024.pdf>.

Biochar

A more durable example of land-based open storage is when CO_2 stabilised in biochar is applied to soil and stored as a long-lived carbon product.[240] The application of biochar to soil offers numerous co-benefits for soil health and agricultural productivity, including improving soil physicochemical properties (e.g. porosity, bulk density, pH, cation exchange capacity), nutrient availability and microbial activity, as well as supporting pollutant adsorption and soil remediation, and reducing soil N_2O emissions and fertiliser requirements.[241]

There is evolving research on the durability of biochar as a CO_2 storage medium. The general consensus is that biochar can durably store carbon for 100 years or above, with Microsoft currently categorising biochar as a medium-durability storage solution (i.e. 100–1,000 years).[242] However, Sanei et al. (2024) found that the durability of biochar can be extended to 100 million years in highly oxidising environments and even more in non-highly oxidising environments, noting that 50% of carbon is assumed to be degraded or lost throughout this period.[243] While the partially contained soil environment in which biochar is applied can impose some risk of reversal into CO_2, in reality the carbon contained in biochar is likely to end up more securely stored in sediments.[244] As a result, the risk of reversal for carbon in biochar is potentially lower than for conventional CDR approaches.

240 Pett-Ridge et al. (2023) Roads to removal: options for carbon dioxide removal in the United States. Lawrence Livermore National Laboratory. <https://www.osti.gov/biblio/2301853>.

241 Li X, Wu D, Liu X, Huang Y, Cai A, Xu H, Ran J, Xiao J, Zhang W (2024) A global dataset of biochar application effects on crop yield, soil properties, and greenhouse gas emissions. Scientific Data 11(1), 1–8. <https://doi.org/10.1038/s41597-023-02867-9>; Omokaro GO, Kornev KP, Nafula ZS, Chikukula AA, Osayogie OG, Efeni OS (2025) Biochar for sustainable soil management: Enhancing soil fertility, plant growth and climate resilience. Farming System 3(4), 100167. <https://doi.org/10.1016/j.farsys.2025.100167>.

242 Microsoft (n.d.) Carbon removal program. <https://www.microsoft.com/en-us/corporate-responsibility/sustainability/carbon-removal-program>.

243 Sanei H, Rudra A, Przyswitt ZMM, Kousted S, Sindlev MB, Zheng X, Nielsen SB, Petersen HI (2024) Assessing biochar's permanence: An inertinite benchmark. International Journal of Coal Geology 281, Article 104409. <https://doi.org/10.1016/j.coal.2023.104409>.

244 Stakeholder consultation.

State of development

Slow pyrolysis to biochar is one of many BiCR+S approaches. It combines the capture of CO_2 during biomass growth with conversion to biochar during the slow pyrolysis process. This biochar can be applied to soil and stored as a long-lived product. Slow pyrolysis to biochar is currently one of the leading CDR approaches nationally and globally, with a thriving market and growing opportunities for carbon credits.

In 2023, the Australia New Zealand Biochar Industry Group (ANZBIG) delivered the Australian Biochar Industry Roadmap 2030, bringing together perspectives of (predominantly) companies and industry groups. The Australian Biochar Industry Roadmap 2030 outlines the key initiatives and actions to scale the existing Australian biochar industry, which was estimated to produce 10,000 to 20,000 tonnes of biochar per year in 2020 and valued at A$50 million in 2023, into a multibillion-dollar industry in 2030 (i.e. estimated to be at least A$1–5 billion per year).[245]

In Kangaroo Island (SA), Re-Vi is leading one of the world's largest biochar for CDR projects, converting 4.5 Mt of bushfire-damaged timber into high-quality, agricultural-grade biochar and removing 2 Mt of CO_2 from the atmosphere.[246]

In WA, Biomass Projects, with support from Residual, is developing a commercial-scale biochar production project with the expectation of removing 500,000 tCO_2/y by 2028, using the invasive species of mesquite as the key biomass feedstock. The project has also received support from Carbonfuture, particularly in integrating digital MRV services.[247]

Rainbow Bee Eater, a Melbourne-based company, has developed a modular pyrolysis system to produce biochar for CDR. In 2020, the company became the first biochar carbon removals supplier outside Europe certified by Puro.earth, with purchasers including Shopify, Microsoft and others.[248]

The International Biochar Initiative and the US Biochar Initiative reported that at least 350,000 tonnes of biochar were produced in 2023, with a compound annual growth rate of 91% from 2021 to 2023. This growth rate is equivalent to 600,000 tCO_2 removed from the atmosphere in 2023; however, only a small portion of this was likely registered as carbon credits, despite the growing biochar carbon credit market. Key identified focus areas to unlock industry growth include market development, high-quality biochar, and access to capital.[249]

6.1.3 MRV storage

The MRV for CDR approaches that disperse captured carbon in open environments is complex. The mechanics of the natural carbon cycle make it hard to distinguish added carbon from natural fluctuations and determine additionality. CO_2 is often dispersed over large areas, making MRV expensive and logistically complex. In terms of ocean-based storage, observations alone are considered insufficient to quantify net removals. Numerical simulations are also required; however, these face large uncertainties and data gaps. Similarly, the MRV of land-based storage faces difficulties in predicting and measuring variables such as background flux, rates of weathering, and alkalinity production. MRV of CDR approaches that use open environment storage still require significant RD&D. For more information on the current state of MRV development for these approaches, see Section 2.1.2–4.1.3. For specific actions and recommendations to improve MRV, refer to Section 14.

245 ANZBIG (2023) Australian Biochar Industry 2030 Roadmap. ANZ Biochar Industry Group. <https://www.anzbig.org/australian-biochar-industry-2030-roadmap.html>.

246 Re-Vi Group (2025) Kangaroo Island Project. <https://re-vi.com/projects/>.

247 Biomass Projects (2025) Transforming invasive species into carbon-capturing biochar. <https://biomassprojects.com.au/>; Carbonfuture (2025) Turning invasive plants into climate action: Carbonfuture MRV+ to track Australia's landmark biochar carbon removal project at half a million tonnes annually. <https://www.carbonfuture.earth/magazine/turning-invasive-plants-into-climate-action-carbonfuture-mrv-to-track-australias-landmark-biochar-carbon-removal-project-at-half-a-million-tonnes-annually>.

248 Rainbow Bee Eater (n.d.) What we do. <https://www.rainbowbeeeater.com.au/what-we-do>; Rainbow Bee Eater (2025) Achievements. <https://www.rainbowbeeeater.com.au/achievements>.

249 International Biochar Initiative (IBI) & US Biochar Initiative (USBI) (2024) 2023 Global Biochar Market Report. BioCycle. <https://www.biocycle.net/biochar-market-report/2023>; Global Biochar Market Report. <https://145249425.hs-sites-eu1.com/2023-global-biochar-market-report>.

7 Mineral storage

Mineral storage refers to approaches that lock away atmospheric CO_2 through mineral carbonation (or carbon mineralisation). Mineral carbonation reactions occur in nature, as a product of rock weathering at the earth's surface (see Section 3.2) or in groundwater systems that come into direct contact with dilute carbonic acid in rainwater or CO_2-rich groundwater. 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.

The fundamental principles of naturally occurring mineral carbonation reactions can be engineered to store CO_2 as carbonate minerals in shorter time frames than observed in natural analogues. Mineral storage solutions include CO_2-reactive underground rock formations, mine tailings, and durable carbonate materials or products. This section outlines in-situ (below-ground) mineral carbonation and two ex-situ (above-ground) approaches: accelerated and passive mineral carbonation. The global and Australian context for each approach will also be reviewed, along with MRV requirements.

While these mineral carbonation approaches are not included in this Roadmap's cost and capacity analysis due to a lack of data availability, their emerging importance is strongly acknowledged. Accordingly, potential next steps, actions, and considerations to scale this CDR approach have been provided in Section 13.5.

7.1 Mineral carbonation

7.1.1 In-situ mineral carbonation

In-situ mineral carbonation involves injecting aqueous CO_2 into shallow, permeable mafic and ultramafic rock formations underground. Mafic and ultramafic rock types include basalt/dolerite and peridotite/komatiite or serpentinite (hydrated peridotite), respectively, which are abundant throughout Australia[250] and globally,[251] and exist in alternative locations that lack conventional geological storage.[252]

Mafic and ultramafic rock formations offer durable and secure CO_2 storage.[253] This is due to the high concentrations of divalent cations such as Mg^{2+} and Ca^{2+} present in the rock-forming minerals, which are reactive to aqueous CO_2.[254] Unlike geological CO_2 storage, where supercritical CO_2 is primarily structurally and stratigraphically trapped within the pore spaces between the grains of sedimentary rocks,[255] in-situ mineral carbonation traps aqueous CO_2 primarily through carbonate mineralisation.[256] Injection of aqueous CO_2 achieves solubility trapping immediately, and in Icelandic basalts, mineralisation of >95% CO_2 has been demonstrated within 2 years.[257]

Australian basalts are, in general, older, colder, less porous, and less permeable than Icelandic basalts due to their age, geological setting, and often complex and protracted histories of metamorphism, deformation, and alteration. However, delineation of suitable mafic and ultramafic geology in Australia is ongoing.[258] Australian serpentinite formations are a potentially favourable alternative,[259] forming significant proportions of Australia's east coast.[260]

250 Thorne JP, Highet LM, Cooper M, Claoué-Long JC, Hoatson DM, Jaireth S, Huston DL, Gallagher R (2014) The Australian Mafic-Ultramafic Magmatic Events GIS Dataset: Archean, Proterozoic and Phanerozoic Magmatic Events. Geoscience Australia. <https://pid.geoscience.gov.au/dataset/ga/82166>.

251 Oelkers EH, Gislason SR, Matter J (2008) Mineral carbonation of CO_2. Elements 4(5), 333–337. <https://doi.org/10.2113/gselements.4.5.333>.

252 Budinis S, Krevor S, Mac Dowell N, Brandon N, Hawkes A (2018) An assessment of CCS costs, barriers and potential. Energy Strategy Reviews 22, 61–81. <https://doi.org/10.1016/j.esr.2018.08.003>.

253 Matter JM, Kelemen PB (2009) Permanent storage of carbon dioxide in geological reservoirs by mineral carbonation. Nature Geoscience 2(12), 837–841. <https://doi.org/10.1038/ngeo683>; Snæbjörnsdóttir SÓ, Sigfússon B, Marieni C, Goldberg D, Gislason SR, Oelkers EH (2020) Carbon dioxide storage through mineral carbonation. Nature Reviews Earth & Environment 1(2), 90–102. <https://doi.org/10.1038/s43017-019-0011-8>..

254 Klein F, McCollom TM (2023) From serpentinization to carbonation: New insights from a CO_2 injection experiment. Science of The Total Environment 901, 165262. <https://www.sciencedirect.com/science/article/pii/S0048969723057510>.

255 NASEM, 2019

256 Kelemen P, Benson SM, Pilorgé H, Psarras P and Wilcox J (2019) An Overview of the Status and Challenges of CO_2 Storage in Minerals and Geological Formations. *Front. Clim.* 1:9. <https://doi.org/10.3389/fclim.2019.00009>

257 Sigfusson B, Gislason SR, Matter JM, Stute M, Gunnlaugsson E, Gunnarsson I, Aradottir ES, Sigurdardottir H, Mesfin K, Alfredsson HA, Wolff-Boenisch D, Arnarsson MT, Oelkers EH (2015) Solving the carbon-dioxide buoyancy challenge: The design and field testing of a dissolved CO_2 injection system. International Journal of Greenhouse Gas Control 37, 213–219. <https://www.osti.gov/biblio/1252547>.

258 CSIRO (2023) Identifying the geological properties of ultramafic rocks for carbon storage potential. CarbonLock Future Science Platform. <https://research.csiro.au/carbonlock/geological-properties-of-ultramafic-rocks/>; CSIRO (2024) Putting Australian enhanced mineralisation on the map. <https://www.csiro.au/en/news/All/Articles/2024/February/mineral-carbonation>.

259 Lacinska AM, Styles MT, Bateman K, Hall M, Brown PD (2017) An experimental study of the carbonation of serpentinite and partially serpentinised peridotites. Frontiers in Earth Science 5, Article 37. <https://doi.org/10.3389/feart.2017.00037>.

260 Austin et al., 2025 (in prep)

7.1.2 Global state of development

In-situ mineral carbonation offers significant potential for CO_2 storage, but it is less developed than geological CO_2 storage and is commercially operating at a kilotonne scale globally. The global potential of CO_2 storage via in-situ mineral carbonation (using certain rock types) are estimated to be between 1.1 and 4.5 $GtCO_2$/y.[261] According to the International Energy Agency's (IEA) State of Energy Innovation report, storage capacity in basalts and peridotites alone could grow from around 0.02 $MtCO_2$/y in 2024 to 2.5 $MtCO_2$/y by 2030.[262] Nonetheless, it is difficult to determine the TRL of mineral carbonation, as this sector is relatively emerging, with only a handful of companies and dedicated funding resources exploring this storage pathway.

Since 2012, the Wallula project (US) and Carbfix (Iceland) have been injecting CO_2 into basalt.[263] Carbfix, an academic-industrial partnership, pioneered a novel approach of in-situ mineral carbonation by dissolving CO_2 in water and injecting it into subsurface basalt formations. Since then, Carbfix pilot tests have shown that up to 95% of injected CO_2 is fully carbonated in under two years.[264] The Wallula project injected supercritical CO_2 into the basalt formation, with modelling indicating over 60% of the CO_2 would mineralise within 2 years.[265] Results from a recent pilot test in the Samail ophiolite, Oman, demonstrate rapid mineralisation of CO_2 (>88% mineralised within 45 days) in partially to pervasively serpentinised peridotites.[266]

Iceland is considered the global leader in in-situ mineral carbonation, with Carbfix storing 4,000 tCO_2/y from Climeworks' Orca DAC facility, and up to 36,000 tCO_2/y from Climeworks' Mammoth DAC facility, since commissioning in May 2024.[267] The Coda Terminal, Carbfix's cross-border carbon transport and storage hub in Iceland, currently in advanced development, is anticipated to store 300,000 tCO_2/y by 2032.[268]

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261 IEAGHG (2024) Measurement, reporting and verification (MRV) and accounting for carbon dioxide removal (CDR) in the context of both project-based approaches and national greenhouse gas inventories (NGHGI). Technical Report 2024-09, October 2024. IEA Greenhouse Gas R&D Programme, Cheltenham, UK. <https://publications.ieaghg.org/technicalreports/2024-09%20Measurement,%20reporting%20and%20verification%20of%20CDR.pdf>.

Fitch P, Battaglia M, Lenton A, Feron P, Gao L, Mei Y, Hortle A, Macdonald L, Pearce M, Occhipinti S, Roxburgh S, Steven A (2022) Australia's sequestration potential, CSIRO.

262 IEA (2024) The State of Energy Innovation. International Energy Agency, Paris, France. <https://iea.blob.core.windows.net/assets/26e9f71e-3a3f-4c82-802b-c2ed97aaae24/Thestateofenergyinnovation.pdf>.

263 IEAGHG (2017) Review of CO_2 Storage in Basalts. Technical Report 2017-TR2. IEA Greenhouse Gas R&D Programme, Cheltenham, UK. <https://publications.ieaghg.org/technicalreports/2017-TR2%20Review%20of%20CO2%20Storage%20in%20Basalts.pdf>.

264 Carbfix (n.d.) Our story. <https://www.carbfix.com/our-story>; Carbon Capture Journal (2019) CarbFix project turns CO_2 into rock. <https://www.carboncapturejournal.com/news/carbfix-project-turns-CO2-into-rock/4243.aspx>.

265 White SK, Spane FA, Schaef HT, Miller QRS, White MD, Horner JA, McGrail PB (2020) Quantification of CO_2 mineralization at the Wallula Basalt Pilot Project. Environmental Science & Technology 54, Issue 22, 14609–14616. <https://doi.org/10.1021/acs.est.0c05142>.

266 Matter JM, Speer J, Day C, Kelemen PB, Ibrahim A, Al Mani S, Tasfai E, Ilyas M, Khimji K, Hasan T (2025) Rapid mineralisation of carbon dioxide in peridotites. Communications Earth & Environment 6, Article 590. <https://www.nature.com/articles/s43247-025-02509-5.pdf>.

267 Carbfix (2024) World's largest direct air capture plant switches on in Iceland. <https://www.carbfix.com/worlds-largest-direct-air-capture-plant-commission>.

268 Global CCS Institute (2024) Global Status of CCS 2024. Global CCS Institute, Melbourne, Australia. <https://www.globalccsinstitute.com/resources/global-status-report/>; Fitch P, Battaglia M, Lenton A, Feron P, Gao L, Mei Y, Hortle A, Macdonald L, Pearce M, Occhipinti S, Roxburgh S, Steven A (2022) Australia's sequestration potential, CSIRO; Carbfix (n.d.) Coda Terminal: A scalable onshore CO_2 mineral storage hub in Iceland. <https://www.carbfix.com/codaterminal>.

7.1.3 Australian state of development

Research on in-situ CO_2 mineralisation in Australia is limited, with the majority of existing mineral carbonation research focusing on ex-situ applications.[269] However, CSIRO's CarbonLock Future Science Platform is investigating in-situ CO_2 mineralisation in basaltic and serpentinite formations to provide evidence for future investment. It is developing a publicly available resource map to support site selection.[270] Furthermore, Australia is co-leading the Carbon Mineralisation Technical Track within Mission Innovation's CDR Mission.[271]

7.1.4 MRV – storage

Similarly to geological CO_2 storage, a range of techniques capable of detecting CO_2 is used for in-situ mineral carbonation MRV (see Section 5.1.3). However, as mineralisation of CO_2 is the dominant trapping mechanism, reactive and non-reactive geochemical and isotopic tracers (and geochemical analyses) are required to monitor CO_2 mineralisation, as opposed to conventional MRV methods used to monitor CO_2 containment (e.g. seismic imaging).[272] Long-term monitoring of mineral storage sites is significantly reduced once mineralisation of CO_2 is verified, as the risk of CO_2 leakage is eliminated.[273,274]

7.2 Ex-situ mineral carbonation

Ex-situ mineral carbonation involves reacting CO_2 with suitable mineral or alkaline feedstocks to produce stable carbonates in above-ground, controlled environments that accelerate mineral carbonation reaction rates and efficiency. Ex-situ mineral carbonation can be applied to a wide range of magnesium- and calcium-rich silicate rocks as well as mining and industrial wastes, including mine tailings, iron/steel slag, pulverised fuel ash, cementitious materials, and incinerator waste.[275] Ex-situ mineral carbonation generally requires a source of concentrated CO_2, although this is not always the case.

Accelerated mineral carbonation (AMC) or engineered ex-situ mineral carbonation is conducted in a controlled aqueous environment (i.e., in water) to enhance reaction rates, with the optional addition of heat and pressure to further increase reactivity.[276] AMC can be applied to pure CO_2 gas streams or CO_2-containing flue gas from industrial processes; however, CO_2 must be sourced from the atmosphere to be considered CDR. Additive salts, such as sodium chloride, sodium bicarbonate, ammonium (bi)sulphate, or organic acids, can be optionally used to adjust the pH, improve the extent of carbonation, and reduce reaction time. AMC can be carried out in one or multiple reactors. The use of multiple reactors can help enhance the reaction rate by altering the solution chemistry or mineral structure, thereby making the reactants more reactive. However, the multi-reactor approach can be energy intensive.[277]

269 Al Kalbani M, Serati M, Hofmann H, Bore T (2023) A comprehensive review of enhanced in-situ CO_2 mineralisation in Australia and New Zealand. International Journal of Coal Geology 265, Article 104316. <https://doi.org/10.1016/j.coal.2023.104316>.

270 CSIRO (2024) Putting Australian enhanced mineralisation on the map. <https://www.csiro.au/en/news/All/Articles/2024/February/mineral-carbonation>.

271 CSIRO (2023) Mission Innovation – Carbon Dioxide Removal (MI-CDR) engagement. CarbonLock Future Science Platform. <https://research.csiro.au/carbonlock/mi-cdr/>.

272 Matter JM, Stute M, Snæbjörnsdottir S, Oelkers EH, Sigurdur R, Gislason SR, Aradottir ES, Sigfusson B, Gunnarsson I, Sigurdardottir H, Gunnlaugsson E, Axelsson G, Alfredsson HA, Wolff-Boenisch D, Mesfin K, Fernandez de la Reguera Taya D, Hall J, Dideriksen K, and Broecker WS (2016) Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions. Science352, 1312-1314 (2016). <https://doi.org/10.1126/science.aad8132>.

273 Burton M and Bryant SL (2009) Surface dissolution: Minimizing groundwater impact and leakage risk simultaneously, Energy Procedia, Volume 1, Issue 1, 2009. 3707-3714, ISSN 1876-6102. <https://doi.org/10.1016/j.egypro.2009.02.169>.

274 Gunnarsson I, Aradóttir ES, Oelkers EH, Clark DE, Arnarson MP, Sigfússon B, Snæbjörnsdóttir SO, Matter JM, Stute M, Júlíusson BM, and Gíslason SR (2018) The rapid and cost-effective capture and subsurface mineral storage of carbon and sulfur at the CarbFix2 site. International Journal of Greenhouse Gas Control, Volume 79, 2018. Pages 117-126. ISSN 1750-5836. <https://doi.org/10.1016/j.ijggc.2018.08.014>.

275 Milani D, McDonald R, Fawell P, Weldekidan H, Puxty G, Feron P (2025) Ex-situ mineral carbonation process challenges and technology enablers: A review from Australia's perspective. Minerals Engineering 222, Article 109124. <https://doi.org/10.1016/j.mineng.2024.109124>.

276 Yadav S, Mehra A (2021) A review on ex situ mineral carbonation. Environmental Science and Pollution Research 28(10), 12202–12231.

277 Milani D, McDonald R, Fawell P, Weldekidan H, Puxty G, Feron P (2025) Ex-situ mineral carbonation process challenges and technology enablers: A review from Australia's perspective. Minerals Engineering 222, Article 109124. <https://doi.org/10.1016/j.mineng.2024.109124>.

Passive ex-situ mineral carbonation simulates the rock weathering reaction that occurs in natural environments using alkaline mining or industrial waste. Passive ex-situ mineral carbonation or enhanced weathering typically does not require a concentrated stream of CO_2, as the alkaline material will passively react with CO_2 in the atmosphere. However, due to the slow reaction rate and low efficiency of natural processes, additional steps or methods are often required, such as manipulating the reactive material (e.g. tailings) to increase the exposed material surface area or applying heat to activate the material and thereby enhance reactions. The materials can then be left in mine-site pits to weather before being buried to store CO_2 durably, or they can be spread in a humidified enclosed facility for weathering and later transferred to storage locations.[278] While ERW can be regarded as type of ex-situ (above-ground) mineral carbonation,[279] for the purpose of this Roadmap, it has been categorised independently (see Section 3.2).

7.2.1 Global state of development

A number of ex-situ mineral carbonation demonstration and pilot projects are currently operating globally, with many innovations in system and process design supporting the scale up to commercial deployment before the end of the decade. An example in the global context is Paebbl, a Dutch start-up focused on developing on-site ex-situ mineral carbonation units that can be integrated into a high-emission source or a DAC facility. Paebbl's technology produces a carbonate material that can replace cement and other cementitious materials in the concrete mix, storing 300 kg of CO_2 per tonne of carbonate material produced.[280]

Paebbl has been operating a pilot and demonstration facility in Rotterdam, which was scaled up to be continuous and capable of capturing 500 tCO_2/y in March 2025. There are plans for a commercial facility to be completed in 2028.[281]

7.2.2 Australian state of development

MCi Carbon is an Australian CCU company that uses a low-temperature, low-pressure AMC process to produce high-value carbonate and/or silica products.[282] MCi Carbon currently plays a fundamental role in decarbonising hard-to-abate industrial emitters. However, it is expected that the process may be adapted to operate with DAC systems, therefore meet the definition of CDR in the near future. In 2023, MCi Carbon commenced construction of one of the world's first mineral carbonation demonstration facilities in Newcastle, which has the expected capacity of storing over 1,000 tCO_2/y in carbonate products.[283] In 2024, MCi Carbon was awarded A$14.5 million through the Australian Government's Carbon Capture Technologies Program to expand and optimise processing capabilities at its Newcastle facilities.[284] MCi Carbon has also signed a long-term strategic cooperation agreement with refractory company RHI Magnesita (Austria) to deploy its technology at commercial scale in Austria, including plans for a commercial-scale facility capable of storing 50,000 tCO_2/y in carbonate products from 2028.[285]

278 Common Capital Pty Ltd (2023) Scaling atmospheric carbon dioxide removal in New South Wales. Report prepared for the NSW Office of Energy and Climate Change. <https://www.energy.nsw.gov.au/sites/default/files/2024-02/Common_Capital_Scaling_atmospheric_CDR_in_NSW_Final.pdf>.

279 World Economic Forum (2023) 5 things to know about carbon mineralization. <https://www.weforum.org/stories/2023/07/carbon-mineralization-things-to-know/>.

280 Paebbl (n.d.) Build future-proof. <https://paebbl.com/build-future-proof>.

281 Paebbl (2025) Paebbl starts operating its continuous demo plant, a world-first for CO_2 mineralisation. <https://paebbl.com/news-feed/paebbl-starts-operating-its-continuous-demo-plant-a-world-first-for-CO_2-mineralisation>.

282 MCi Carbon (n.d.) Technology. <https://mcicarbon.com/technology/>.

283 MCi Carbon (n.d.) Technology. <https://mcicarbon.com/technology/>.

284 MCi Carbon (2024) MCi Carbon awarded $14.5m Carbon Capture Technologies Program grant to accelerate mission. <https://mcicarbon.com/mci-carbon-awarded-14-5m-carbon-capture-technologies-program-grant-to-accelerate-mission/>.

285 RHI Magnesita (2023) RHI Magnesita and Australian cleantech MCi Carbon enter long-term strategic cooperation to decarbonise refractories. <https://www.rhimagnesita.com/rhi-magnesita-and-australian-cleantech-mci-carbon-enter-long-term-strategic-cooperation-to-decarbonise-refractories/>; MCi Carbon (n.d.) Technology. <https://mcicarbon.com/technology/>.

Arca is an Australian example of how ex-situ mineral carbonation can be implemented as a CDR approach (i.e. involving both CO_2 capture and storage). It recently completed a pilot project utilising mine tailings from BHP's Mount Keith nickel mine as a feedstock, and aiming to accelerate the passive uptake of atmospheric CO_2 directly into mine tailings without using a concentrated CO_2 stream obtained using a capture process such as DAC.[286] The project also included the tested use of autonomous rovers to churn the surface of carbonated tailings, exposing new reactive feedstock for carbonation while measuring and collecting data on the rate and volume of CO_2 capture, conducting MRV in real-time.[287] Arca has also developed a patented, fully electrified technology called Mineral Activation, which utilises microwave radiation to break down the mineral lattice of reactive minerals, enhancing feedstock reactivity.[288] In February 2025, Arca announced strategic partnerships with a number of WA stakeholders and industry to assess opportunities for ex-situ mineral carbonation at WA mining operations and support sustainable and collaborative regional strategy development.[289]

7.2.3 MRV – storage

MRV methodologies for ex-situ mineral carbonation are in the early stages of development, requiring ongoing RD&D to standardise and apply them to commercial projects. The MRV of ex-situ mineral carbonation approaches is challenging due to the slow reaction rate and the complex and highly variable composition of the feedstock materials, which can lead to undesirable reactions with CO_2 or other environmental factors over time.[290] The complexity of MRV also varies depending on the closed vs open setting of the ex-situ mineral carbonation operation.[291]

Material streams and net CO_2 removal can be closely monitored in closed systems (e.g., AMC), whereas it is more challenging to monitor these factors in open systems (e.g., passive ex-situ mineral carbonation or enhanced weathering). Moving forward and leveraging critical knowledge gained from leading industry players such as Arca, focused RD&D efforts are needed to advance MRV methodologies in open systems, and improve standardisation between methods and protocols to ensure consistency and comparability across sites and projects.[292]

It has been suggested that MRV methodologies for ex-situ mineral carbonation approaches can be based on those being developed for ERW, due to similarities in capturing CO_2 in finely ground minerals.[293] The key difference between the two approaches is the of primary storage: ex-situ mineral carbonation stores CO_2 as carbonate minerals, whereas ERW predominantly stores CO_2 as bicarbonate ions in soil pores, with minor storage in carbonate minerals (see Section 6.1.3). These soluble bicarbonate ions eventually run off into the local watershed, adjacent rivers, and eventually the ocean.[294]

286 Arca (2023) Arca announces funding support from the B.C. Centre for Innovation and Clean Energy to capture atmospheric carbon dioxide and transform it into rock. <https://www.businesswire.com/news/home/20231128286670/en/Arca-Announces-Funding-Support-from-the-B.C.-Centre-for-Innovation-and-Clean-Energy-to-Capture-Atmospheric-Carbon-Dioxide-and-Transform-it-into-Rock>.

287 Arca (n.d.) Frequently asked questions. <https://arcaclimate.com/frequently-asked-questions/>.

288 Arca (n.d.) Frequently asked questions. <https://arcaclimate.com/frequently-asked-questions/>.

289 Arca (2025) Arca announces partnerships to drive carbon removal projects at WA mine sites. <https://arcaclimate.com/wp-content/uploads/2025/02/EXT-20250217-AU-Arca-Partnership-Press-Release-FINAL-for-Arca.docx.pdf>.

290 Hitch M, Li J (2023) Developing a verification framework for carbon sequestration through mineral carbonation of mine tailings: an Australian context. In Geoenvironmental and Geotechnical Issues of Coal Mine Overburden and Mine Tailings. (Eds. F Kusin, VM Molahid) 109–131. Springer, Singapore. <https://doi.org/10.1016/j.exis.2025.101696>.

291 Stakeholder consultation.

292 Hitch M, Li J (2023) Developing a verification framework for carbon sequestration through mineral carbonation of mine tailings: an Australian context. In Geoenvironmental and Geotechnical Issues of Coal Mine Overburden and Mine Tailings. (Eds. F Kusin, VM Molahid) 109–131. Springer, Singapore. <https://doi.org/10.1016/j.exis.2025.101696>; Milani D, McDonald R, Fawell P, Weldekidan H, Puxty G, Feron P (2025) Ex-situ mineral carbonation process challenges and technology enablers: A review from Australia's perspective. Minerals Engineering 222, Article 109124. <https://doi.org/10.1016/j.mineng.2024.109124>.

293 Stakeholder consultation.

294 In-field carbon dioxide removal via weathering of crushed basalt applied to acidic tropical agricultural soil. Science of the Total Environment 955, 176568. <https://doi.org/10.1016/j.scitotenv.2024.176568> <https://www.sciencedirect.com/science/article/pii/S004896972406724X?via%3Dihub - s0005>; Carbon Dioxide Removal Mission (2022) Carbon dioxide removal technology roadmap: innovation gaps and landscape analysis.

Part III: Capacity and cost analysis

This Roadmap uses quantitative analysis to build an evidence base for Australia's potential for novel CDR, understand the costs now and by 2050, and highlight regions where CDR might be economically viable, recognising that community engagement is critical.

This section focuses on four CDR approaches (see highlighted icons in Figure 24) that combine specific CO_2 capture and storage process to create durable CDR approaches (discussed further in Part II). For each approach, specific capture and storage processes have been used as representative processes based on technology maturity, scalability, durability and suitability to Australia.

While these processes provide a foundation for analysis, other existing and emerging capture and storage processes have the potential to be scalable, durable and economically viable in the future. The quantitative analysis methodology has been designed to be transparent and adaptable, and while it focuses on selected CDR approaches, it can be extended as new data becomes available.

Prior to presenting the cost and capacity results, Section 8: Analytical scope and methodology outlines the methodology, scope and limitations of the quantitative analysis. Additional details on the modelling approach and assumptions can be found in the *Australian CDR Roadmap – Modelling Appendix*.

Figure 24: A summary of the novel CDR capture and storage approaches and processes considered for analysis in this Roadmap.

CO_2 CAPTURE	CO_2 STORAGE				
	Geological storage		Mineral storage	Open environments	
Biologically captured during biomass growth	BiCR+S – fast pyrolysis to H_2 (geological storage) >1,000 years	BiCR+S – combustion (geological storage) >1,000 years	BiCR+S (mineral carbonation) >1,000 years	BiCR+S – slow pyrolysis to biochar 100–1,000 years	Conventional CDR 10–100 years
Geochemically bound in minerals				ERW >1,000 years	OAE >1,000 years
Chemically captured as gas	DAC+S (geological storage) >1,000 years		DAC+S (mineral carbonation) >1,000 years		

8 Analytical scope and methodology

The quantitative methodology applied within this Roadmap aims to build an evidence base for Australia's potential for novel CDR through transparent, objective and proportionate economic analysis. This analysis has three objectives:

- Estimate Australia's realisable novel CDR capacity based on conservative assumptions on resource availability.
- Estimate CDR costs in the near term and by 2050.
- Identify regions where CDR could be economically viable, recognising further community engagement is required.

To realise these three objectives, a bottom-up analysis has been carried out, underpinned by an assessment of the availability of resources necessary for the novel CDR approaches considered and informed by a pioneering assessment of CDR potential in the US (see Box 5). A series of conservative constraints has been applied to estimate this resource availability, as summarised in Table 6 and discussed later in this section. Regional cost inputs have also been used to understand how the cost of CDR may vary with location.

This regional focus identifies local opportunities in a way that is not possible through integrated assessment modelling or least-cost optimisation modelling. The resulting evidence base can support decision-making at a local level, allowing communities to weigh up opportunities for novel CDR against local priorities and needs.

Box 5: Adaptation of the analytical methodology and approach from the Roads to Removal report (US).

This Roadmap leverages the modelling approach, assumptions and insights from the *Roads to Removal: Options for Carbon Dioxide Removal in the United States* report, a multi-year, national-scale, collaborative scientific study of the potential for CDR in the US. In particular, the *Roads to Removal* report helps inform this Roadmap's decision to conduct regional-level assessment of the cost and capacity of CDR, as well as the baseline process, assumptions and constraints for the analysis of DAC and BiCR processes. This Roadmap has adapted the *Roads to Removal* approach to suit the Australian context.

We would like to thank the researchers at the Lawrence Livermore National Laboratory, who are the main authors of the *Roads to Removal* report, for reviewing the initial results produced by this Roadmap, and providing valuable insights and guidance to ensure the role of CDR is clearly communicated across different levels of government, industry and community.

8.1 Methodology

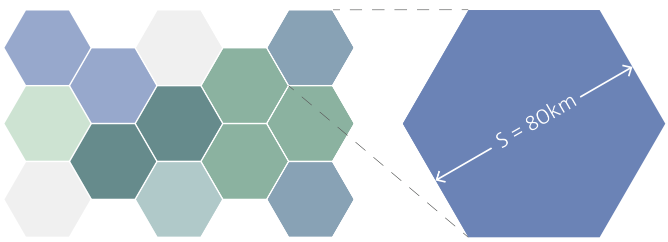
The methodology for assessing the cost and capacity of CDR approaches involves three broad steps, which are described in detail in the *Australian CDR Roadmap – Modelling Appendix* and briefly outlined below:

1. A series of regional inputs are collated, including constraints (informing capacity analysis) and cost assumptions (informing levelised cost analysis) at an appropriate regional level to capture meaningful regional variation (see Section 8.3).
2. A techno-economic model is developed for each CDR approach and applied at the defined regional level, drawing on the regional cost assumptions.
3. Regional capacity analysis is undertaken in parallel to the techno-economic modelling and aggregated to produce an estimate of Australia's annual realisable capacity. This is technically a rate rather than a capacity or quantity, but the term capacity is used for simplicity.

The methodology is implemented across the four representative CDR approaches, with adjustments made to accommodate the specific characteristics of each approach.

To capture meaningful regional variation and facilitate the visualisation of CDR capacity and cost across regions, a grid of hexagonal bins (hexbins) covering continental Australia has been created. Each hexbin has a width of 80 km, as shown in Figure 25, which represents an area of approximately 5,500 km^2. Analysis of CDR cost and capacity is carried out at the hexbin level, and then aggregated to a national level to produce estimates of Australia's realisable CDR capacity.

Figure 25: Hexbin used for spatial resolution in the cost and capacity analysis, with an 80 km diagonal distance.

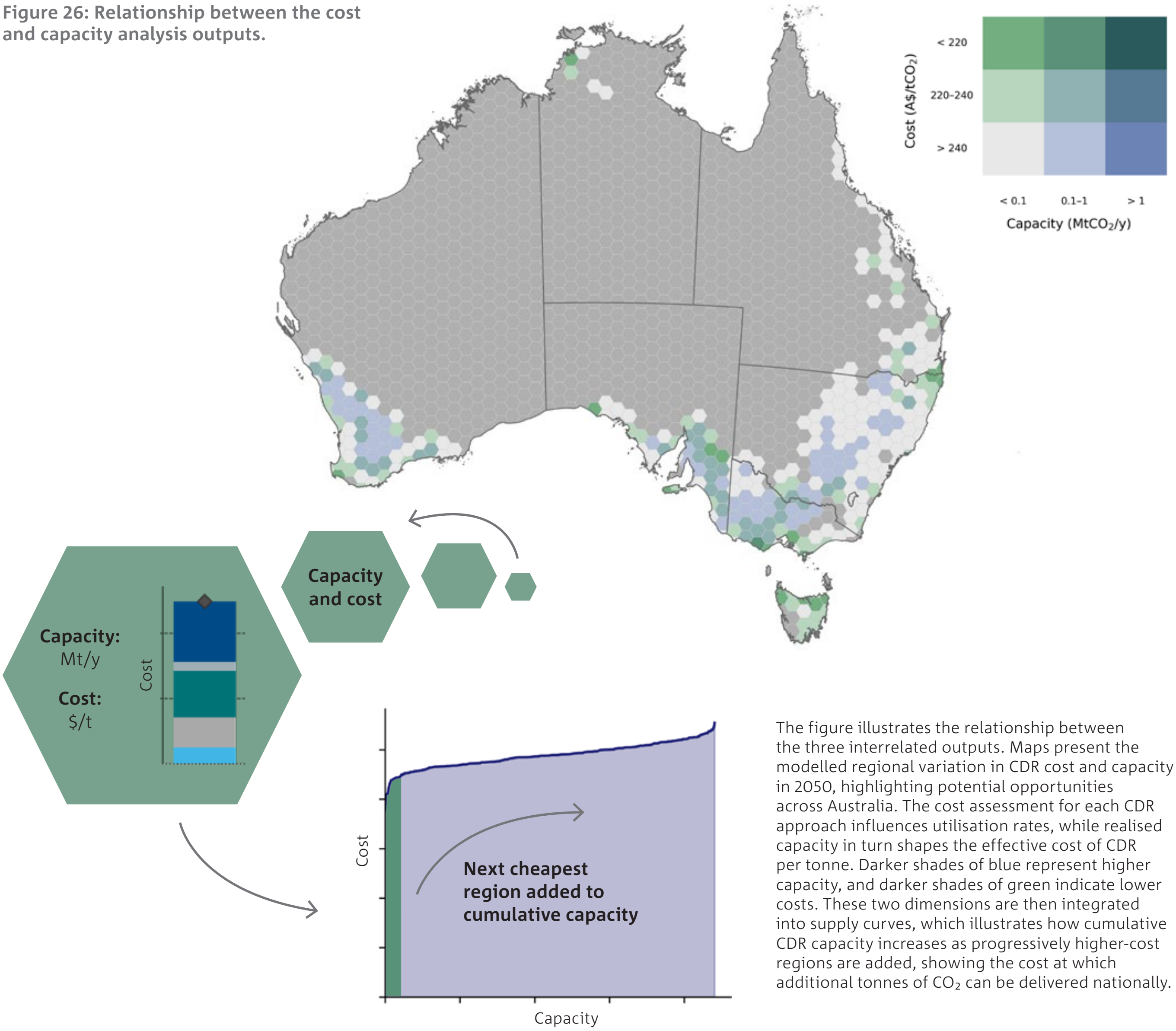


8.2 Outputs

The quantitative analysis consists of three interrelated outputs (visualised in Figure 26):

1. Maps visualising the modelled CDR variation in cost and capacity across regions in 2050 to identify regional opportunities. This mapping is undertaken for two cases:
    a. **Realisable capacity:** an estimate of Australia's annual potential for CDR based on conservative assumptions.
    b. **High ambition:** an estimate of Australia's annual potential for CDR when key assumptions are relaxed.
2. Levelised cost of CDR analysis broken down by cost component for a typical region to understand key cost drivers and opportunities for reductions. Levelised costs are modelled for two scenarios:
    a. **First-of-a-kind (FOAK):** a project commenced in 2025, using current processes.
    b. **Nth-of-a-kind (NOAK):** a facility commenced in 2050, reflecting the potential for reductions in different cost components over time.
3. Supply curves, combining the cost and capacity analysis into a single aggregate output for Australia to enable comparison of novel CDR with other carbon management strategies.

Figure 26: Relationship between the cost and capacity analysis outputs.



The figure illustrates the relationship between the three interrelated outputs. Maps present the modelled regional variation in CDR cost and capacity in 2050, highlighting potential opportunities across Australia. The cost assessment for each CDR approach influences utilisation rates, while realised capacity in turn shapes the effective cost of CDR per tonne. Darker shades of blue represent higher capacity, and darker shades of green indicate lower costs. These two dimensions are then integrated into supply curves, which illustrates how cumulative CDR capacity increases as progressively higher-cost regions are added, showing the cost at which additional tonnes of CO_2 can be delivered nationally.

8.3 Regional constraints and inputs

The constraints and inputs that are varied regionally are summarised in Table 6. Additional details on these constraints are provided below, and in the *Australian CDR Roadmap – Modelling Appendix*.

These constraints are applied to each hexbin to estimate the realisable capacity and cost of each CDR approach in each hexbin. National capacity estimates are calculated by summing the capacity of all hexbins.

8.3.1 Land available for VRE

DAC+S and OAE approaches require a substantial amount of VRE to power their operations to maximise net CO_2 removal. Generating this amount of VRE would, in turn, require a large area of land. This analysis assumes that VRE is generated locally (i.e. within a given hexbin).

To estimate the amount of land available for VRE generation, constraints were applied to existing land use data to exclude several land uses, including state and national parks, protected areas, built-up areas and intensive agricultural land (see Figure 27). Renewable Energy Zones (REZs) were also excluded because any electricity used for CDR must be additional to electricity intended for grid decarbonisation (see Box 6). Remaining land assumed to be available for VRE was constrained by socially acceptable limits for different VRE generation. Up to 1% of remaining land in each hexbin is assumed to be available for solar PV installation, while up to 5% is assumed to be available for onshore wind, reflecting its potential to coexist with other land uses.

ERW and BiCR+S approaches also require renewable energy but in much lower quantities. The cost and amount of energy needed for these approaches are included in their cost analysis, but do not act as a capacity constraint and are modelled without considering regional variability.

Table 6: Constraints and inputs used in the cost and capacity analysis.

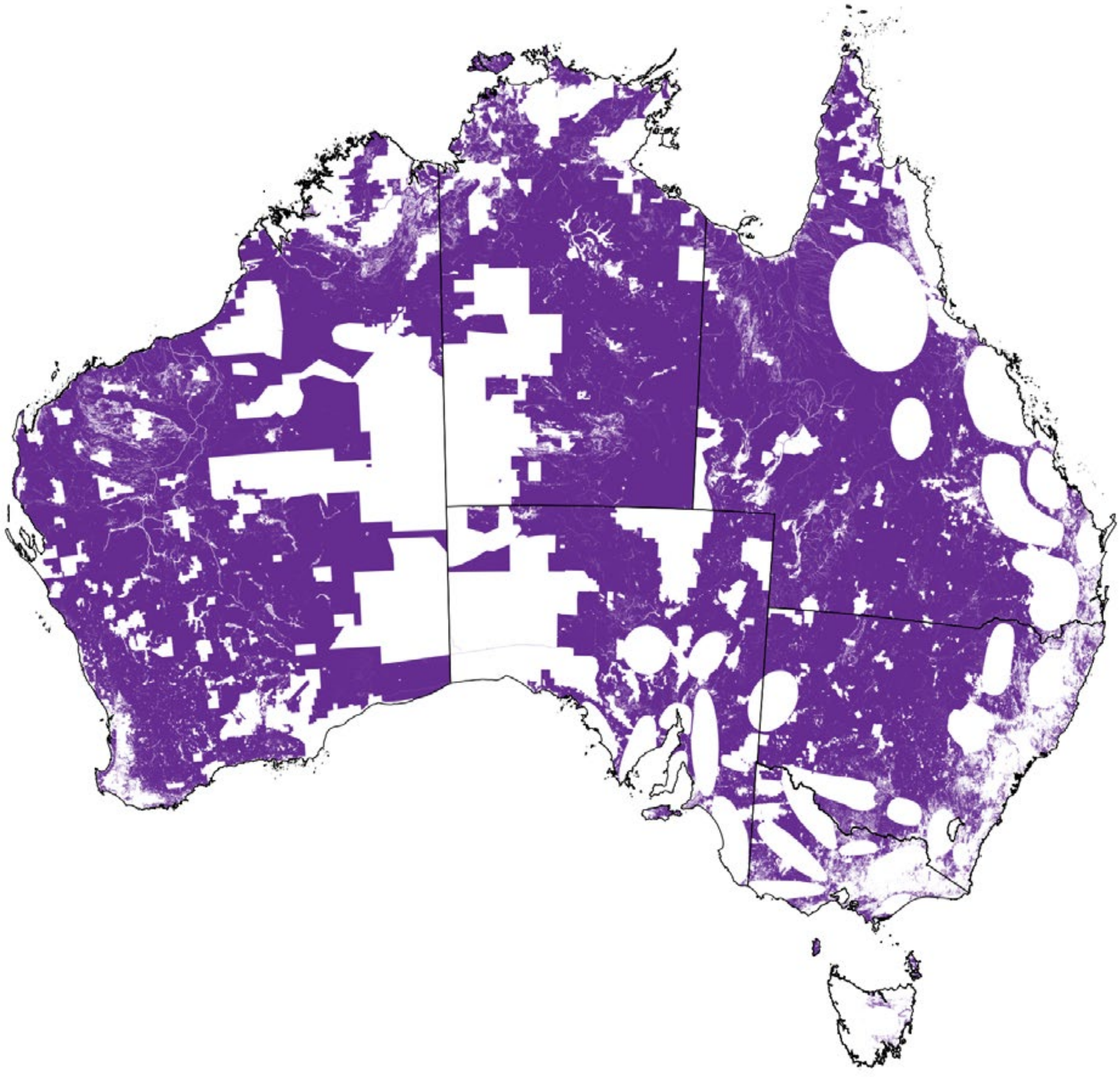
CONSTRAINT/APPROACH	DAC+S	OAE	BICR+S	ERW
Land available for variable renewable energy (VRE)	Constraint applied to the capacity analysis	Constraint applied to the capacity analysis		
Regional VRE generation potential	Constraint applied to the capacity analysis and input to the cost analysis	Constraint applied to the capacity analysis and input to the cost analysis		
Location cost factors	Input to the cost analysis	Input to the cost analysis	Input to the cost analysis	
Geological storage availability	Constraint applied to the capacity analysis		Constraint applied to the capacity analysis	
Proximity to coastline and existing desalination plants		Constraint applied to the capacity analysis		
Biomass feedstock availability			Constraint applied to the capacity analysis	
Rock feedstock availability				Constraint applied to the capacity analysis
Agricultural land availability				Constraint applied to the capacity analysis
Feedstock transport costs			Constraint applied to the capacity analysis and input to the cost analysis	Constraint applied to the capacity analysis and input to the cost analysis

- Constraint applied to the capacity analysis and input to the cost analysis
- Constraint applied to the capacity analysis
- Input to the cost analysis

Box 6: Exclusion of Renewable Energy Zones from CDR capacity analysis.

The exclusion of REZs was applied to avoid diverting renewable electricity from Australia's electricity sector, and ensure the national CDR capacity estimates produced in this Roadmap are in addition to emissions reductions. In reality, there may be potential to leverage surplus renewable capacity in existing electricity grids to support CDR facility operations. This could reduce the need for dedicated renewable infrastructure, but it introduces trade-offs regarding the most effective use of grid electricity, especially in the context of broader decarbonisation strategies. See the *Australian CDR Roadmap – Modelling Appendix* for more details.

Figure 27: Map of suitable land for variable renewable energy generation, taking into account existing land use, Renewable Energy Zones, land contiguity and slope.



8.3.2 Regional VRE generation potential

VRE generation potential and cost will vary across different regions as areas with higher solar and wind capacity factors and greater resource diversity tend to have lower electricity costs. The CSIRO Energy Systems team has modelled firmed VRE costs for different geographic locations across Australia (see Figure 28). The modelling considers solar and onshore wind generation technologies, with storage provided by battery energy storage systems. The lowest cost combination of solar, wind and battery energy storage systems is then determined for a range of firming levels, and the resulting generation potential and levelised cost of electricity can be used in regional modelling.

VRE firming plays a critical role in determining the cost-effectiveness and scalability of energy intensive CDR approaches such as DAC+S and OAE. This firming incurs additional costs but is necessary to achieve higher rates of utilisation (i.e. the proportion of time that a facility is operational for). This in turn increases the amount of CO_2 removed per year, reducing levelised capital costs. Optimising this balance is essential: higher firming reduces levelised capital cost, but raises energy costs. The techno-economic model used in this analysis identifies the optimal firming level for each region by minimising the levelised cost of CDR.

The annual generation potential in each hexbin based on this optimal firming level is also calculated, and used in combination with the land availability constraint to estimate the CDR capacity in each hexbin. Further details on these assumptions and the approach taken can be found in the *Australian CDR Roadmap – Modelling Appendix*.

Relaxing current firming assumptions, by diversifying energy sources or integrating with existing infrastructure, could unlock greater DAC+S potential and reduce costs. However, doing so requires careful, region-specific analysis to weigh the benefits against system-wide and community-level impacts.

8.3.3 Location cost factors

Project costs can also vary regionally due to differences in transportation costs, labour rates and the lack of supporting infrastructure in more remote regions (as shown in Figure 29). To account for these differences, regional cost multipliers are applied to the capital cost of each CDR approach and the levelised cost of VRE. These adjusted costs are then incorporated into the optimisation model to inform the selection of the optimal firming level.

Figure 28: Regional cost of electricity at different firming levels across Australia in 2050.

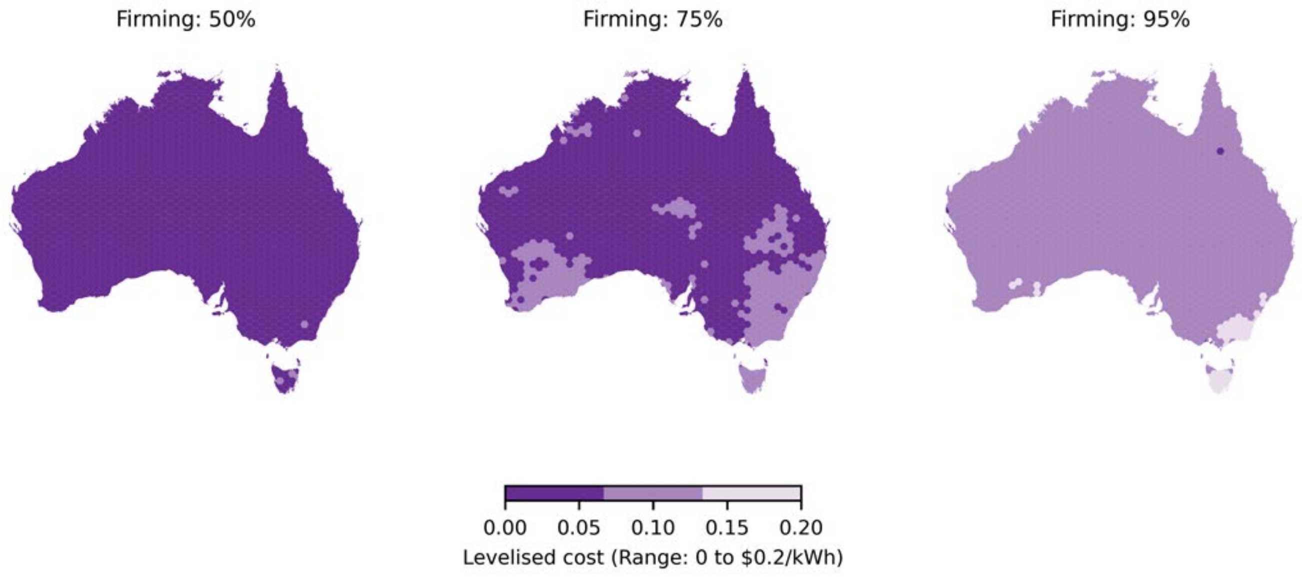
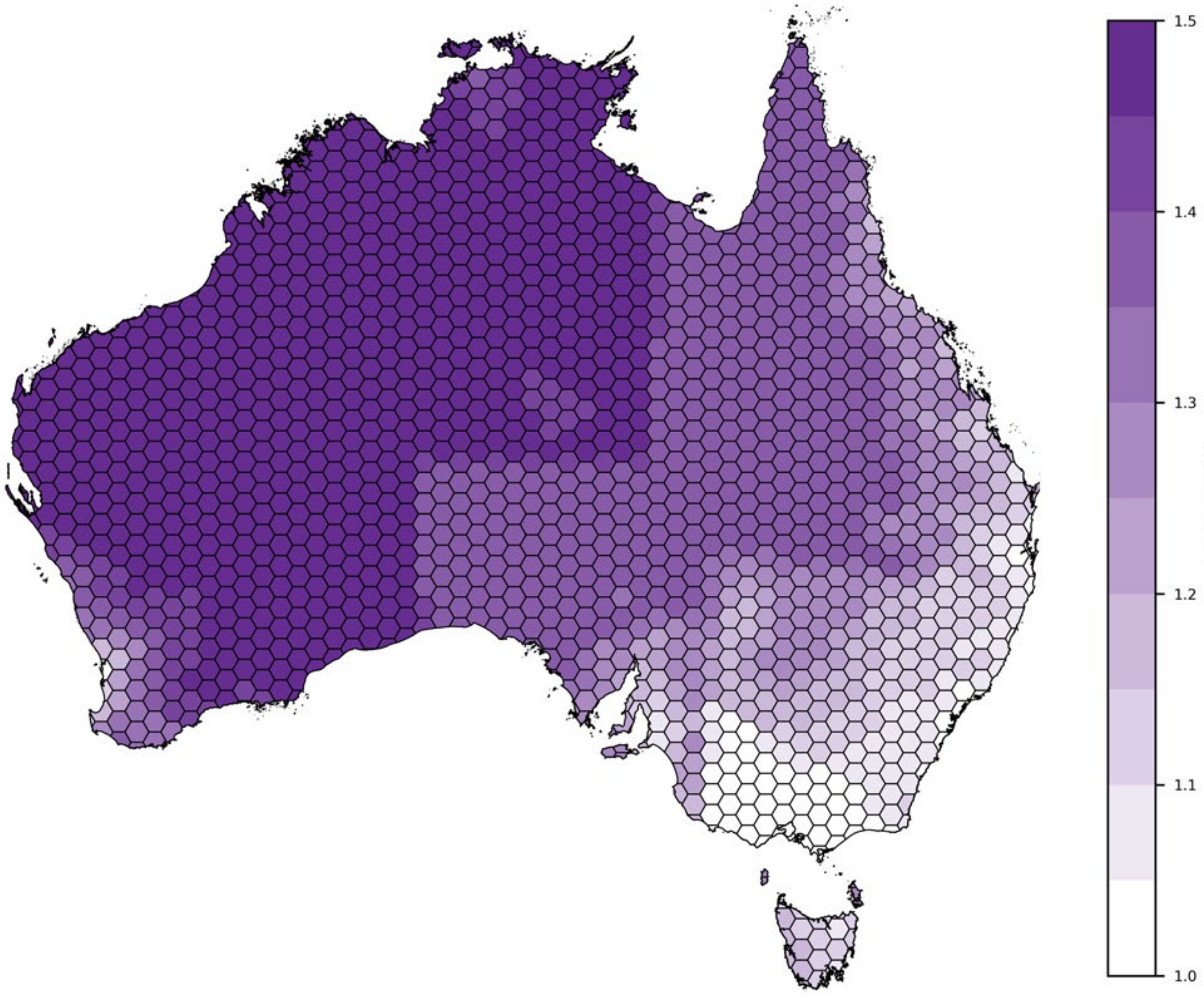


Figure 29: Location cost factors across different regions in Australia.



8.3.4 Geological storage availability

The DAC+S and BiCR+S approaches considered in this analysis rely on geological CO_2 storage to durably store the captured CO_2. The realisable capacity analysis assumes that these processes will be sited within 100 km of geological storage sites that are either currently operational for CCS projects or have been proven and developed to be prospective in the near to medium term (subject to geological assessment criteria, see Box 4). This assumption would allow DAC+S and BiCR+S projects to leverage existing reservoir knowledge and CO_2 transport, injection and storage infrastructure. Locations more than 100 km from geological storage are modelled to have no realisable capacity for DAC+S or BiCR+S in this analysis. The cost of CO_2 transport and storage is included in the cost analysis of DAC+S and BiCR+S approaches, but it does not vary by location.

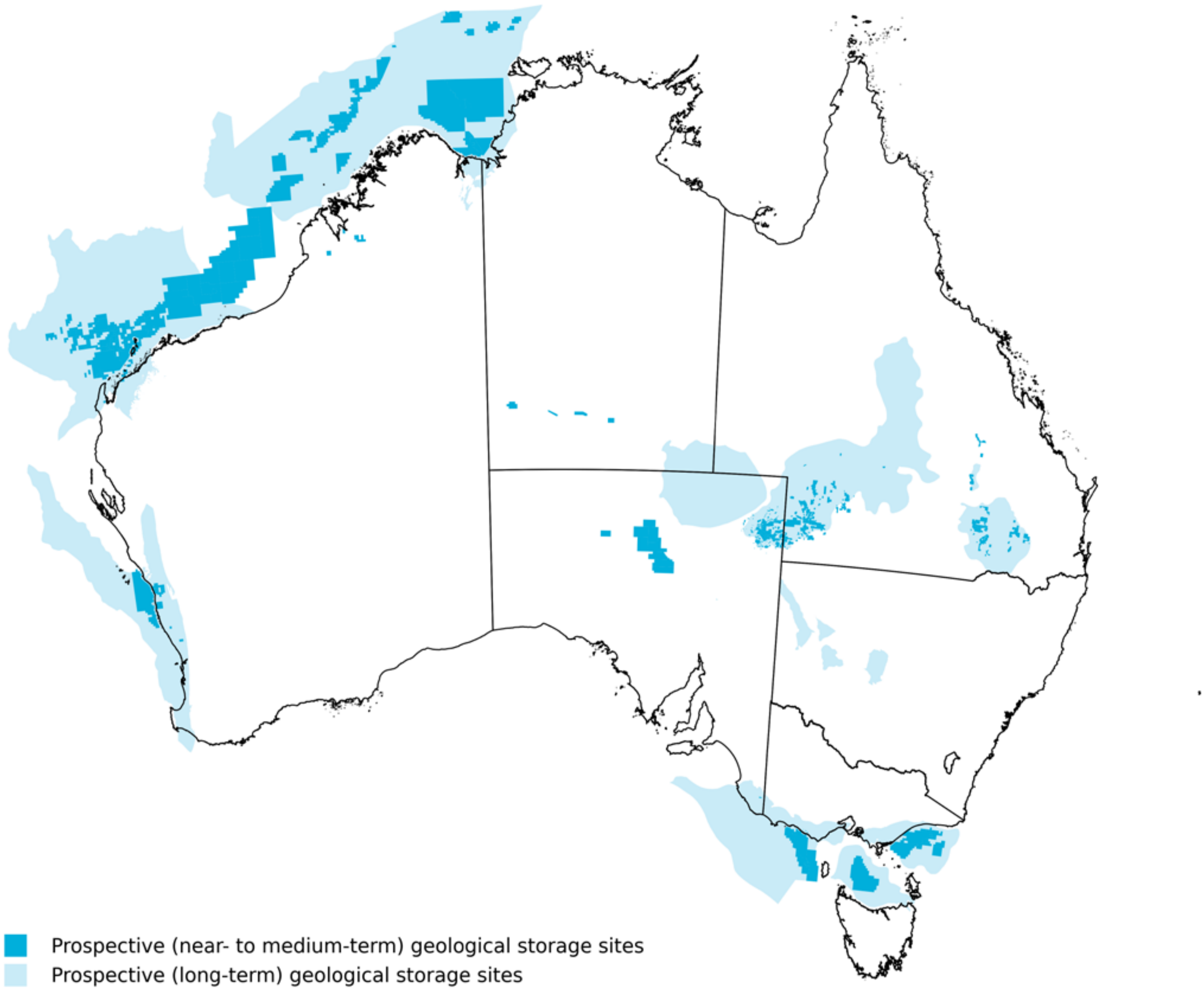
Consultation with geological storage experts within Geoscience Australia and CSIRO has led to the development of Figure 30, showing two tiers of geological storage locations. The first tier reflects locations of existing CO_2 storage permits, and locations considered to be prospective in the near to medium term. This tier is used to develop realisable capacity estimates for DAC+S and BiCR+S approaches in Sections 9 and 10. An additional tier of geological storage reflects locations considered to be prospective in the long term. This tier is used to develop high ambition capacity estimates for DAC+S and BiCR+S approaches. These high ambition results should not be directly compared to the realisable capacity estimate, given the different timescale ranges in prospectivity.

Improving the classification of this storage capacity from prospective to discovered (contingent and commercial storage capacity) would require significant additional geological data collection, including reservoir and seal evaluation, pilot and demonstration projects, and community engagement efforts (see Box 4 for more details). There may also be storage locations in geological basins not shown on this map that are discovered (i.e. become prospective storage resources) through further investigation.[295] Further information on geological storage classification can be found in Section 5.

8.3.5 Proximity to coastline and existing desalination plants

The realisable capacity for OAE is estimated in a similar manner to that of DAC+S, namely by estimating the VRE generation potential in suitable regions. Rather than being defined by geological storage availability, the suitable regions for OAE are those in 100km proximity to existing desalination plants (see Figure 31) (for the realisable capacity estimate) or coastal regions (for the high ambition estimate).

Figure 30: Map of prospective (near- to medium-term; and long-term) geological storage sites in Australia.[296]



295 Talukder A, Dance T, Michael K, Clennell B, Gee R, Northover S, Stalker L and Ross A (2024). CO_2, H_2 and compressed air energy storage site screening study – selected onshore basins in the Northern Territory. Northern Territory Geological Survey, Record 2024-005.

296 Data collated through consultation with stakeholders from Geoscience Australia and CSIRO.

The capacity for VRE generation in each coastal location is estimated as described in Section 8.3.2, again assuming no inter-regional electricity transmission. The cost of this VRE generation at different levels of firming is also modelled and used in the regional cost analysis.

The modelled OAE process also requires a supply of crushed rock to neutralise the acidic byproduct. The cost of this rock is considered in the analysis but does not vary by location as it is not a significant cost component.

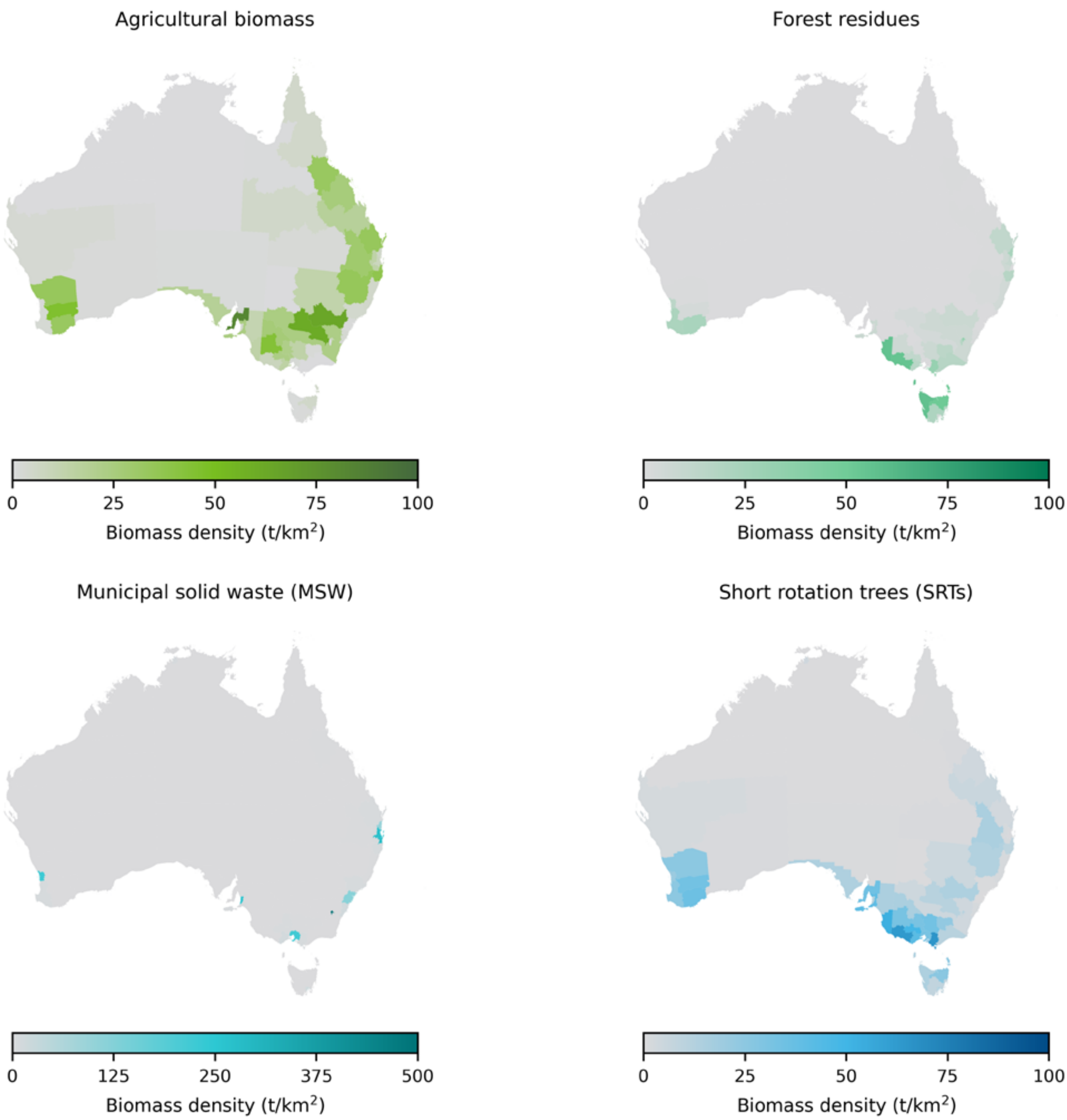
8.3.6 Biomass feedstock availability

For BiCR+S, biomass availability represents a key constraint on realisable CDR capacity. Regional estimates of annual biomass availability were used to assess the volume of feedstock for BiCR+S approaches in 2050 (see Figure 32). Biomass types include agricultural biomass (i.e. crop stubble, grasses, bagasse), residues from plantation forests, municipal solid waste (MSW), and biomass from short rotation trees (SRT). The physical composition and carbon removal potential of each feedstock were considered when assessing its suitability for different BiCR+S approaches and the amount of CDR it could support.

Figure 31: Location of existing desalination plants.[297]

297 Geoscience Australia (2012) Major desalination plants. <https://pid.geoscience.gov.au/dataset/ga/74784>.

Figure 32: Projected density of four types of biomass considered for BiCR+S approaches by 2050, based on the Australian Bureau of Statistics's (ABS) Statistical Areas Level 2.[298]



Note: A 5x larger scale is used for the MSW density, compared to the scale of other biomass feedstocks

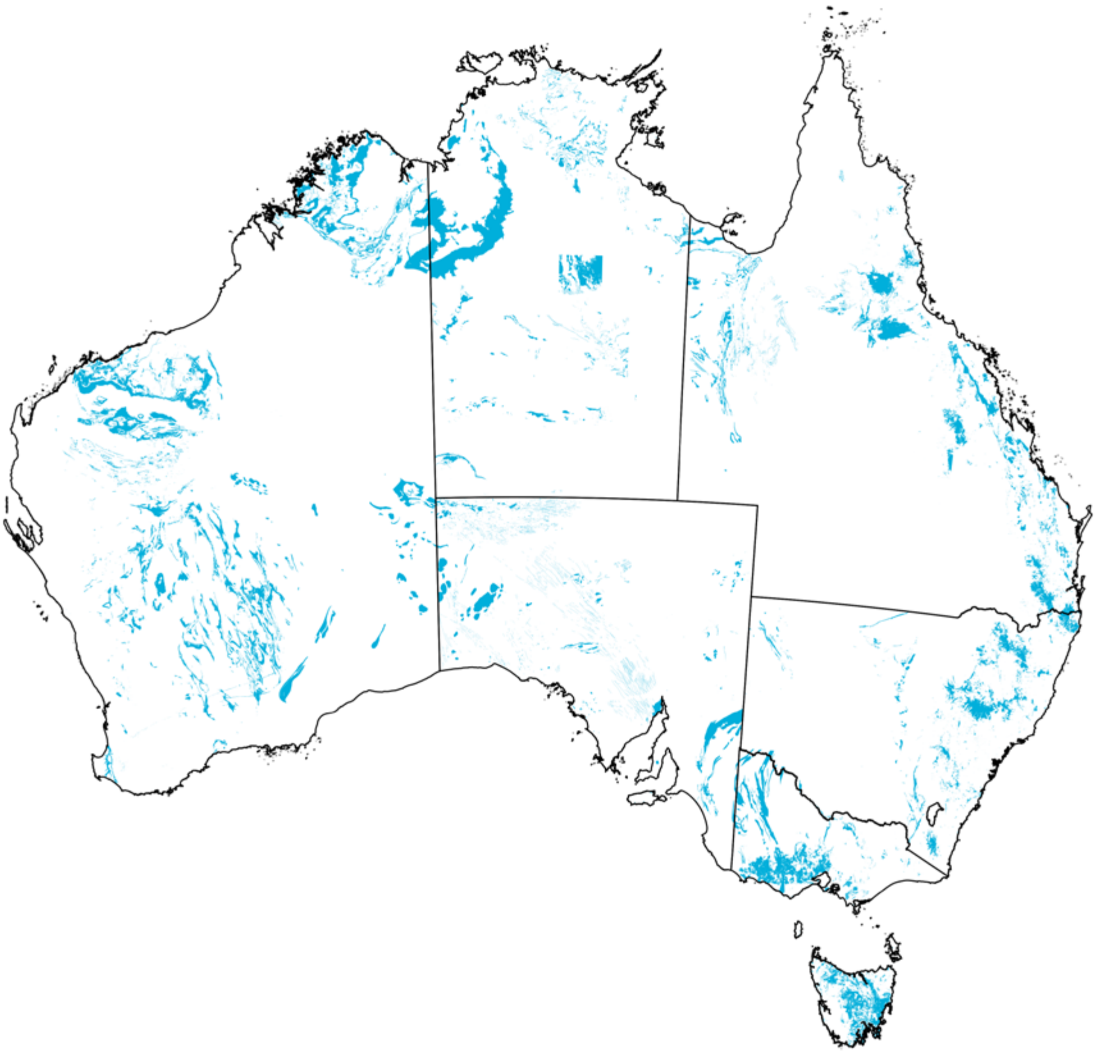
298 Crawford DF, O'Connor MH, Jovanovic T, Herr A, Raison RJ, O'Connell DA, Baynes T (2016) A spatial assessment of potential biomass for bioenergy in Australia in 2010, and possible expansion by 2030 and 2050. GCB Bioenergy 8, 707. doi:10.1111/gcbb.12295

8.3.7 Rock feedstock availability

The availability of suitable rock is a key constraint for ERW, which requires the application of mafic or ultramafic rocks, such as basalt, that react with atmospheric CO_2 when applied to land. Data from Geoscience Australia on the relative abundance and location of suitable mafic rocks were used to inform our rock availability and distribution analysis to assess the feasibility of ERW in Australia (see Figure 33).[299] The quantity of rock that could be mined nationally was constrained to 100 Mt per year in the realisable capacity analysis, approximately 50% of the current level of quarrying for construction materials in Australia. A regional limit of 10 Mt per year per hexbin was also applied. The high ambition analysis assumed a maximum of 1 Gt of mined rock per year, with the same 10 Mt per year limit per hexbin.

The costs of transporting crushed rock from the mine location to the application site was modelled similarly to BiCR+S transport costs (see Section 8.3.9).

Figure 33: Extent of areas consisting of dominantly mafic lithologies across Australia, as per geological mapping summarised and compiled in Thorne et al. (2014). The source dataset was filtered to only areas dominated by mafic rocks (as opposed to those with *subordinate* mafic rocks), but otherwise not filtered for any further criteria including age, alteration or metamorphism.[300]



299 New dataset provides clues to potential mineralisation | Geoscience Australia - Thorne, J. P., Cooper, M., Claoue-Long, J. C., Highet, L., Hoatson, D. M., Jaireth, S., Huston, D. L., & Gallagher, R. (2014). *The Australian Mafic-Ultramafic Magmatic Events GIS Dataset: Archean, Proterozoic and Phanerozoic Magmatic Events* [Dataset]. Geoscience Australia. <https://doi.org/10.4225/25/54125552CDA7C>.

300 Thorne, J. P., Cooper, M., Claoue-Long, J. C., Highet, L., Hoatson, D. M., Jaireth, S., Huston, D. L., & Gallagher, R. (2014). *The Australian Mafic-Ultramafic Magmatic Events GIS Dataset: Archean, Proterozoic and Phanerozoic Magmatic Events* [Dataset]. Geoscience Australia. <https://doi.org/10.4225/25/54125552CDA7C>.

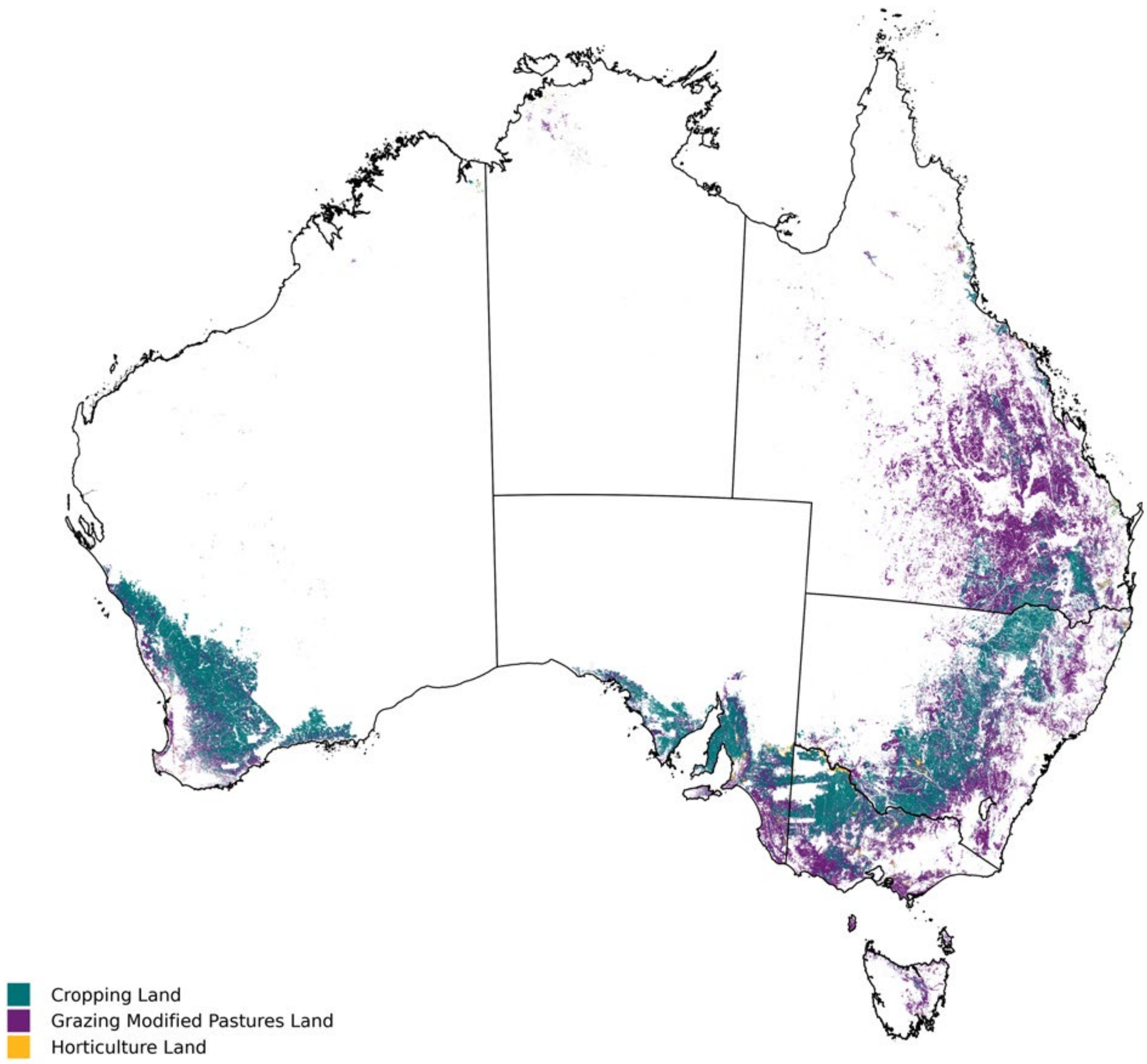
8.3.8 Agricultural land availability

The capacity of ERW was constrained by the availability of suitable agricultural land (see Figure 34). Cropping, horticultural, and modified pasture land types are considered suitable for ERW, and the capacity analysis assumed the rock application rate 40 tonnes per hectare. Up to 5% of suitable agricultural land per region is assumed to be technically available for ERW in the realisable capacity analysis, while up to 100% of agricultural land is available in the high analysis, depending on the regional supply of crushed rock.

8.3.9 Feedstock transport costs

Feedstock, either biomass for BiCR+S or crushed mafic rock for ERW, must be transported from its source to its place of use. The cost of this transport is estimated using the CSIRO's Transport Network Strategic Investment Tool (TraNSIT) model, assuming an A-double truck configuration and no backloading. A logit model is used to allocate available feedstock to suitable locations for either BiCR+S or ERW on a least-cost basis. A maximum transport cost of A$100 per tonne of feedstock is applied, a trade-off between maximising capacity and minimising cost.
This approach applies a constraint on the realisable capacity of CDR based on the proximity of feedstock to suitable project locations.

Figure 34: Map of suitable agricultural land for ERW approaches.[301]



301 Department of Agriculture, Fisheries and Forestry (2025) Catchment scale land use profiles Web Map. <https://www.agriculture.gov.au/abares/aclump/land-use/catchment-scale-land-use-webmap>.

8.4 Known limitations

8.4.1 Social acceptance for CDR

Social acceptance of novel CDR is likely to constrain Australia's realisable CDR capacity. There are a number of possible reasons for this, including a perception that CDR reduces the incentive to decarbonise, concerns over unintended impacts and local opposition. While attempts have been made to reflect possible social constraints in the realisable capacity estimates (e.g. through land use and resource availability constraints), there remains significant uncertainty in the socially acceptable level of CDR uptake in Australia.

8.4.2 Electricity transmission and CO_2 transport

Renewable electricity generation is assumed to be co-located with geological storage in the case of DAC+S, and with coastal areas in the case of OAE. This assumption is conservative and does not account for the potential of inter-regional enabling infrastructure such as electricity transmission or, in the case of DAC+S, CO_2 pipelines to connect areas with complementary resource availability. Similarly, CO_2 pipelines could open up new locations for cost effective BiCR+S facilities. Optimisation modelling can be used to forecast where long-distance transmission lines or pipelines could cost effectively connect areas with high renewable generation potential and high storage potential. It is beyond the scope of this Roadmap to do this, but it could be a focus of future work.

8.4.3 Uncertainty in inputs and assumptions

There are a number of additional uncertainties related to specific inputs and assumptions used in the analysis.

Novel CDR approaches cost and performance

All of the CDR approaches considered in this analysis make use of novel CDR process combinations that have not been demonstrated at scale. There is significant uncertainty in both the current cost estimates and future cost projections of the modelled CDR processes. Similarly, there is uncertainty in the energy and raw material requirements, process assumptions and MRV protocols used in the modelling. These uncertainties are reflected in the levelised cost and capacity results presented in this Roadmap.

The regional variation of modelling inputs provides a range of possible CDR costs, but this range does not capture all cost uncertainty.

Emerging renewable energy technologies

As stated in Section 8.3.2, this analysis only considers solar and onshore wind generation technologies, with storage provided by battery energy storage systems. While these assumptions simplify the analysis, they exclude other renewable electricity generation and storage technologies that could enhance firming and improve costs. For instance, offshore wind and hydropower could be viable options where available. Given the high energy demands of many CDR approaches (particularly thermal energy in the case of DAC+S), technologies such as waste industrial process heat, geothermal energy and concentrated solar thermal, alongside thermal energy storage technologies, could also significantly reduce electricity demand and its cost. Incorporating these alternatives could improve CDR facility utilisation and efficiency, reduce costs, and expand realisable CDR capacity, particularly in regions with suitable resources.

Feedstock availability

Feedstocks are finite and are likely to be subject to competing uses. For example, biomass resources may be subject to competition from low-carbon liquid fuels production. This competition may reduce the realisable capacity of CDR approaches that rely on these feedstocks.

Life cycle analysis (LCA)

The impact of LCA on the levelised cost of CDR has been considered at a high level in this analysis. Examples include estimates of embedded emissions in CDR facility construction, and emissions resulting from feedstock transport. In reality, the LCA process will need to be carried out at a project level as part of an MRV framework to confirm the net cost of CDR.

Discount rate

The discount rate is an important input into any analysis of future costs and benefits. A 10% discount rate has been used to assess levelised cost in the FOAK scenario, while a 5% discount rate has been used in the NOAK scenario. Refer to Box 7 for a discussion on discount rates in cost-benefit analysis, and the *Australian CDR Roadmap – Modelling Appendi*x for additional detail on the modelling approach.

Box 7: Discount rates.

Discount rates reflect time preference.

Discount rates are an important element of cost-benefit analysis in public and private decision-making. They are used to convert future benefits or costs into present value, reflecting society's preference to have something of value today rather than in a future time period. A higher discount rate applies a greater discount to benefits or costs in future time periods relative to today, while a lower rate applies a smaller discount.

How do discount rates relate to CDR?

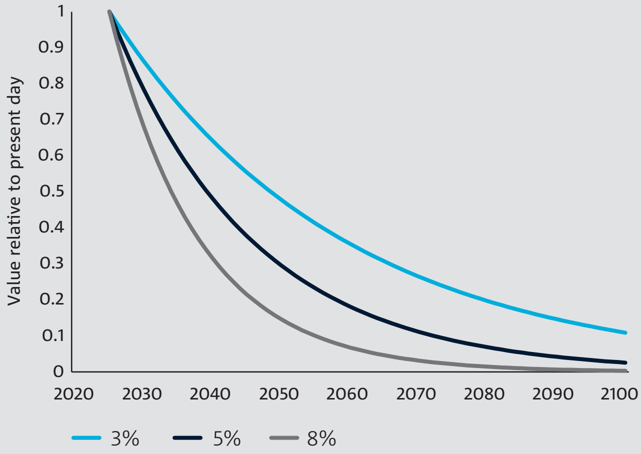
Investment in CDR is expected to yield long-term, cumulative and transformative benefits. By removing CO_2 from the atmosphere, CDR aims to reduce the long-term risks posed by climate change on our environment, society and economy. In setting this objective, an implicit acknowledgement of the concern for future generations' welfare is being made. This suggests a lower discount rate may be more appropriate when evaluating CDR and emissions reduction initiatives to objectively quantify future returns.

The impact of different discount rates on the weighting of future impacts is shown in Figure 35. It is difficult to reconcile higher discount rates with the aim of CDR. Higher rates will tend to prioritise welfare in the near term and deprioritise long-term economic, social and environmental impacts of investment decisions.

Setting a discount rate for carbon management.

There is no universally agreed discount rate for climate or carbon management policies. Literature[302] suggests several frameworks that can be used to derive suitable rates, based either on overall social wellbeing impacts (measured as social welfare equivalence) or on market prices and financial returns (measured as market based/financial equivalence) over time. Social welfare equivalence rates are typically lower than financial equivalence rates.

Figure 35: Present value of future impacts under a range of discount rates.



An agreement on the discount rate, or a range of rates, used to evaluate different emissions reductions or carbon removal approaches would ensure an objective comparison across the carbon management portfolio. Selecting a lower rate will tend to favour investment in emissions reductions and carbon removal that provides durable and sustainable net emissions reductions.

While private investment will continue to be driven by maximisation of shareholder returns (financial equivalence rates), there is an opportunity to consider a lower social welfare equivalence rate when making investment decisions concerning climate change and other intergenerational challenges.

If the effects of climate change persist and become increasingly reflected in financial markets and the broader economy, financial equivalence rates may converge with lower social welfare equivalence rates. Waiting for this market response runs the risk of underinvestment in climate change solutions like CDR.

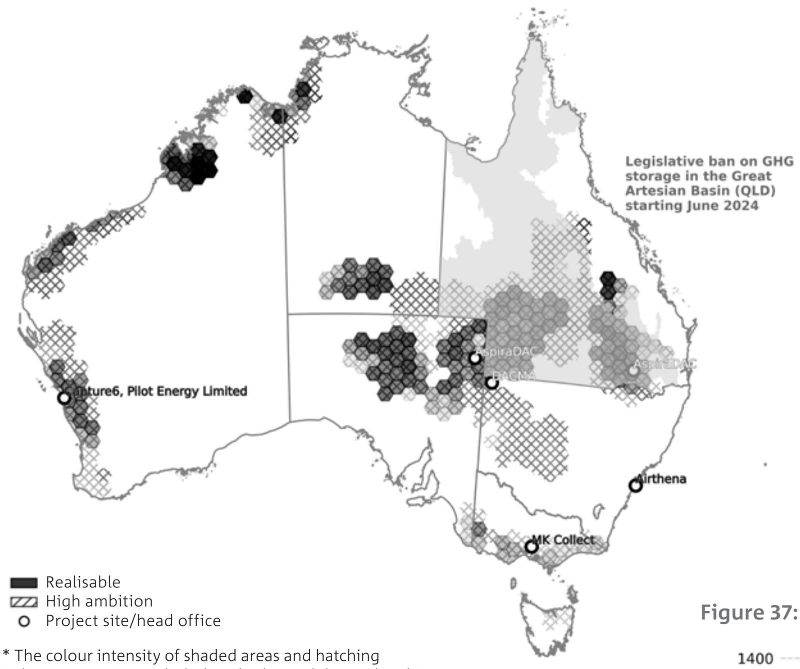
302 Goulder LH, Williams RC III (2012) The choice of discount rate for climate change policy evaluation. Climate Change Economics 3(4), 1250024. <https://www.web.stanford.edu/~goulder/Papers/Published%20Papers/Choice%20of%20Discount%20Rate%20for%20Cl%20Ch%20Policy%20Evals%20%28Goulder-Williams,%20CCE%202012%29.pdf>; Harrison M (2010) Valuing the Future: The Social Discount Rate in Cost-Benefit Analysis. Productivity Commission, Canberra. <https://www.pc.gov.au/research/supporting/cost-benefit-discount/cost-benefit-discount.pdf>.

9 Direct air capture + storage (DAC+S)

By 2050, solid adsorbent DAC with geological storage could capture and store up to 216 MtCO_2/y in Australia. The projected 2050 cost for an Nth-of-a-kind solid adsorbent DAC plant is A$400–480 per t$CO_2$, reflecting potential cost reductions from current levels.

Direct air capture and storage (DAC+S) describe a range of CDR approaches that separate and remove CO_2 from the atmosphere and store it deep underground in suitable geological formations. This Roadmap focuses on solid adsorbent and liquid absorbent DAC processes (TRL 7–9); however, it is recognised that many other emerging DAC processes are under development. For example, cryogenic DAC, electrode-based DAC, moisture-swing solid adsorbent DAC, mineral-based solid adsorbent DAC. Similarly, while this Roadmap uses geological storage to assess Australia's DAC+S potential, other options like mineral storage could be viable with further RD&D.

Figure 36: Location of Australia's DAC+S capacity.



* The colour intensity of shaded areas and hatching indicates capacity, with darker shades and denser hatching representing high capacity.

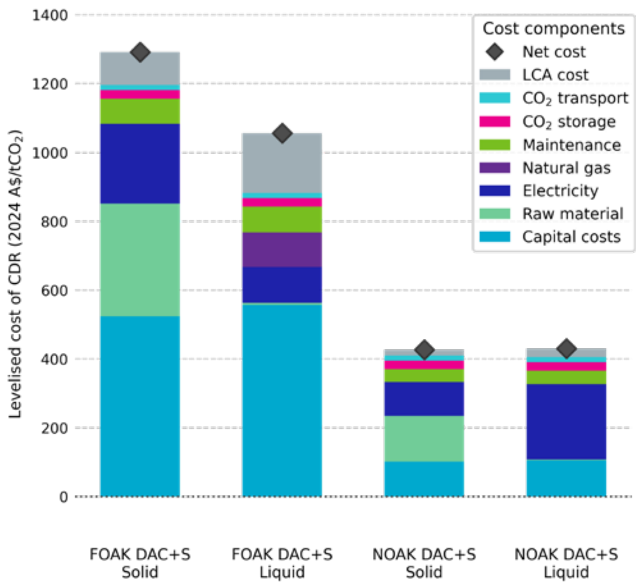
Key capacity considerations:

- *Geological storage* – location within 100 km of geological storage site is assumed, no long-distance CO_2 pipelines.
- *Renewable energy* – only locally generated VRE is assumed, no long-distance electricity transmission.
- *Energy efficiency of DAC processes* – significant uncertainty exists and directly affects capacity modelling.

Key cost considerations:

- *Capital cost of DAC+S facility* is a significant cost driver, especially when considering flexible operation of DAC+S to suit VRE generation.
- *Raw material costs* – adsorbent costs for solid adsorbent DAC are significant and uncertain.
- *Energy requirements and costs* – electrical and heat energy.

Figure 37: Levelised cost of DAC+S.



9.1 Overview

This section presents the results of cost and capacity modelling for DAC+S, focusing on solid adsorbent and liquid absorbent DAC processes (highlighted in grey in Figure 38). Using the methodology described in Section 8.1, it estimates Australia's annual realisable capacity for DAC+S and the cost per tonne of CO_2 removed. It explores the key constraints, regional opportunities, and levers that could influence deployment at scale.

9.2 Australian capacity and costs for DAC+S

Based on this Roadmap's analysis, Australia could have the capacity to capture and store up to 216 $MtCO_2$/y in 2050 through solid adsorbent DAC processes paired with geological storage, with a projected cost in 2050 from A$400 to A$480 per tCO_2 captured for a NOAK project.

Results of realisable capacity and cost modelling for DAC+S in Australia are shown in Figure 39. These results are for a solid adsorbent DAC process; however, analysis has also been carried out on a liquid absorbent process, resulting in a similar regional distribution.

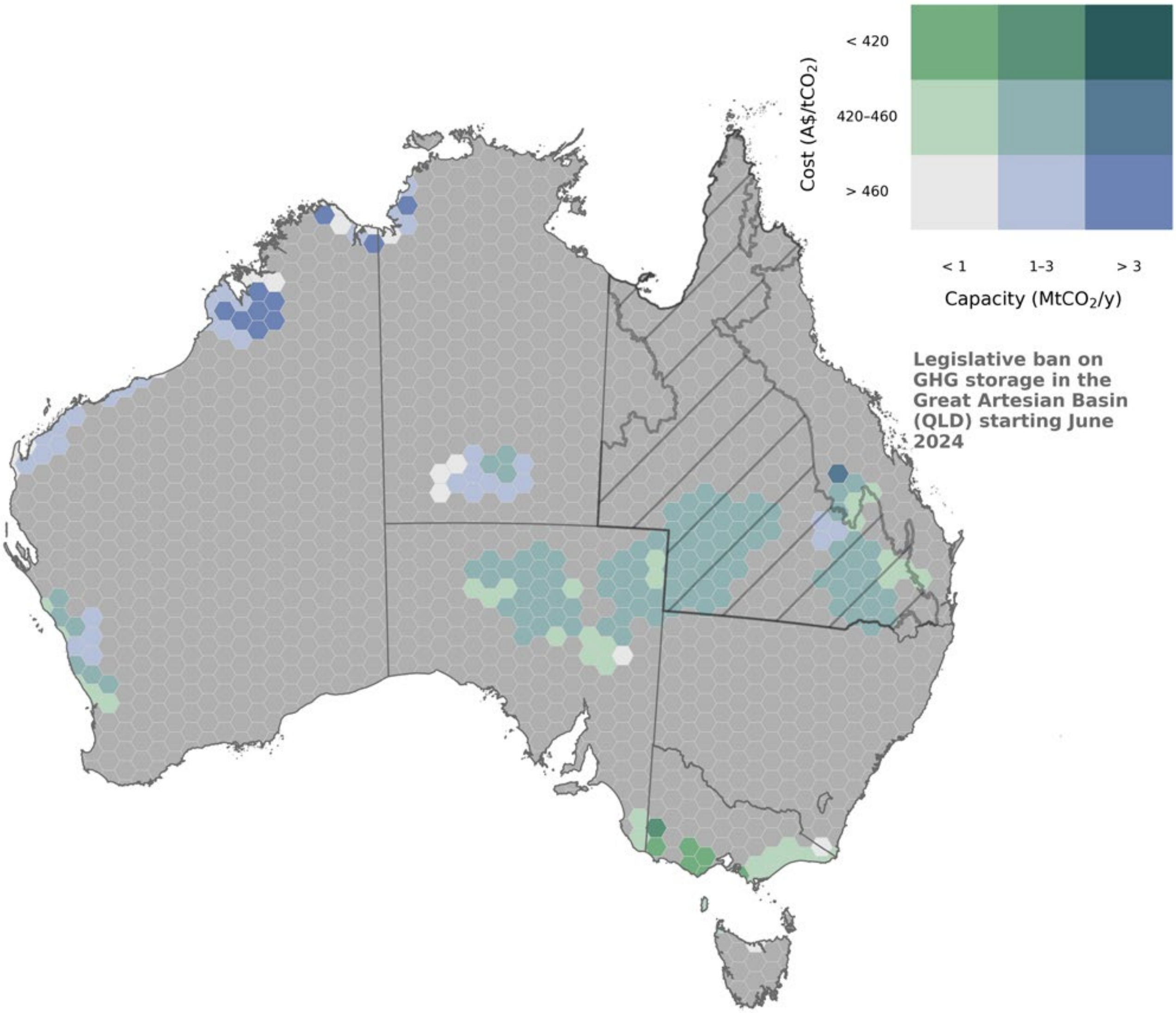
Realisable DAC+S capacity was identified across WA, the NT, SA, Queensland[303] and Victoria. This assessment is based on the assumed co-location with geological storage sites and use of locally generated renewable electricity as described in Section 8.3.

Figure 38: Two DAC+S approaches are examined in this section of the cost and capacity analysis; solid adsorbent and liquid absorbent DAC+S.

CO_2 CAPTURE	CO_2 STORAGE				
	Geological storage		Mineral storage	Open environments	
Biologically captured during biomass growth	BiCR+S – fast pyrolysis to H_2 (geological storage) >1,000 years	BiCR+S – combustion (geological storage) >1,000 years	BiCR+S (mineral carbonation) >1,000 years	BiCR+S – slow pyrolysis to biochar 100–1,000 years	Conventional CDR 10–100 years
Geochemically bound in minerals				ERW >1,000 years	OAE >1,000 years
Chemically captured as gas	DAC+S (geological storage) >1,000 years		DAC+S (mineral carbonation) >1,000 years		

303 While shown on Figure 39, the DAC+S capacity that requires geological storage in Queensland is not included in the realisable capacity estimate, due to the current ban on GHG storage activities in the Great Artesian Basin (Box 8). If this capacity were included, Australia's realisable capacity for DAC+S would increase by approximately 50%.

Figure 39: 2050 cost and capacity assessment for solid adsorbent DAC+S; Darker shades of blue indicate higher capacity, while darker shades of green denote lower costs.



The capacity and levelised cost estimates both vary significantly across regions, driven by the regional cost and capacity inputs described in Section 8.3.

Areas with high-capacity estimates will typically have large areas of available land for renewable energy generation, increasing the amount of solar and wind generation that could be installed. These areas are also likely to have high solar and wind generation potential, meaning the installed generation capacity will generate energy more effectively.

Low levelised costs are driven by cheap, highly firmed renewable energy generation potential, enabling high DAC+S facility utilisation. Renewable electricity is a key input into the CO_2 capture process, meaning the cost of this electricity has a significant impact on overall CDR costs. Areas with higher solar and wind capacity factors and greater diversity will have lower electricity costs.

Areas with low levelised costs will also typically have low regional cost factors, reflecting the likelihood that construction of DAC+S facilities near urban or industrial centres will result in lower construction and operational expenses compared to construction in remote areas with limited infrastructure and access to labour.

Figure 39 highlights regional cost and capacity insights that can be used to inform scale-up and demonstration projects. For example, Victoria was found to have lower DAC+S capacity (due to limited land availability for wind and solar PV) in comparison to WA. However, its lower construction costs relative to more remote regions lead to lower levelised costs, indicating that it could be a suitable location for pilot or demonstration projects with lower DAC+S capacities when co-located with supporting CO_2 transport and storage infrastructure.

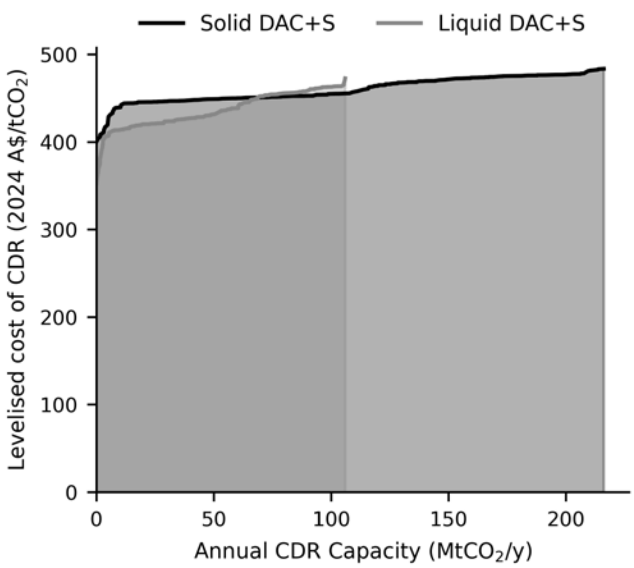
Another key insight from this analysis is that only a small portion of the available geological storage capacity is utilised in the estimated realisable annual DAC+S capacity. For example, estimates for the storage capacity of the Petrel Sub-basin (offshore NT) are in the order of gigatonnes (6.48 Gt of CO_2[304] and 15.9 Gt of CO_2[305]), whereas the estimated realisable annual capacity in this region is in the order of megatonnes per year. This suggests that annual CDR capacity is likely to be constrained by energy availability and land use considerations rather than geological storage capacity.

Box 8: Queensland's ban on GHG storage activities in the Great Artesian Basin.

In 2024, Queensland Government introduced the Mineral and Energy Resources and Other Legislation Amendment Act 2024,[306] banning all GHG storage and enhanced petroleum recovery activities in the Great Artesian Basin. In particular, any approved or pending permits and applications in the Great Artesian Basin under the Greenhouse Gas Storage Act 2009, the Petroleum Act 1923, the Petroleum and Gas (Production and Safety) Act 2004 and the Environmental Protection Act 1994 are to be withdrawn or rescinded. Future exploration activities in this Basin are also prohibited, however activities outside this Basin may still be considered, subject to existing regulatory assessment and approval processes.[307] Given the relative size of the Great Artesian Basin, the scope for CCS, as well as realisable and theoretical capacity for CDR, within Queensland is significantly reduced and subjected to high uncertainty.

As described in Section 8.1, the cost and capacity analysis has been combined into a supply curve for DAC+S in Australia, shown in Figure 40. This supply curve shows the realisable capacity for solid adsorbent DAC+S (216 $MtCO_2$/y) and liquid absorbent DAC+S (106 $MtCO_2$/y). Both estimates exclude capacity that requires geological storage in Queensland (see Box 8). The lower capacity of the liquid absorbent approach is driven by its higher energy requirement per tonne of CO_2 captured. This is an area of active RD&D, see Section 13 for further discussion. The variation is levelised cost is primarily driven by regional variation in renewable electricity costs and construction costs (through location cost factors).

Figure 40: Supply curve for DAC+S using solid adsorbents and liquid absorbents (excluding Queensland) in 2050.



304 Northern Territory Government (2024) Carbon Capture Utilisation and Storage. <https://territorygas.nt.gov.au/projects/carbon-capture-utilisation-and-storage>.

305 Consoli C, Nguyen V, Morris R, Lescinsky D, Khider K, Jorgensen D and Higgins KL (2014) Regional assessment of the CO_2 storage potential of the Mesozoic succession in the Petrel Sub-basin, Northern Territory, Australia: summary report. Geoscience Australia.

306 Queensland Government (2024) Mineral and Energy Resources and Other Legislation Amendment Act 2024, Act No. 33 of 2024. <https://www.legislation.qld.gov.au/view/pdf/asmade/act-2024-033>.

307 Department of Natural Resources and Mines, Manufacturing and Regional and Rural Development (2025) Greenhouse gas storage in Queensland. <https://www.nrmmrrd.qld.gov.au/mining-exploration/initiatives/greenhouse-gas-storage-in-queensland>.

9.3 Levers to influence CDR cost

Capital costs, raw material (adsorbent) costs, electricity costs and the decarbonisation of heat energy represent the key areas for cost reductions between FOAK and NOAK projects.

The modelled levelised costs of solid adsorbent and liquid absorbent DAC+S are shown in Figure 41. Costs for both FOAK and NOAK projects highlight the potential for cost reductions through RD&D.

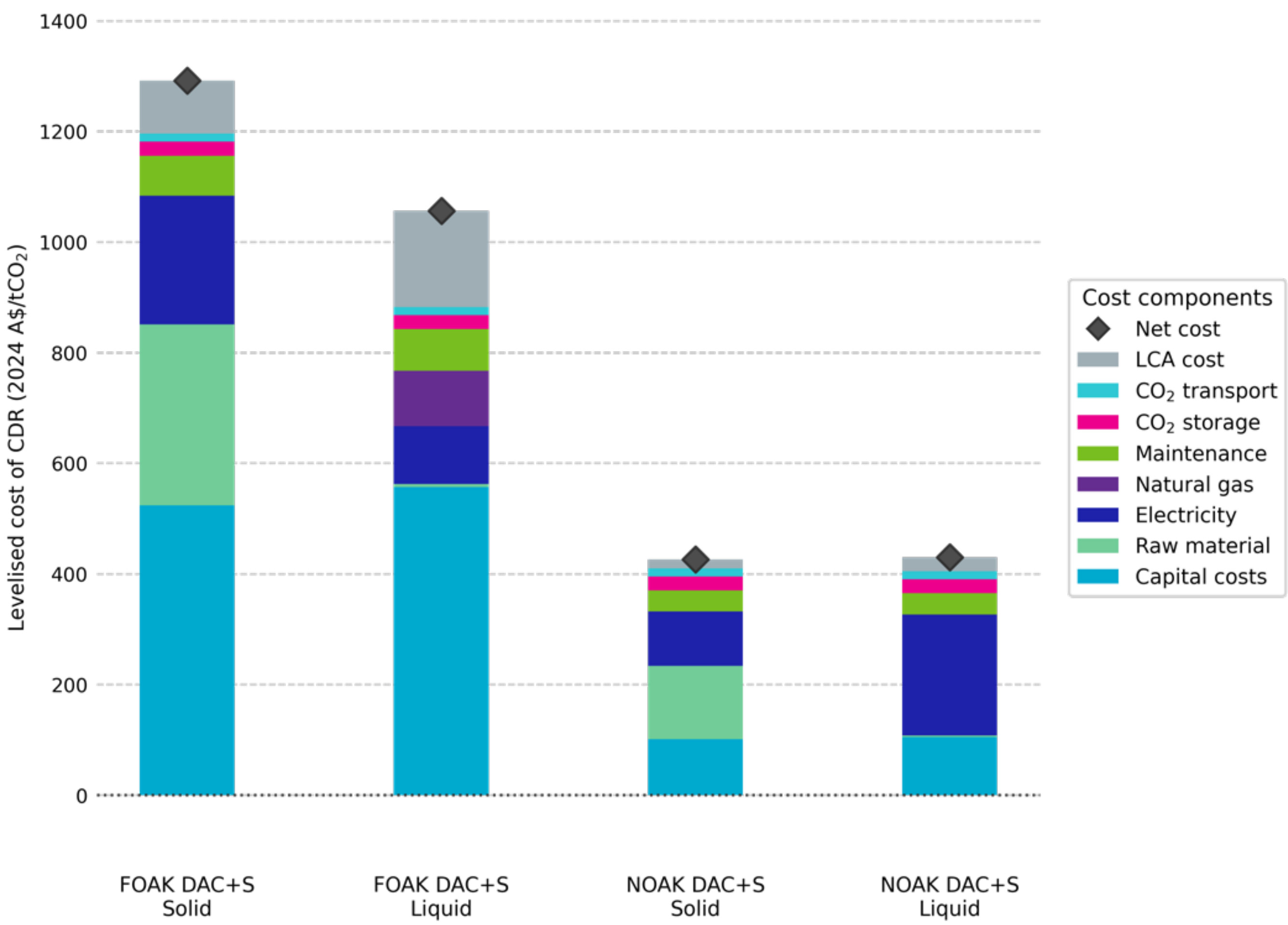
The inputs and assumptions underlying these levelised costs are provided in the *Australian CDR Roadmap – Modelling Appendix*. The costs reflect one possible combination of inputs, but as explained in Section 8: Analytical scope and methodology, a number of inputs are varied in the regional analysis to understand the potential variation in cost across different regions. This variation explains the difference in cost results between Figure 40 and Figure 41.

9.3.1 Capital costs

Capital cost of solid adsorbent DAC+S projects may be reduced through RD&D in modular facility designs, taking advantage of lower build costs through mass production and learning by doing effects. These designs can also improve the cost effectiveness of pilot scale solid adsorbent DAC+S projects relative to most liquid absorbent DAC+S projects, which are typically less modular. The capital cost per tonne of CO_2 removed (the levelised capital cost) can also be reduced by increasing the design life of the facility, allowing it to capture more CO_2 over its operational life, and by securing lower costs of capital for mature, lower risk projects.

Liquid absorbent facilities also have significant potential for capital cost reductions. This is primarily driven by learning-by-doing effects as more facilities are built, and cost reductions are realised in design and construction. Increased project lifetimes and reduced cost of capital also contribute to a lower levelised capital cost.

Figure 41: Levelised cost of CDR for solid adsorbent and liquid absorbent DAC+S.



9.3.2 Raw material (adsorbent) costs

Adsorbent cost and performance improvements can lead to significant levelised cost reductions for solid adsorbent DAC+S. Reductions can be achieved by lowering adsorbent production costs through large-scale manufacturing, increasing adsorbent lifetime to reduce the adsorbent make-up requirement per tonne of CO_2 captured, and by reducing sorbent regeneration energy requirements.

9.3.3 Electricity costs

Levelised electricity costs can be reduced in multiple ways. Consideration of different electricity generation and storage technologies, or sources of waste heat, may result in lower costs. As explained in Section 8.3.2, only solar, wind and battery energy storage systems have been considered in this analysis. Making use of other generation technologies, or waste heat, could reduce electricity costs.

As discussed in Section 8.3.2, there is a trade-off between electricity cost and firming level. Highly firmed electricity allows DAC+S facilities to operate for a greater proportion of time, meaning they can remove more CO_2 each year and achieve lower levelised capital costs. The results in Figure 41 reflect 90% utilisation, while those in Figure 39 and Figure 40 optimise utilisation to achieve the lowest possible levelised cost based on regional electricity and capital costs.

It is also possible that optimisation of DAC+S facility operation (e.g. via sequencing of regeneration cycles or use of electrical/thermal energy storage) could improve costs and the viability of variable renewable electricity use.

9.3.4 Conversion to zero emissions energy source

The liquid absorbent DAC process modelled in this analysis requires high temperature heat to regenerate the absorbent. The FOAK facility is modelled to use natural gas combustion as the source of high temperature heat. While direct emissions from this gas combustion are captured, the upstream emissions due to natural gas production (e.g. methane leakage) must be accounted for.

The net cost shown in Figure 41 adjusts the levelised cost to account for these upstream natural gas emissions and other life cycle emissions. By comparison, the NOAK facility uses renewable electricity as a source of high temperature heat. Its net cost is significantly closer to its levelised cost largely due to the absence of upstream natural gas emissions. However, in the NOAK scenario, an electric-only DAC process would require high temperature electric kilns, which are not currently commercially viable. RD&D will be required to advance the development of high temperature electric kilns to reduce the levelised costs of CDR in the NOAK scenario.

9.4 Levers to influence CDR capacity

Assumptions related to geological storage, and the availability and cost of energy and land, are key levers to expanding the capacity of DAC+S beyond the projected realisable capacity in 2050.

Australia's realisable DAC+S capacity and costs are closely interconnected. In particular, improved classification of geological storage resources, the use of electricity and CO_2 transmission to open up new project locations, optimisation of DAC+S facility operation and improved efficiency through RD&D can significantly increase the feasible scale of deployment. As previously noted, however, not all DAC+S capacity should be pursued, given the trade-offs involved.

This section explores the key levers that could influence DAC+S capacity in Australia, helping to inform more strategic and efficient deployment pathways.

9.4.1 Geological storage

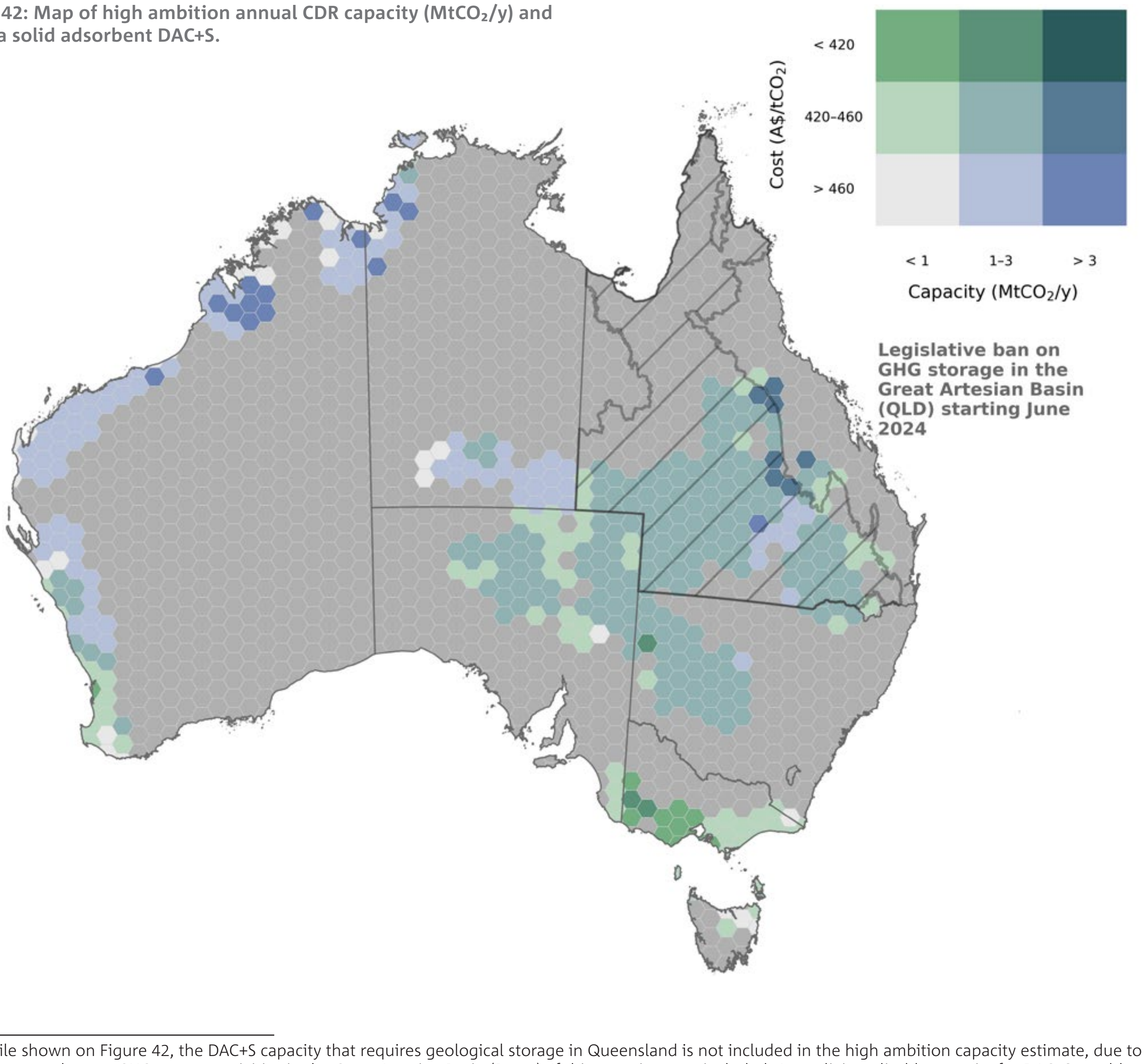
Development of geological storage sites and supporting infrastructure could significantly expand DAC+S capacity in the future, with a high ambition estimate of over 453 $MtCO_2$/y of CDR in 2050.

As stated, the realisable DAC+S potential assumes the use of geological storage sites that are either currently operational for CCS projects or have been proven and developed to a stage nearing commercial viability (commercial geological storage capacity). It is expected that, in the future, new geological storage sites and supporting infrastructure based in areas with prospective geological CO_2 storage could be established and matured for CDR purposes, increasing the overall capacity for DAC+S (Figure 42).

To explore this assumption, a high ambition capacity estimate was created by considering the areas associated with prospective geological CO_2 storage basins (see Section 8.3.4).

The inclusion of prospective storage resources, as opposed to expected commercial geological storage capacity assumptions, resulted in a modelled capacity of over 453 $MtCO_2$/y from solid adsorbent DAC+S with significant new opportunities for DAC+S in NSW and Tasmania, and increased potential in other states.[308]

Figure 42: Map of high ambition annual CDR capacity ($MtCO_2$/y) and cost via solid adsorbent DAC+S.



308 While shown on Figure 42, the DAC+S capacity that requires geological storage in Queensland is not included in the high ambition capacity estimate, due to the current ban on GHG storage activities in the Great Artesian Basin (Box 8). If this capacity were included, Australia's realisable capacity for DAC+S would increase by approximately 45%.

9.4.2 Energy and land use

Australia's DAC+S capacity could be increased by relaxing current energy and land use assumptions, but doing so would require careful consideration of regional priorities and constraints.

As discussed in Section 8.3, the realisable DAC+S potential is based on conservative assumptions regarding both renewable energy availability and the land required for energy infrastructure to meet the high energy demands of many current DAC processes.

As discussed in Section 8.3.4, only land located within 100 km of geological storage locations has been considered for siting of DAC+S facilities and the associated co-located electricity generation. Relaxing this constraint through either electricity transmission or CO_2 transport infrastructure could significantly increase Australia's capacity for DAC+S. The socially acceptable level of renewable electricity development may also vary regionally and may increase above the levels assumed in this analysis.

It is important to note that DAC+S remains considerably more land-efficient than conventional approaches like afforestation. This capacity analysis finds that DAC+S requires between 50–150 km² of land for renewable energy generation per Mt of CDR annually. By comparison, an environmental plantings project using a similar land area (100 km²) may remove 0.07–0.09 $MtCO_2$/y, noting this rate is very sensitive to the location and type of planting.[309] DAC+S facilities do not rely on arable land and can be located on marginal land or non-productive land, helping reduce pressure on food production and competing land uses.[310] DAC+S facilities offer siting flexibility and can be strategically located near geological storage sites, reducing the need for extensive CO_2 transport infrastructure such as CO_2 pipelines and lowering associated establishment and operational costs.[311]

9.4.3 DAC+S facility utilisation and firming

Expanding VRE firming assumptions to include other technologies or grid integration can impact DAC+S facility costs and utilisation and could improve cost-effectiveness and increase Australia's realisable CDR capacity.

VRE firming plays a critical role in determining the cost-effectiveness and scalability of DAC+S in Australia. As stated in Section 8.3.2, this analysis assumes the use of solar and wind electricity generation, along with battery energy storage systems to ensure a consistent electricity supply. This firming incurs additional costs but is necessary to maintain reliable DAC+S facility operation.

Relaxing current firming assumptions, by diversifying energy sources or integrating with existing grid infrastructure, could therefore unlock greater DAC+S potential and reduce costs. However, doing so requires careful, region-specific analysis to ensure electricity used is in addition to the electricity required for emissions reductions and does not place pressure on electricity prices in regional communities.

9.4.4 Technological RD&D

Modelling highlights the trade-offs between solid adsorbent and liquid absorbent systems, while RD&D into emerging DAC processes could offer a long-term path to greater capacity and lower costs.

The 2050 realisable capacity estimates presented in this Roadmap are based on the solid adsorbent DAC+S pathway. However, modelling also examined the implications of using liquid absorbent DAC+S, revealing that process choice significantly affects both capacity and cost outcomes.

The energy efficiency forecasts used in this analysis are uncertain, with significant RD&D focused on improving the energy efficiency of DAC processes. This can not only increase Australia's capacity for DAC+S (by removing more CO_2 per unit of electricity) but can also reduce the cost of this removal. Emerging DAC processes offer promising opportunities to reduce energy use (see Section 4.1.2).

309 Meat & Livestock Australia (2023) Co-benefit of trees on farm: carbon sequestration. <https://www.mla.com.au/contentassets/114de5c6f64f4e75978346929cc5150e/sequestration-fact-sheet.pdf> (Figure 1 - 6.6 – 8.6tCO_2e/ha/y over 30 years).

310 Carbon Engineering (2020) Pale Blue Dot Energy and Carbon Engineering create partnership to deploy Direct Air Capture in the UK. <https://carbonengineering.com/news-updates/pale-blue-dot-energy-and-carbon-engineering-partnership/>.

311 AKT Engineering (n.d.) Direct air capture – energy system – IEA. <https://aktengineering.com.au/direct-air-capture-energy-system-iea/>.

9.5 Other considerations

Beyond capacity levers and considerations, local climatic conditions and water use are relevant factors to consider when scaling up DAC+S.

9.5.1 Climatic conditions

The local ambient temperature and relative humidity can influence the system performance, water usage and energy requirements of DAC processes and should be considered when deploying DAC+S facilities.[312,313]

For solid adsorbent DAC processes, humidity adds pressure to the regeneration process, avoiding deep vacuum regeneration conditions.[314] High ambient humidity can lead to co-adsorption of water to solid adsorbents in the capturing stage, increasing the CO_2 adsorption capacity of amine-based materials but decreasing for other solid adsorbent materials. High humidity may also lead to an increased energy requirement to remove water from solid adsorbents in the regeneration stage. However, in the case of the amine-based materials using a vacuum steam regeneration process, the adsorbent does not need to be dried during regeneration.[315]

Higher ambient temperatures can accelerate chemical reactions in liquid absorbent DAC processes, potentially increasing the rate of CO_2 absorption into the liquid.[316] However, they can also reduce the liquid absorbent's capacity to hold CO_2, thereby decreasing overall capture efficiency.[317] Hot and low relative humidity conditions accelerate water loss in liquid absorbent DAC processes, requiring large water make-up or capture systems.

This analysis has not considered the impact of climatic conditions on DAC+S performance. This is a key area of focus for future research.

9.5.2 Water use

Based on the IEA's 2021 Global Assessment of Direct Air Capture Costs report,[318] the modelling conducted assumes that a FOAK DAC+S facility would require between 1.6 m^3 (solid adsorbent) or 2–4 m^3 (liquid absorbent) of water per tCO_2. Modelling currently assumes that the water requirement will reduce over time with NOAK facilities requiring between 1–2 m^3 of water per tCO_2. The difference in water requirements could be partially due to the sensitivity of liquid absorbent processes to both ambient temperature and relative humidity, as opposed to solid adsorbent processes which are predominantly sensitive to relative humidity.

While the assumptions and discussion offer a high-level understanding of the impact of climatic factors on DAC processes and their associated water requirements, real-world climate interactions are far more complex and vary significantly by location. Therefore, further RD&D, such as developing innovative sorbent materials, especially solid adsorbents, and trialling DAC+S across a range of geographic and climatic conditions, may be necessary to identify optimal temperature and humidity ranges for efficient operation. The water requirements of DAC+S facilities is an important consideration when deploying projects at arid locations with limited water availability, potentially requiring choosing an appropriate capture process, optimising the process design, implementing water management strategies and balancing with the water demand and use from other sectors.[319] Examples of effective water management strategies include using hygroscopic solutions which naturally absorb or adsorb moisture from the surrounding environment, and integrating water capture systems into solid adsorbent DAC+S processes, which not only reduces water requirements but also creates favourable conditions (i.e. pressurised and non-vacuum) for the regeneration stage.[320]

312 An K, Farooqui A, McCoy ST (2022) The impact of climate on solvent-based direct air capture systems. Applied Energy 325(119895), 1–14. <https://doi.org/10.1016/j.apenergy.2022.119895>.

313 Pett-Ridge et al. (2023) Roads to removal: options for carbon dioxide removal in the United States. Lawrence Livermore National Laboratory. <https://www.osti.gov/biblio/2301853>.

314 Stakeholder consultation.

315 Pett-Ridge et al. (2023) Roads to removal: options for carbon dioxide removal in the United States. Lawrence Livermore National Laboratory. <https://www.osti.gov/biblio/2301853>.

316 Shorey P, Abdulla A (2024) Liquid solvent direct air capture's cost and carbon dioxide removal vary with ambient environmental conditions. Communications Earth & Environment 5(607), 1–12. <https://doi.org/10.1038/s43247-024-01773-1>.

317 Gul A, Tezcan Un U (2022) Effect of temperature and gas flow rate on CO_2 capture. European Journal of Sustainable Development Research 6(2), em0181. <https://doi.org/10.21601/ejosdr/11727>.

318 IEAGHG (2021) Global assessment of direct air capture costs. Technical Report 2021-05, December 2021. <https://publications.ieaghg.org/technicalreports/2021-05%20Global%20Assessment%20of%20Direct%20Air%20Capture%20Costs.pdf>.

319 https://www.nature.com/articles/s44286-024-00032-6

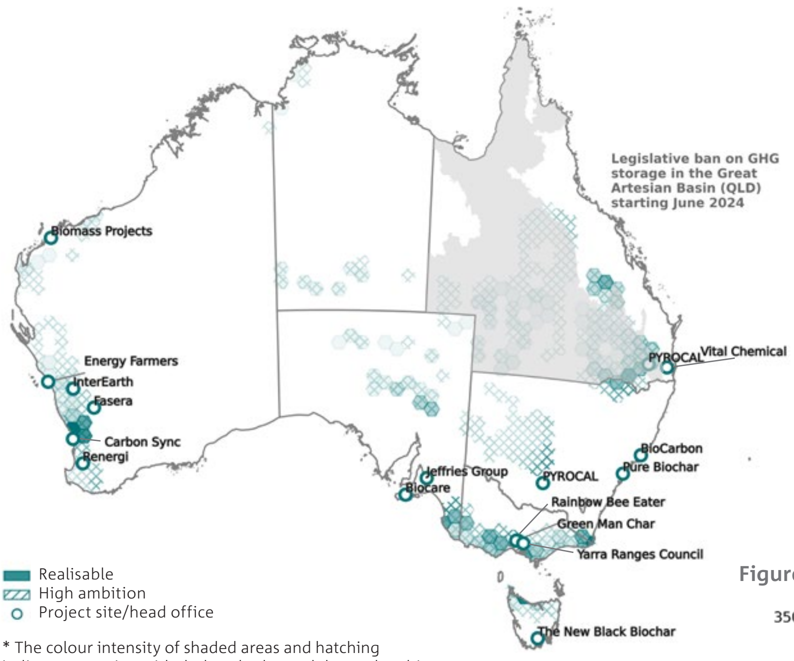
320 Stakeholder consultation

10 Biomass carbon removal + storage (BiCR+S)

Based on this Roadmap's analysis and depending on the BiCR+S approaches considered, Australia could have the capacity to capture and store up to 88 $MtCO_2$/y in 2050. The projected 2050 cost for an Nth-of-a kind project ranges from A$140–260 per tCO_2.

Biomass carbon removal and storage (BiCR+S) include approaches that transform biomass carbon into long-lived products such as biochar, or capture high-purity CO_2 from biomass carbon conversion for geological and mineral storage while producing energy or other co-products. BiCR describes thermochemical or biological processes that convert biomass carbon into forms that can be durably stored. This Roadmap focuses on fast pyrolysis to H_2 and combustion to electricity (TRL 6–9) to capture high-purity CO_2. However, it is recognised that many other emerging and alternative BiCR processes are under development, such as gasification, hydrothermal liquefaction and biological processes. Similarly, while this Roadmap only considers geological storage to assess Australia's BiCR+S potential, other storage options such as mineral storage could be viable with further RD&D.

Figure 43: Location of Australia's realisable BiCR+S capacity.



* The colour intensity of shaded areas and hatching indicates capacity, with darker shades and denser hatching representing high capacity.

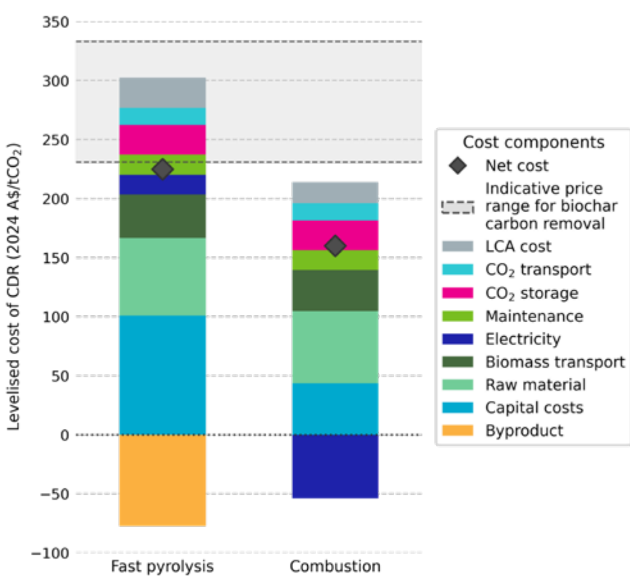
Key capacity considerations:

- *Biomass availability* represents a key constraint on realisable BiCR+S capacity.
- *New geological storage sites and infrastructure* could enable an additional 25 Mt/y of CDR via BiCR+S in 2050.
- *Transport infrastructure* could expand BiCR+S facility catchment areas, increasing capacity.

Key cost considerations:

- *Raw material (biomass) costs* are sensitive to feedstock pricing and require consideration of feedstock trade-offs on a case-by-case basis.
- *The cost of biomass transport* is a major cost factor – and it varies significantly depending on the type of feedstock and its proximity to a biorefinery.
- *Byproduct sales* – specifically H_2 (pyrolysis) and electricity (combustion) can offset levelised costs.

Figure 44: Levelised cost of BiCR+S in 2050 (NOAK scenario).



10.1 Overview

This section presents the results of cost and capacity modelling for BiCR+S, focusing on fast pyrolysis to H_2 and combustion to electricity processes and geological storage (highlighted in teal in Figure 45). Using the methodology from Seciton 8, it estimates Australia's annual realisable capacity using BiCR+S and the cost per tonne of CO_2 removed. It explores the key constraints, regional opportunities, and levers that could influence deployment at scale.

10.2 Australian capacity and costs for BiCR+S

Based on this Roadmap's analysis and depending on the BiCR+S approach considered, Australia could have the capacity to capture and store up to 88 $MtCO_2$/y in 2050. The projected 2050 cost for a NOAK facility ranges from A$140 to A$260 per tCO_2.

Results of the realisable capacity and cost modelling for BiCR+S in Australia in 2050 are shown in Figure 46. These results consider the combustion to electricity BiCR+S approach; however, analysis has also been carried out on the fast pyrolysis to H_2 BiCR+S approach, resulting in a similar regional distribution.

While a conservative estimate, these BiCR+S approaches could account for approximately 20% of Australia's current (2025) annual CO_2 emissions.[321] Realisable potential was identified across WA, the NT, SA, Victoria, Tasmania and Queensland[322] (see Figure 46). This assessment is based on the assumed co-location with geological storage sites and proximity of suitable feedstocks as described in Section 8.3.4 and 8.3.6 respectively.

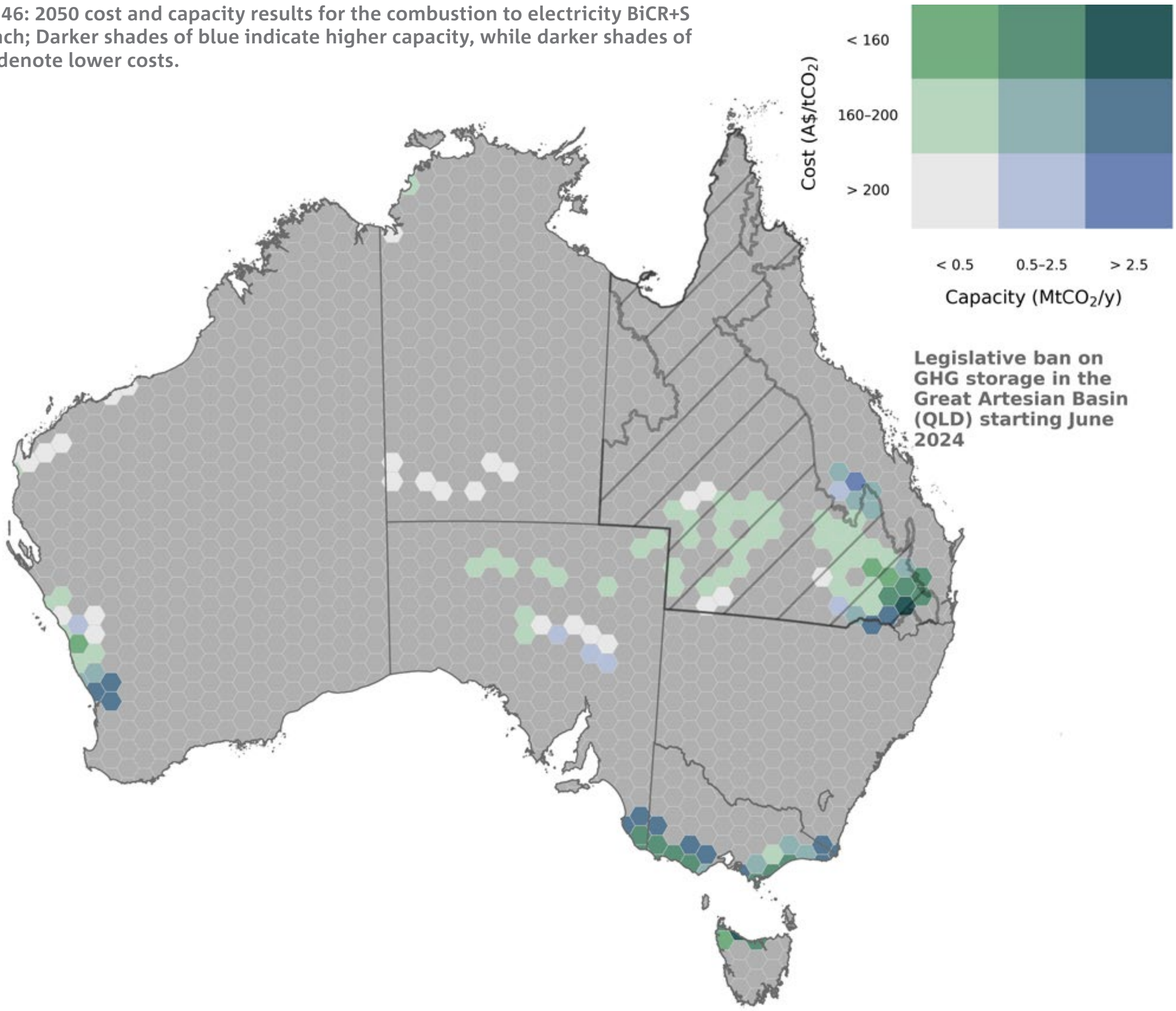
Figure 45: Two BiCR+S approaches are examined in this section of the cost and capacity analysis; Fast pyrolysis to H_2 and Combustion to electricity.

CO_2 CAPTURE	CO_2 STORAGE				
	Geological storage		Mineral storage	Open environments	
Biologically captured during biomass growth	BiCR+S – fast pyrolysis to H_2 (geological storage) >1,000 years	BiCR+S – combustion (geological storage) >1,000 years	BiCR+S (mineral carbonation) >1,000 years	BiCR+S – slow pyrolysis to biochar 100–1,000 years	Conventional CDR 10–100 years
Geochemically bound in minerals				ERW >1,000 years	OAE >1,000 years
Chemically captured as gas	DAC+S (geological storage) >1,000 years		DAC+S (mineral carbonation) >1,000 years		

321 Australia's total CO_2 emissions data is sourced from Department of Climate Change, Energy, the Environment and Water (2025) Quarterly update of Australia's National Greenhouse Gas Inventory: December 2024. <https://www.dcceew.gov.au/sites/default/files/documents/nggi-quarterly-update-december-2024.pdf>.

322 While shown on Figure 46, this estimate excludes the realisable capacity that requires geological storage in Queensland, due to the current ban on GHG storage activities in the Great Artesian Basin (Box 8). If this capacity were included, Australia's realisable capacity for BiCR+S would increase by approximately 33%.

Figure 46: 2050 cost and capacity results for the combustion to electricity BiCR+S approach; Darker shades of blue indicate higher capacity, while darker shades of green denote lower costs.



The capacity and levelised cost estimates both vary significantly across regions, driven by the regional cost and capacity inputs described in Section 8.3.

Areas with high capacity and low cost estimates will typically have access to a large quantity of feedstock within a cost-effective transport distance. A maximum transport cost per tonne of feedstock is applied as described in Section 8.3.9, a trade-off between maximising capacity and minimising cost.

Figure 46 highlights regional cost and capacity insights that can be used to inform scale-up and demonstration projects. For example, locations in WA, SA, Victoria and Queensland combine high capacity and low cost, indicating they may be suitable locations for demonstration projects with potential for future scale up.

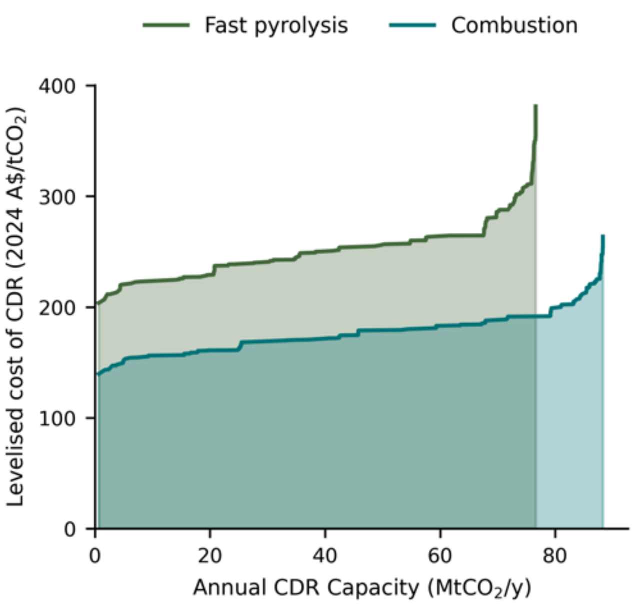
Another key insight from this analysis is that only a small portion of the available geological storage capacity is utilised in the estimated realisable annual BiCR+S capacity. This suggests that annual CDR capacity is likely to be constrained by feedstock availability rather than geological storage capacity.

As described in Section 8.1, the cost and capacity analysis has been combined into a supply curve for BiCR+S in Australia. The levelised cost of deploying BiCR+S to achieve the identified realisable capacity by 2050 varies across regions. Figure 47 presents the cumulative annual capacity of BiCR+S for fast pyrolysis to H_2 and combustion to electricity, with this capacity sorted in order of increasing cost.

Cost differences in Figure 47 are driven by the inputs described in Section 8.3. Levelised cost of CDR via combustion to electricity is modelled to be lower than for fast pyrolysis to H_2. This is due to the lower capital costs of the combustion to electricity process, but also the assumed market price of coproducts (i.e. electricity for combustion to electricity, and H_2 for fast pyrolysis to H_2), which reduces the net cost of CDR. See Section 10.3 for a breakdown of the cost components of each process, and Section 10.3.3 for a discussion on byproduct revenue.

The cost of biomass transport is the primary driver of cost variation within each process. The sharp increase in levelised cost at higher capacity levels observed in Figure 47 is due to significantly longer transport distances in locations that do not have nearby biomass supply. This result suggests that it may not be economically viable to transport all biomass resources to potential biorefinery sites that are co-located with geological storage, noting the limitations of this analysis.

Figure 47: Supply curve for two BiCR+S approaches in 2050.



10.3 Levers to influence CDR cost

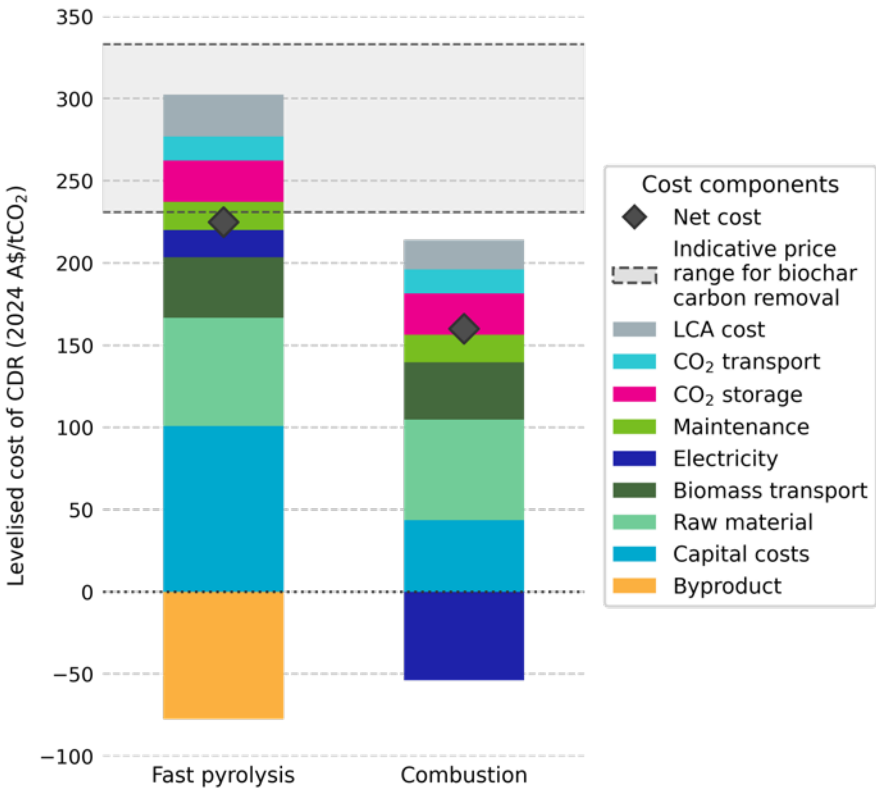
Raw material costs (the biomass farmgate price), biomass transport costs, and by product revenue represent the key levers to influence the levelised cost of BiCR+S CDR.

The modelled levelised costs of two BiCR+S approaches; fast pyrolysis to H_2 and combustion to electricity are shown in Figure 48. Given their technical maturity, the results are focused on NOAK facilities constructed in 2050. As shown in Figure 48, the shaded band represents the indicative price range for biochar carbon removal credits, used as a proxy for FOAK projects. Importantly, although NOAK results are presented for 2050, these BiCR+S facilities could be deployed earlier than this. FOAK BiCR+S projects are likely to carry a cost premium, but given the relative maturity of these processes this is not expected to be as significant as the FOAK cost premiums modelled for OAE or DAC+S.

The inputs and assumptions underlying these levelised costs are provided in the *Australian CDR Roadmap – Modelling Appendix*. The net levelised costs range from A$231 to A$333 per tCO_2 and are below the average current market price for high quality biochar production via slow pyrolysis.[323] The costs reflect one input scenario, but as explained in Section 8.1 inputs have been varied in the regional analysis to understand cost differences across regions. This variation explains the difference in cost results between Figure 47 and Figure 48.

323 Supercritical (2024) Boom or bust? 2024 Biochar Market Outlook.

Figure 48: BiCR+S levelised cost of CDR in 2050 (NOAK Scenario).[324]



10.3.1 Raw material (biomass) costs

BiCR processes rely on biomass feedstocks. They must cover the cost of biomass collection and compete with other potential end uses of this feedstock.

This analysis assumes a farmgate biomass price of A$70 per tonne, reflecting harvesting and opportunity costs to the landowner or producer. In practice, biomass prices will depend on supply and demand across the bioeconomy. Choices between end uses (of which BiCR+S is one of many) will be shaped by market demand, policy incentives, and local conditions.

An overview of the types of biomass considered in this Roadmap is provided in Section 8.3.6. Utilising agricultural biomass such as crop residues, bagasse and grasses can generate additional revenue for farmers, especially where residues would otherwise incur disposal costs. However, redirecting agricultural biomass for BiCR processes could reduce the amount of biomass (especially bagasse) available for other existing uses, such as electricity generation. Incentivising the collection of forest residues for use in BiCR processes can bring a co-benefit of improved fire management. A proposed tax credit[325] in the US seeks to maximise this co-benefit while also encouraging investment in BiCR+S projects. The benefits of using MSW include the covered costs of collection and the environmental and economic benefits of landfill diversion (e.g. methane reduction). Finally, carbon crops such as short rotation trees represent a potential economic activity for marginal land but may compete with other land uses including agriculture.

324 The indicative price range for biochar spans the average current market prices of low-quality and high-quality biochar removal credits sourced from: Supercritical (2024) Boom or bust? 2024 Biochar Market Outlook.

325 U.S. Senate Committee on Environment and Public Works (2025) The Wildfire Reduction and Carbon Removal Act of 2025 – One-pager. <https://www.epw.senate.gov/public/_cache/files/c/1/c1d5d5a9-e09a-434e-a671-8bcab5c347a6/402F228798C6323275305CE5538ADDCD56C1D8C7A825D7155523DA2EF80EBFFD.wildfire-reduction-and-carbon-removal-one-pager.pdf>.

10.3.2 Biomass transport costs

Transportation of biomass to a biorefinery is a major cost factor in BiCR+S approaches. It varies significantly depending on the type of biomass feedstock and its proximity to a biorefinery.

The levelised cost analysis presented in Figure 48 applies a static transport cost of A$40 per tonne for biomass movement. However, the impact of transportation costs is more apparent in the capacity analysis, which adopts a regional perspective. Estimated transport costs are based on the distance between Australian biomass feedstock sources and a potential BiCR+S facility co-located with geological storage (see Section 8.3).

There are a variety of opportunities to optimise transport costs. For example, the current analysis assumes the transport of wet biomass, with drying occurring at the BiCR+S facility; however, transport costs could be reduced by drying and pelletising the biomass closer to the source, which can also prevent rapid degradation of certain feedstocks like bagasse.

The mode of transport can be optimised depending on the volume of biomass and distance of travel. For example, trucks can be used to transport small volumes of biomass over short to medium distances, while rail or shipping can be more cost-effective for larger volumes over longer distances (see *Australian CDR Roadmap – Modelling Appendix*). Using zero emissions transport vehicles could lead to reductions in net emissions and improvements in energy efficiency and net cost.

10.3.3 Byproduct revenue

Byproducts can generate significant revenue and influence the overall levelised cost of CDR via BiCR+S.

In this analysis, byproduct sales are treated as a negative cost and subtracted from the total levelised cost of CDR. For simplicity, the analysis aims to maximise carbon removal. It assumes H_2 (sold at A$3.43/kg) as the byproduct of the pyrolysis processes and electricity (sold at A$97/MWh) as the byproduct of combustion, excluding any additional incentives such as the Hydrogen Production Tax Incentive. The relative levelised costs of the modelled BiCR+S facilities are sensitive to these assumptions, with the demand (and market price) for electricity, H_2 and other byproducts in the vicinity of a potential BiCR+S site likely to influence pathway selection.

The flexibility of the analysed thermochemical processes is particularly important in the energy domain as the different byproducts create potential trade-offs in revenue and emission reduction potential. For example, hard-to-abate sectors with limited low-emissions technology options may value emissions reductions via the generation of low-carbon fuels or chemicals (leveraging the carbon content of the biomass feedstock) over maximising H_2 and CO_2 production purely for CDR purposes.

In terms of costs, this affects not only the potential revenue from byproducts but also has implications for biorefinery capital investment. For instance, instead of developing a dedicated biorefinery optimised for carbon removal and co-located with geological storage, a proponent might opt to integrate BiCR processes into an existing biofuel refinery, where CO_2 is already emitted and separated as part of the process. This approach could reduce transport costs and significantly lower upfront capital requirements, as demonstrated by commercial examples such as Drax and Toshiba ESS.

10.4 Levers to influence CDR capacity

Assumptions related to feedstock supply, geological storage and transportation are key levers to expand the projected realisable capacity of BiCR+S up to 113 $MtCO_2/y$ potential in 2050.

Australia's realisable BiCR+S capacity and costs are closely interconnected. Reducing the distance between biomass supply and suitable co-located biorefinery and geological storage sites can significantly increase the feasible scale of deployment. As previously noted, however, not all BiCR+S capacity should be pursued, given the trade-offs involved.

This section explores the key levers that could influence BiCR+S capacity, helping inform more strategic and efficient deployment pathways.

10.4.1 Feedstock supply

Australia's capacity to scale BiCR+S will require a deeper understanding of its biogenic feedstocks and greater consideration of trade-offs to optimise its use.

To estimate the potential biomass available for Australia's BiCR+S capacity analysis, data on the annual biomass availability was sourced from existing datasets and derived from prior modelling efforts which can be found in the *Australian CDR Roadmap – Modelling Appendix*.

As previously discussed, using Australia's biogenic feedstocks for BiCR+S has trade-offs. It can displace current biomass use for energy generation or animal feed, and compete for resources with other primary industries in the case of growing new carbon crops.

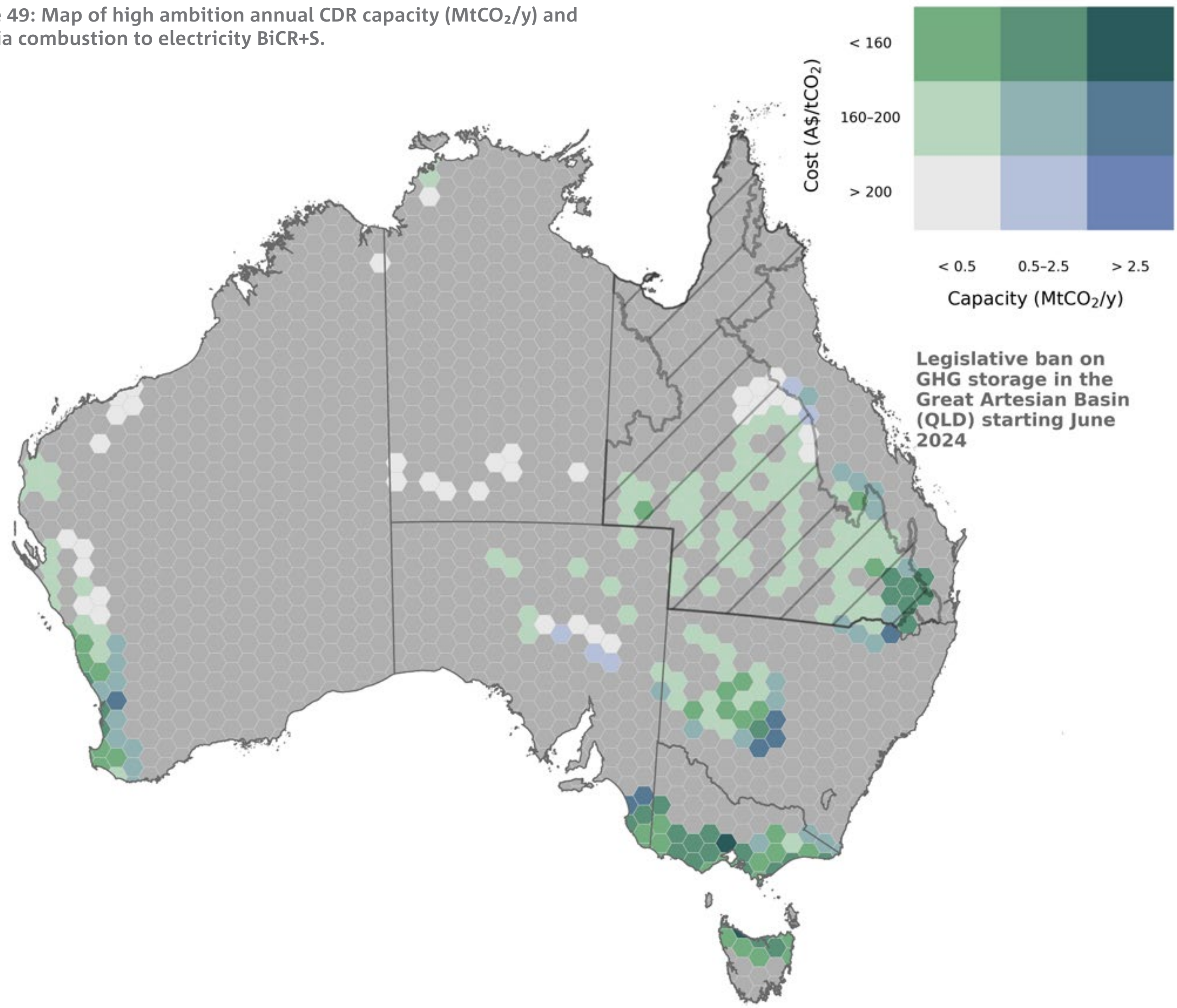
Except for short rotation trees, all biomass sources considered are second generation waste or residue feedstocks, to limit land use competition. Short rotation trees are typically grown on marginal lands rather than competing directly for land with agriculture as is the case for many carbon crops, however land use change impacts remain an important consideration.

10.4.2 Geological storage

Developing geological storage sites and supporting infrastructure could significantly expand BiCR+S capacity in the future, with a high ambition estimate of up to 113 $MtCO_2$/y of CDR in 2050.

As stated, the realisable BiCR+S potential assumes the use of geological CO_2 storage sites that are either currently operational for CCS projects or have been proven and developed to a stage nearing commercial viability (see Section 8.3.4). It is expected that, in the future, new geological CO_2 storage sites and supporting infrastructure based in areas with prospective geological CO_2 storage could be established and matured for CDR purposes, increasing the overall capacity for BiCR+S. To explore this assumption, a high ambition capacity estimate was created by considering the areas associated with prospective geological CO_2 storage basins (see Section 8.3.4).

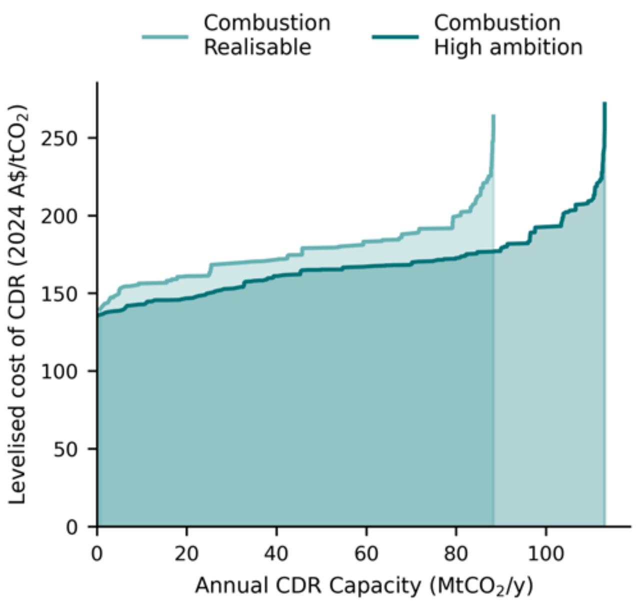
Figure 49: Map of high ambition annual CDR capacity ($MtCO_2$/y) and cost via combustion to electricity BiCR+S.



The inclusion of prospective storage resources, as opposed to expected commercial geological storage capacity assumptions resulted in an increase in the modelled capacity to up to 113 $MtCO_2$/y from BiCR+S (depending on BiCR+S representative approach used), with opportunities opening across Australia (Figure 49). The additional geological storage locations open up more prospective sites for biorefineries, which in turn increases the amount of biomass within a cost-effective transport distance of these sites. There is also a modelled reduction in average cost, as shown in Figure 49, because biomass does not have to be transported as far, on average, to the potential biorefinery sites.

Improving the classification of this storage capacity from prospective to discovered (contingent and commercial storage capacity, see Box 4) will require significant additional geological data collection, including reservoir and seal evaluation, and pilot and demonstration projects and community engagement efforts (see Box 4 for more details). There may also be storage locations in geological basins not shown on this map that are discovered (i.e. become prospective storage resources) through further investigation.[326]

Figure 50: Comparison of 2050 supply curves for combustion to electricity BiCR+S under realisable and high ambition cases.



10.4.3 Transportation infrastructure

Existing transportation networks influence Australia's realisable capacity for BiCR+S.

A complete BiCR+S approach consists of a supply chain connecting biomass sources, a BiCR+S facility and a CO_2 storage location. The longer this supply chain is, the greater the reliance on transport infrastructure. As discussed, this cost and capacity analysis has assumed that BiCR+S facilities are within 100 km of a geological storage site, applying an upper limit on the distance that CO_2 is transported.

This analysis has only considered road transport of biomass, drawing on transport cost data from CSIRO's TraNSIT model. Considering rail and sea transport may increase the realisable capacity of BiCR+S by increasing the cost-effective catchment of a given BiCR+S facility. Australia's realisable capacity could also be increased by using CO_2 pipelines to increase the distance between BiCR+S facilities and CO_2 storage locations. This could open new opportunities for BiCR+S facilities to be sited near large catchments of biomass, potentially increasing capacity. Given the challenges in developing new long-distance pipeline infrastructure, further work is required to explore the potential of this lever.

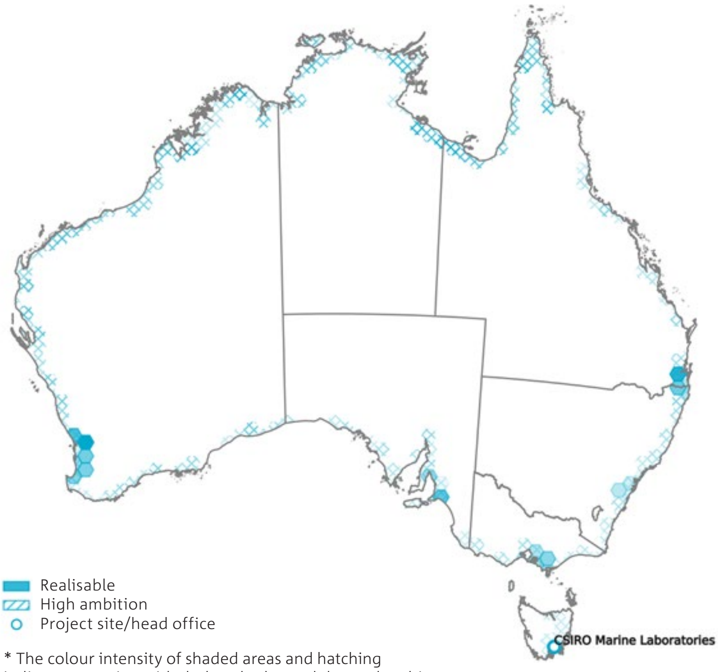
326 Talukder A, Dance T, Michael K, Clennell B, Gee R, Northover S, Stalker L and Ross A (2024). CO_2 , H_2 and compressed air energy storage site screening study – selected onshore basins in the Northern Territory. Northern Territory Geological Survey, Record 2024-005.

11 Ocean alkalinity enhancement (OAE)

Australia may have the potential to remove up to 7 MtCO_2/y in 2050 using OAE facilities co-located with desalination plants. The projected 2050 cost of co-located Nth-of-a-kind plants ranges from A$80–140 per t$CO_2$ removed. For standalone plants, up to 114 MtCO_2/y capacity may be realisable, with projected costs ranging from A$210–390 per t$CO_2$ removed.

Ocean alkalinity enhancement (OAE) approaches utilise the naturally occurring equilibrium reaction between atmospheric CO_2 and seawater by controllably adding a source of alkalinity. This elevates seawater pH and allows additional atmospheric CO_2 to be taken up by the ocean. This Roadmap focuses on the electrolytic OAE approach (TRL 5–8), specifically a closed loop model demonstrated by US based company Equatic; however, it is recognised that other emerging OAE approaches are under development, for example, CO_2 stripping, electrodialytic OAE, and mineral addition OAE.

Figure 51: Location of Australia's realisable OAE capacity.



* The colour intensity of shaded areas and hatching indicates capacity, with darker shades and denser hatching representing high capacity.

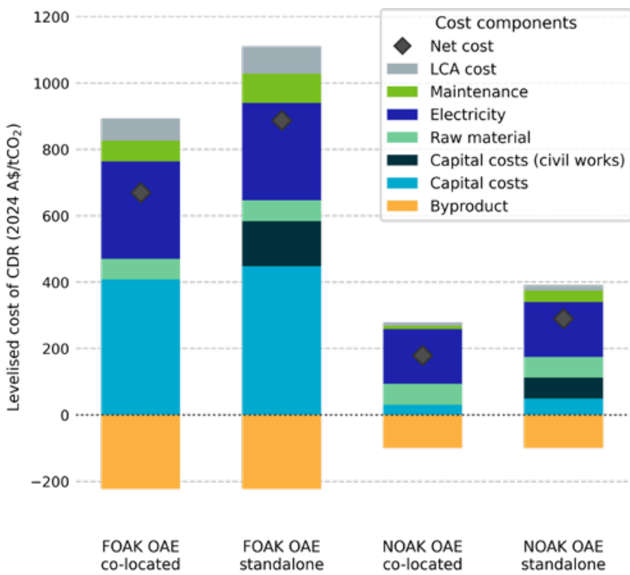
Key capacity considerations:

- *Co-location with existing water infrastructure* – this criterion reduces capacity but also reduces levelised cost.
- *Renewable energy* – only locally generated VRE is assumed, no long-distance electricity transmission.
- *Energy efficiency of electrochemical OAE processes* – opportunity for RD&D in alternative processes and improved electrochemical cells.

Key cost considerations:

- *Capital costs* – Co-locating with existing water infrastructure is a more cost-effective FOAK approach than building standalone OAE facilities, which is likely needed for NOAK plants.
- *Energy requirements and costs* – cost reduction achievable by optimising plant utilisation and electrolyser energy consumption.
- *Byproduct revenue* – H_2 byproduct is a source of revenue which can be used to offset operating costs.

Figure 52: Levelised cost of OAE.



11.1 Overview

This section presents the results of cost and capacity modelling for OAE, focusing on a closed loop electrolytic OAE approach (highlighted in blue in Figure 53). Using the methodology from Section 8, it estimates Australia's annual realisable capacity using OAE and the cost per tonne of CO_2 removed. It explores the key constraints, regional opportunities, and levers that could influence deployment at scale.

11.2 Australian capacity and costs for electrolytic OAE

Based on this Roadmap's analysis, Australia could have the capacity to capture and store up to 7 $MtCO_2/y$ in 2050 through electrolytic OAE, with a projected cost in 2050 from A$80 to A$140 per tCO_2 captured for a NOAK project.

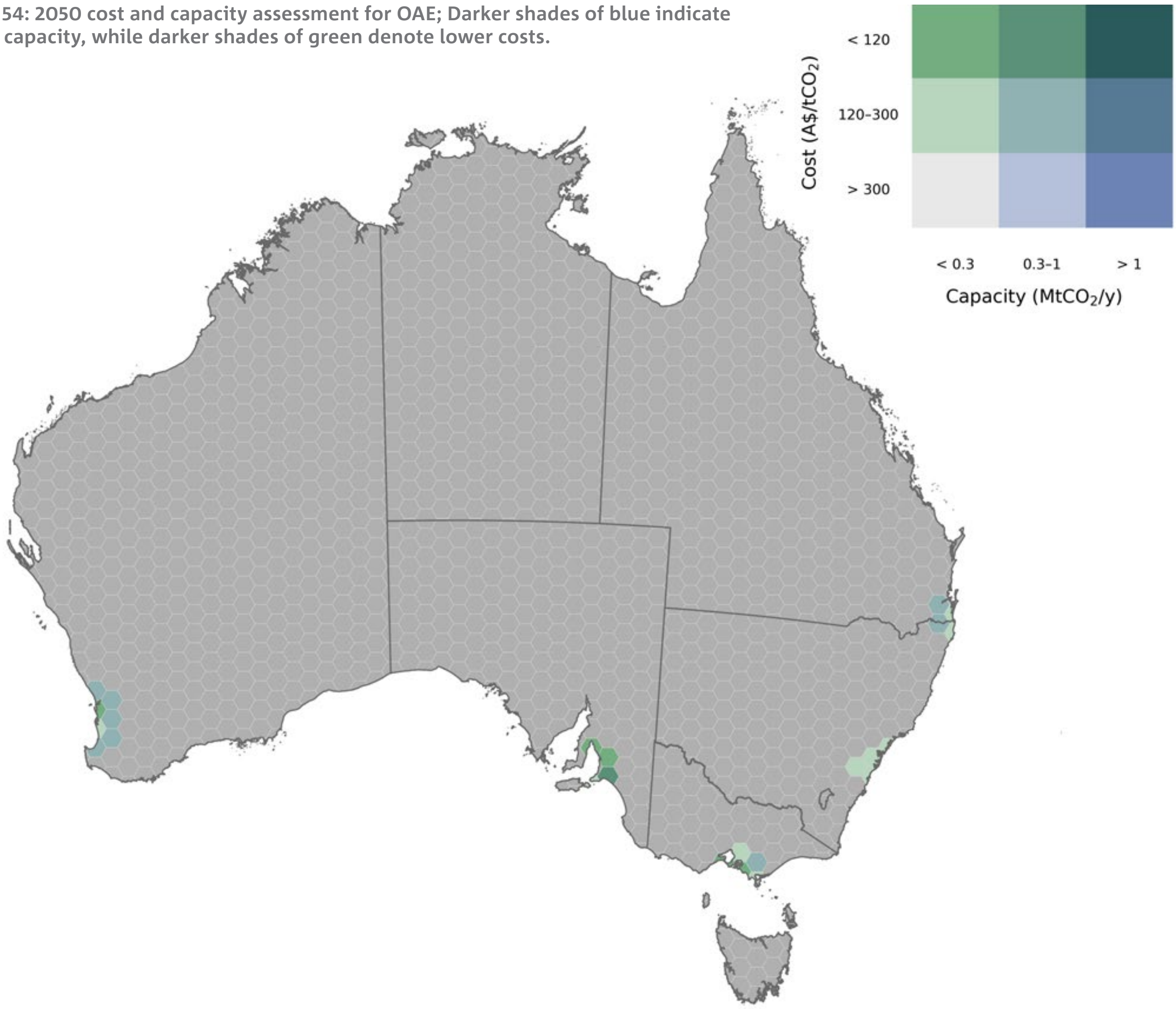
Results of realisable capacity and cost modelling for OAE in Australia are shown in Figure 54. Realisable potential was identified across WA, SA, Victoria, NSW and Queensland. This assessment is based on the assumed co-location with desalination plants (noting other water infrastructure could also be considered[327]) and use of locally generated renewable electricity as described in Section 8.3.

Figure 53: A closed loop electrolytic OAE process is examined in this section of the cost and capacity analysis.

CO_2 CAPTURE	CO_2 STORAGE				
	Geological storage		Mineral storage	Open environments	
Biologically captured during biomass growth	BiCR+S – fast pyrolysis to H_2 (geological storage) >1,000 years	BiCR+S – combustion (geological storage) >1,000 years	BiCR+S (mineral carbonation) >1,000 years	BiCR+S – slow pyrolysis to biochar 100–1,000 years	Conventional CDR 10–100 years
Geochemically bound in minerals				ERW >1,000 years	OAE >1,000 years
Chemically captured as gas	DAC+S (geological storage) >1,000 years		DAC+S (mineral carbonation) >1,000 years		

327 Stakeholder consultation has indicated that water and wastewater treatment plants, power plants, and industrial facilities fitted with seawater intakes including mining operations are other co-location options. These options have not been considered in this Roadmap, and may provide opportunities to cost-effectively increase the realisable capacity of OAE in Australia.

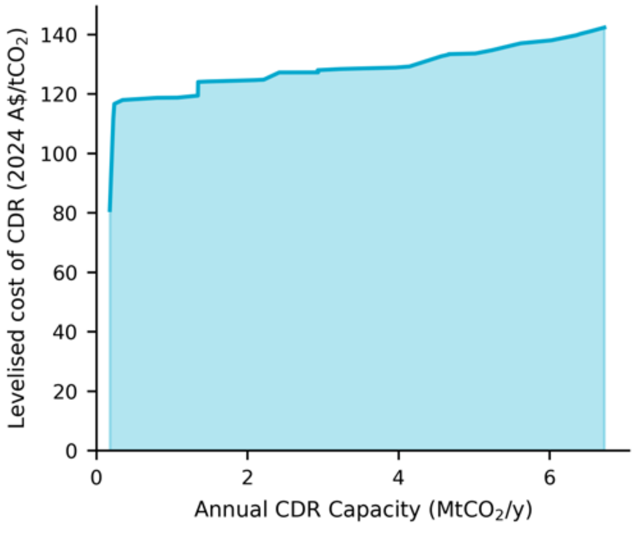
Figure 54: 2050 cost and capacity assessment for OAE; Darker shades of blue indicate higher capacity, while darker shades of green denote lower costs.



Capacity is constrained by the potential to generate VRE in proximity to these desalination plants. Locations within 100 km of an existing desalination plant were considered viable for VRE development. Capacity is lower in hexbins that overlay major centres (Gold Coast, Sydney, Melbourne, Adelaide and Perth) due to the lack of available land for VRE generation. There is greater capacity for VRE generation in the hexbins adjacent to Perth and the Gold Coast where land is more readily available.

As described in Section 8.1, the cost and capacity analysis has been combined into a supply curve for OAE in Australia. The variation in levelised cost is primarily driven by differences in VRE costs and associated firming levels.

Figure 55: Supply curve for OAE co-located with desalination plants in 2050.



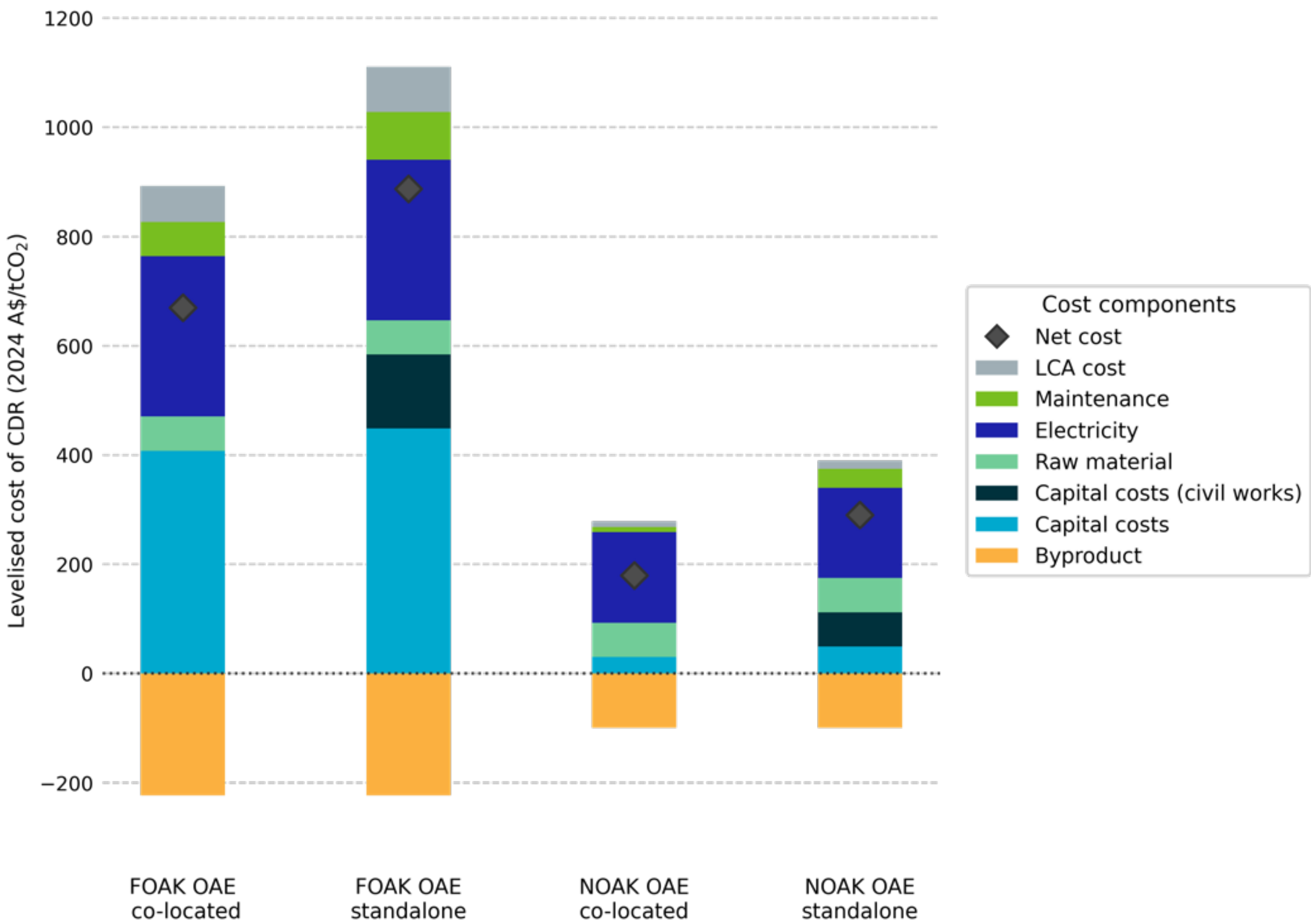
11.3 Levers to influence CDR cost

Optimising capital and energy costs represent the key areas for cost reductions between FOAK and NOAK projects, while byproducts including H_2 represent a pathway to generate revenue and offset ongoing operating costs.

The modelled levelised costs of OAE are shown in Figure 56. Costs for both FOAK and NOAK projects highlight the potential for cost reductions. OAE facilities require ocean intake, screening, prefiltration and outfall systems similar to those used in desalination and other water or wastewater treatment infrastructure. As such, there is an opportunity to develop OAE facilities that are co-located with existing or planned water treatment infrastructure to take advantage of their existing systems. Cost estimates are produced for OAE facilities co-located with existing infrastructure, and for standalone OAE facilities.

The inputs and assumptions underlying these levelised costs are provided in the *Australian CDR Roadmap – Modelling Appendix*. The costs reflect one possible combination of inputs, but as explained in Section 8.1, a number of inputs are varied in the regional analysis to understand the potential variation in cost across different regions. This variation explains the difference in cost results between Figure 55 and Figure 56.

Figure 56: Levelised cost of CDR for OAE facilities co-located with existing infrastructure and for standalone OAE facilities.



11.3.1 Capital costs

Capital costs are modelled to have the greatest potential for cost reduction.

Capital costs are modelled to decline in the NOAK scenario due to several factors: an extended facility lifetime (from 20 to 30 years), reduced technology risk associated with increased maturity, and a projected reduction in electrolyser costs from A$4,550/kW to A$760/kW. These cost estimates are based on industry consultation, with the NOAK cost consistent with forecasts in CSIRO's GenCost report.[328]

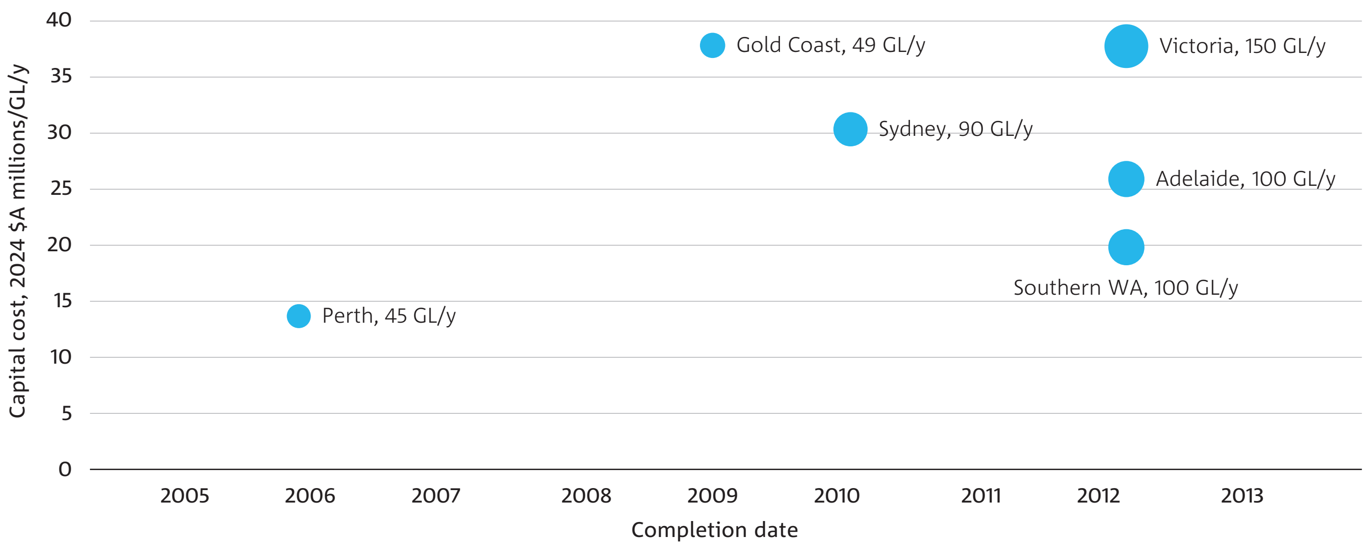
Co-location with existing water infrastructure is projected to be a more cost-effective approach than constructing a standalone facility, particularly for a FOAK facility. FOAK facilities typically have shorter operational lifespans and higher costs of capital compared to NOAK facilities. This makes capital cost efficiency a key consideration. Leveraging existing infrastructure can help minimise capital cost. For NOAK facilities, upgrading existing facilities may be less feasible due to site-specific limitations and scalability constraints.

The cost of intake and outfall infrastructure for a standalone facility could be significant based on recent desalination plant construction costs in Australia and requires further investigation.

A large-scale standalone OAE facility would require significant civil works (i.e. dedicated ocean intake, screening, prefiltration, and outfall systems, as described above). The cost of this infrastructure in Australia can be approximated by considering construction costs of Australian desalination plants. These costs are illustrated in Figure 57, with costs expressed per cubic metre of annual plant capacity.

These plants required complex diffuser systems to meet strict environmental regulations, especially in ecologically sensitive marine areas. In some cases, intake and outfall infrastructure accounted for up to 30% of total installed capital costs.[329] However, OAE facilities may not require such complex diffuser systems if their effluent closely matches the salinity of ambient seawater, suggest potential for cost reductions. By comparison, similar infrastructure in US desalination plants have accounted for only 10%[330] of total capital costs. The modelled civil costs for the NOAK standalone facility in Figure 56 reflect 14%[331] of the average total capital costs for existing Australian desalination plants shown in Figure 57.

Figure 57: Capital costs of Australian desalination plants, expressed per GL of annual capacity.



328 Graham, P., Hayward, J. and Foster J. (2025) GenCost 2024-25: Final report, CSIRO, Australia.

329 Costs 10 to 30 see: WateReuse Association Desalination Committee (2012) Seawater desalination costs: white paper. Revised January 2012. <https://watereuse.org/wp-content/uploads/2015/10/WateReuse_Desal_Cost_White_Paper.pdf>.

330 WateReuse Association Desalination Committee (2012) Seawater desalination costs: white paper. Revised January 2012. <https://watereuse.org/wp-content/uploads/2015/10/WateReuse_Desal_Cost_White_Paper.pdf>.

331 Based on seawater intake, pretreatment and outfall costs from Saline Water Conversion Corporation (2023) Capital cost elements report. <https://www.swcc.gov.sa/uploads/Capital-Cost-Elements-Report2023.pdf>.

11.3.2 Energy costs

Facility utilisation has a significant impact on levelised capital costs.

The costs presented in Figure 56 are based on a utilisation rate of 90%. Further cost optimisation is possible by varying facility utilisation to take advantage of low-cost, variable renewable electricity. Electrolysers and their associated systems can be designed to be easily switched off during periods of high electricity prices and back on when prices are more affordable. The trade-off to this electricity cost saving is a reduced annual utilisation, which inflates levelised capital cost.

Electrolyser energy consumption remains the dominant operating cost for OAE.

In the FOAK scenario, 2.3 MWh of gross energy input is required per tonne of CO_2 removed to power the electrolysers (the energy required to pump the seawater is negligible by comparison).[332] This is forecast to reduce to 1.7 MWh per tCO_2 removed in the NOAK case. This is approaching the physical efficiency limit for electrolysis, providing higher confidence that this energy requirement will not reduce further. The lower electricity cost component for the NOAK facility in Figure 56 is the result of this efficiency improvement as well as a modest reduction in electricity price.

11.3.3 Byproduct revenue

Byproducts in this case H_2 and solid carbonate represent a pathway to generate revenue and offset ongoing operating costs.

OAE can produce significant quantities of H_2. In the realisable capacity estimate, approximately 195,000 tonnes of H_2 per year are produced, increasing to 3.3 Mt per year in the high ambition case (see Section 11.4.1). This high ambition estimate represents 22% of the National Hydrogen Strategy's 15 Mt of H_2 per year production target,[333] highlighting the opportunity for OAE to support both carbon management and decarbonisation objectives. To maximise this opportunity, OAE facilities will need to be sited near suitable offtakers of H_2 or connected to transport and storage infrastructure.

Revenue from H_2 byproduct sales is represented as a negative cost and subtracted from the net levelised cost of CDR. Approximately 0.03 tonnes of H_2 can be produced for each tonne of CO_2 removed, meaning a 1 $MtCO_2$/year NOAK facility would produce 30,000 tonnes of H_2 byproduct per year. Higher H_2 prices are modelled in the FOAK case to reflect likely market prices, which explains the larger FOAK revenue. It is important to note that the revenue estimates in Figure 56 do not account for any additional incentives, such as the Hydrogen Production Tax Incentive, which could further subsidise the levelised cost of OAE.

The solid carbonates produced through the OAE process can either be stored on land or returned to the ocean. In the current modelling, it is assumed that these carbonates are retained on land but not sold. However, solid carbonates could have commercial value in Australia in industries such as construction or agriculture, with potential market prices ranging from A$38 to A$77 per tonne.[334] If sold as a byproduct, this could contribute to a net reduction in overall OAE costs, highlighting the need for further investigation into market viability and economic impacts.

11.4 Levers to influence CDR capacity

Assumptions related to OAE facility co-location, energy and land availability and process choices are key levers that could impact Australia's projected costs and realisable capacity in 2050.

Australia's realisable OAE capacity and costs are closely interconnected. While co-locating OAE with a desalination plant is a cost-effective deployment strategy in the near term, standalone OAE facilities may be required if OAE is to scale beyond the realisable capacity estimate. Furthermore, increasing VRE generation and improving process and energy efficiency through RD&D can increase the feasible scale of deployment. As previously noted, however, not all OAE capacity should be pursued, given the trade-offs involved.

This section explores the key levers that could influence OAE capacity outcomes, helping to inform more strategic and efficient deployment pathways.

332 La Plante EC, Simonetti DA, Wang J, Al-Turki A, Chen X, Jassby D, Sant GN (2021) Saline water-based mineralization pathway for gigatonne-scale CO_2 management. ACS Sustainable Chemistry & Engineering 9(3), 1073–1089. <https://doi.org/10.1021/acssuschemeng.0c08561>.

333 Department of Climate Change, Energy, the Environment and Water (2024) National Hydrogen Strategy 2024. <https://www.dcceew.gov.au/sites/default/files/documents/national-hydrogen-strategy-2024.pdf>.

11.4.1 Standalone OAE facility vs co-located facility

While co-locating OAE with desalination plants can reduce costs significantly, the limited number of plants in Australia would constrain OAE capacity potential.

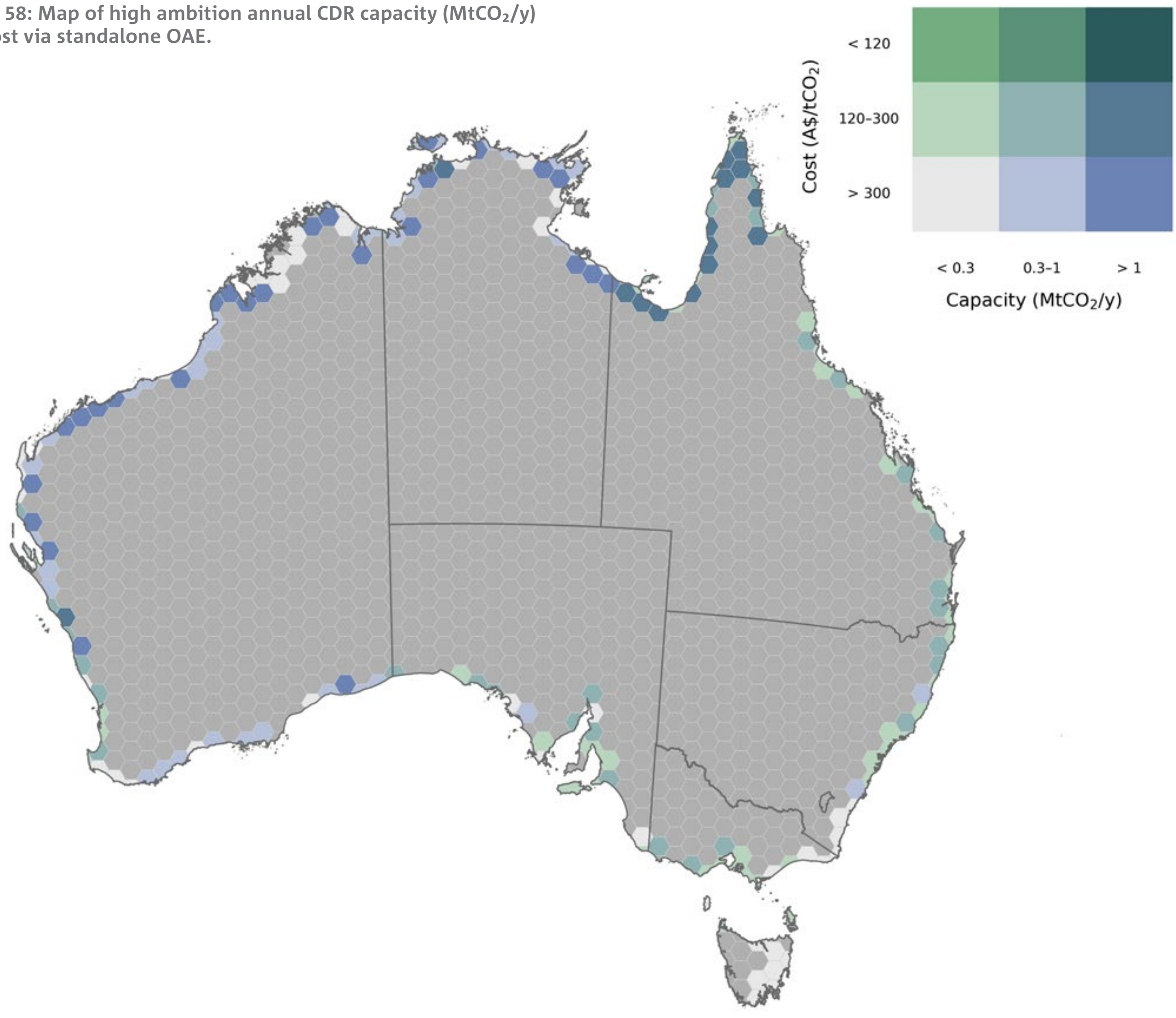
The co-location of OAE with desalination plants provides significant cost reductions, particularly for FOAK projects. However, with limited large-scale desalination facilities available in Australia, such an approach would be limited to the realisable capacity estimate provided above.

To understand the potential for OAE in the high ambition case, the capacity of standalone NOAK facilities has also been modelled. Similar land availability constraints are applied to estimate the VRE generation potential, however this high ambition case considers all coastal hexbins rather than only those within 100 km of a desalination plant.

Costs of the standalone OAE facilities include an allowance for intake and outfall infrastructure, increasing levelised costs as shown in Figure 56.

The resulting capacity for standalone OAE is shown in Figure 58. Australia's extensive coastline gives it the potential to support approximately 114 Mt of annual OAE capacity in 2050 at costs of between A$210 and A$390 per tCO_2. The NT and WA are modelled to have high capacity due to the potential for renewable energy generation and available land in these areas. The Gulf of Carpentaria is modelled to have particularly high capacity. By comparison, Australia's East and South-East coasts were modelled to have lower capacity due to land availability constraints and lower potential for renewable energy generation. It is important to note that the capacity identified for OAE would not necessarily be additional to the capacity identified for DAC+S in Section 9, as both approaches require renewable electricity.

Figure 58: Map of high ambition annual CDR capacity ($MtCO_2$/y) and cost via standalone OAE.



11.4.2 Energy and land use

Australia's OAE capacity could be increased by relaxing current energy and land use assumptions.

The realisable and high ambition OAE capacity are based on conservative assumptions regarding both renewable energy availability and the land required for energy infrastructure to meet the high energy demands of OAE processes. Relaxing these constraints could significantly increase Australia's capacity for OAE. For example, given the coastal requirements of OAE, development of transmission lines could be used to connect cheap and plentiful inland VRE generation with OAE facilities. This may increase the overall capacity for OAE in Australia, but dedicated transmission infrastructure would come at an additional cost. The socially acceptable level of renewable electricity development may also vary regionally, and may increase above the levels assumed in this analysis.

An alternative strategy would be to consider other forms of energy to support OAE beyond those considered in this analysis (see Section 8.3.2). For example, offshore wind energy offers a valuable alternative for OAE, as it provides a co-located low emissions energy source which is unlikely to be as financially viable for land-based electrification and decarbonisation efforts in the near term. Using offshore wind energy would not require the need to build additional transmission infrastructure and can support more remote OAE deployments.

11.4.3 Technological RD&D

Operating an OAE facility requires significant energy input, providing an opportunity for improving process and energy efficiency RD&D in electrochemical cells and other deployment systems.

While this analysis focuses on the electrolytic OAE process, there are other processes such as electrodialysis that may have lower energy requirements and are being rapidly demonstrated and scaled up, but face their own technological challenges.[335] Considerations for high-potential alternatives like electrodialysis and continuous advancements of electrolysis can be beneficial for driving down energy consumption and operating costs for OAE projects in Australia.

OAE approaches can also be established at an offshore facility or deployed as mobile systems at sea. Offshore OAE facilities are likely not limited in scale expansion and could utilise renewable energy from offshore wind farms.

334 Stakeholder consultation.

335 Eisaman MD, Geilert S, Renforth P, Bastianini L, Campbell J, Dale AW, Foteinis S, Grasse P, Hawrot O, Löscher CR, Rau GH, Rønning J (2023) Assessing the technical aspects of ocean-alkalinity-enhancement approaches. In Guide to Best Practices in Ocean Alkalinity Enhancement Research. (Eds. A Oschlies, A Stevenson, LT Bach, K Fennel, REM Rickaby, T Satterfield, R Webb, J-P Gattuso) 3. Copernicus Publications, State Planet. https://doi.org/10.5194/sp-2-oae2023-3-2023

11.5 Other considerations

11.5.1 Co-benefits and environmental considerations

OAE approaches can be applied to brines other than seawater, such as desalination plant brines and geological fluids, potentially bringing an environmental co-benefit.[336] An OAE facility installed downstream of a desalination plant could benefit from increased ion concentration in desalination plant brine, while at the same time reducing the salinity of this brine prior to its return to the ocean. There may also be opportunities to recirculate between the OAE facility and desalination plant, improving the desalination plant's water recovery rate and reducing the design requirements and environmental impact of ocean outfall infrastructure. These synergies require further investigation, but have the potential to lessen the environmental impact and improve the affordability of both desalination and CDR.

Chlorine gas produced from some electrochemical OAE processes is difficult to dispose and a potential environmental hazard.[337] In addition to developing the method and infrastructure to handle chlorine gas, operations would need to consider chlorine resistant materials and technologies (e.g. catalysts) to protect other equipment and infrastructure.[338] For example, Equatic utilises oxygen selective anodes to prevent chlorine gas production.

Hydrochloric acid produced by some electrochemical OAE processes can be neutralised with alkaline rocks inside the boundary limit of the OAE facility, an approach adopted by Equatic, or at alkaline waste ponds at sand and gravel operations.[339] In the future, hydrochloric acid produced from OAE approaches could play a role in supporting other CO_2 capture and storage processes, such as being used to pre-treat silicate rocks to enhance the kinetics and capacity of ERW and CO_2 mineralisation storage methods.[340]

11.5.2 Closed systems vs open systems

The closed system process modelled here uses additional capital equipment to capture atmospheric CO_2 in the alkaline solution within the facility limits. This allows for robust MRV of carbon removal but increases capital costs. Alternatively, the alkalinity produced by an electrochemical OAE process can be returned to the ocean, with the ocean surface acting as the exchange medium. Further research is needed to explore this approach and its potential to support the scale-up of OAE. CSIRO has active research projects that aim to improve our understanding of air-sea CO_2 equilibration rates, inform robust MRV protocols and better understand the environmental impacts of short-term increases in ocean alkalinity on marine phytoplankton and other organisms.[341]

336 Eisaman MD et al (2023) Assessing the technical aspects of ocean-alkalinity-enhancement approaches. In Guide to Best Practices in Ocean Alkalinity Enhancement Research. (Eds. A Oschlies, A Stevenson, LT Bach, K Fennel, REM Rickaby, T Satterfield, R Webb, J-P Gattuso) 3. Copernicus Publications, State Planet. <https://doi.org/10.5194/sp-2-oae2023-3-2023>.

337 Eisaman MD et al (2023) Assessing the technical aspects of ocean-alkalinity-enhancement approaches. In Guide to Best Practices in Ocean Alkalinity Enhancement Research. (Eds. A Oschlies, A Stevenson, LT Bach, K Fennel, REM Rickaby, T Satterfield, R Webb, J-P Gattuso) 3. Copernicus Publications, State Planet. <https://doi.org/10.5194/sp-2-oae2023-3-2023>.

338 Yang L-J, Guan H-Y, Yuan S, Sun T, Jiang A-N, Feng J-J (2024) Research progress of chlorine corrosion resistance in seawater electrolysis: materials and technologies. Chemical Engineering Journal 475(158458), 1–15. <https://doi.org/10.1016/j.cej.2024.158458>.

339 Eisaman MD et al (2023) Assessing the technical aspects of ocean-alkalinity-enhancement approaches. In Guide to Best Practices in Ocean Alkalinity Enhancement Research. (Eds. A Oschlies, A Stevenson, LT Bach, K Fennel, REM Rickaby, T Satterfield, R Webb, J-P Gattuso) 3. Copernicus Publications, State Planet. <https://doi.org/10.5194/sp-2-oae2023-3-2023>; Equatic (2025) The Equatic process. <https://www.equatic.tech/the-equatic-process>.

340 Isometric (2024) World-first protocol for ocean alkalinity enhancement. <https://isometric.com/writing-articles/world-first-protocol-for-ocean-alkalinity-enhancement>; Eisaman MD et al (2023) Assessing the technical aspects of ocean-alkalinity-enhancement approaches. In Guide to Best Practices in Ocean Alkalinity Enhancement Research. (Eds. A Oschlies, A Stevenson, LT Bach, K Fennel, REM Rickaby, T Satterfield, R Webb, J-P Gattuso) 3. Copernicus Publications, State Planet. <https://doi.org/10.5194/sp-2-oae2023-3-2023>.

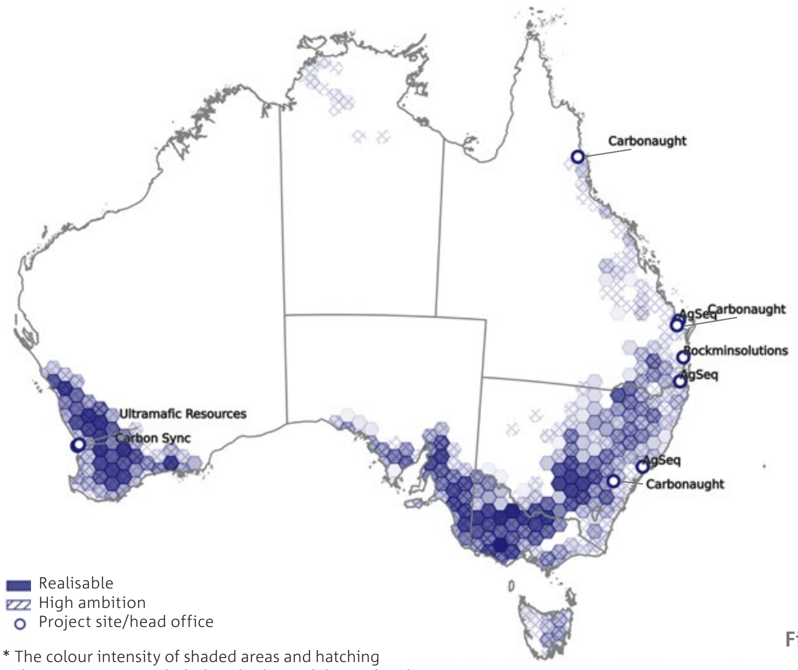
341 CSIRO (2024) Ocean alkalinity enhancement. <https://www.csiro.au/en/research/environmental-impacts/emissions/carbon-dioxide-removal/ocean-alkalinity-enhancement>.

12 Enhanced Rock Weathering (ERW)

Australia may have the potential to remove up to 22 $MtCO_2$/y in 2050 using ERW. The projected 2050 costs of Nth-of-a-kind deployment scenarios range from A$190–280 per tCO_2 captured.

Enhanced rock weathering (ERW) approaches accelerate the naturally occurring reaction between atmospheric CO_2 dissolved in rainwater and calcium- and magnesium-rich silicate rocks. This is done by crushing and deliberately dispersing these rocks on large areas of land or in the ocean. This Roadmap focuses on agricultural ERW (TRL 6–8) to capture and store atmospheric CO_2; however, it is recognised that other emerging ERW approaches are under development, for example, coastal ERW and river alkalinity enhancement.

Figure 59: Location of Australia's realisable ERW capacity.



* The colour intensity of shaded areas and hatching indicates capacity, with darker shades and denser hatching representing high capacity.

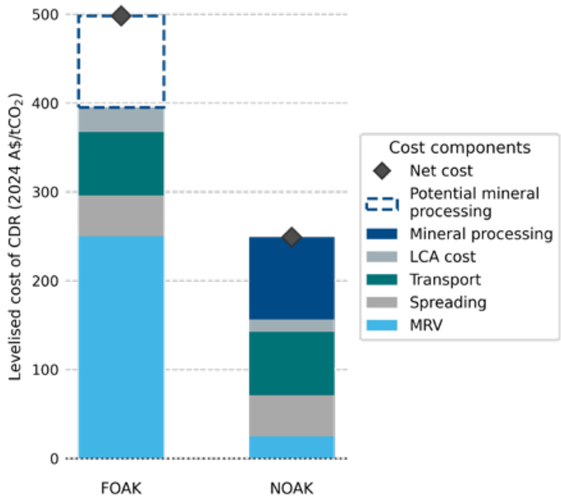
Key capacity considerations:

- *Scaling quarrying* from 100 Mt of rocks per year to 1 Gt per year could enable 220 $MtCO_2$/y removed but raises significant social and environmental trade-offs.
- ERW's potential can only be realised with *buy-in from farmers and other primary industries.*

Key cost considerations:

- *MRV* is the largest cost driver, ongoing protocol development and field data accumulation will be critical to cost reductions.
- *Assumed weathering and carbon removal rates* influence ERW efficiency – higher values could accelerate CO_2 removal and reduce material and spreading costs.
- *Transport costs* are significant, and increase with the distance between extraction and application sites.

Figure 60: Levelised cost of ERW.



12.1 Overview

This section presents the results of cost and capacity modelling for ERW, focusing on approaches implemented on agricultural land (highlighted in purple in Figure 61). Using the methodology from Section 8.1, it estimates Australia's annual realisable capacity for ERW and the cost per tonne of CO_2 removed. It explores the key constraints, regional opportunities, and levers that could influence deployment at scale.

12.2 Australian capacity and costs for agricultural ERW

Based on this Roadmap's analysis, Australia could have the capacity to capture and store up to 22 $MtCO_2$/y in 2050 through agricultural ERW, with a projected cost in 2050 from A$190 to A$280 per tCO_2 removed for a NOAK project.

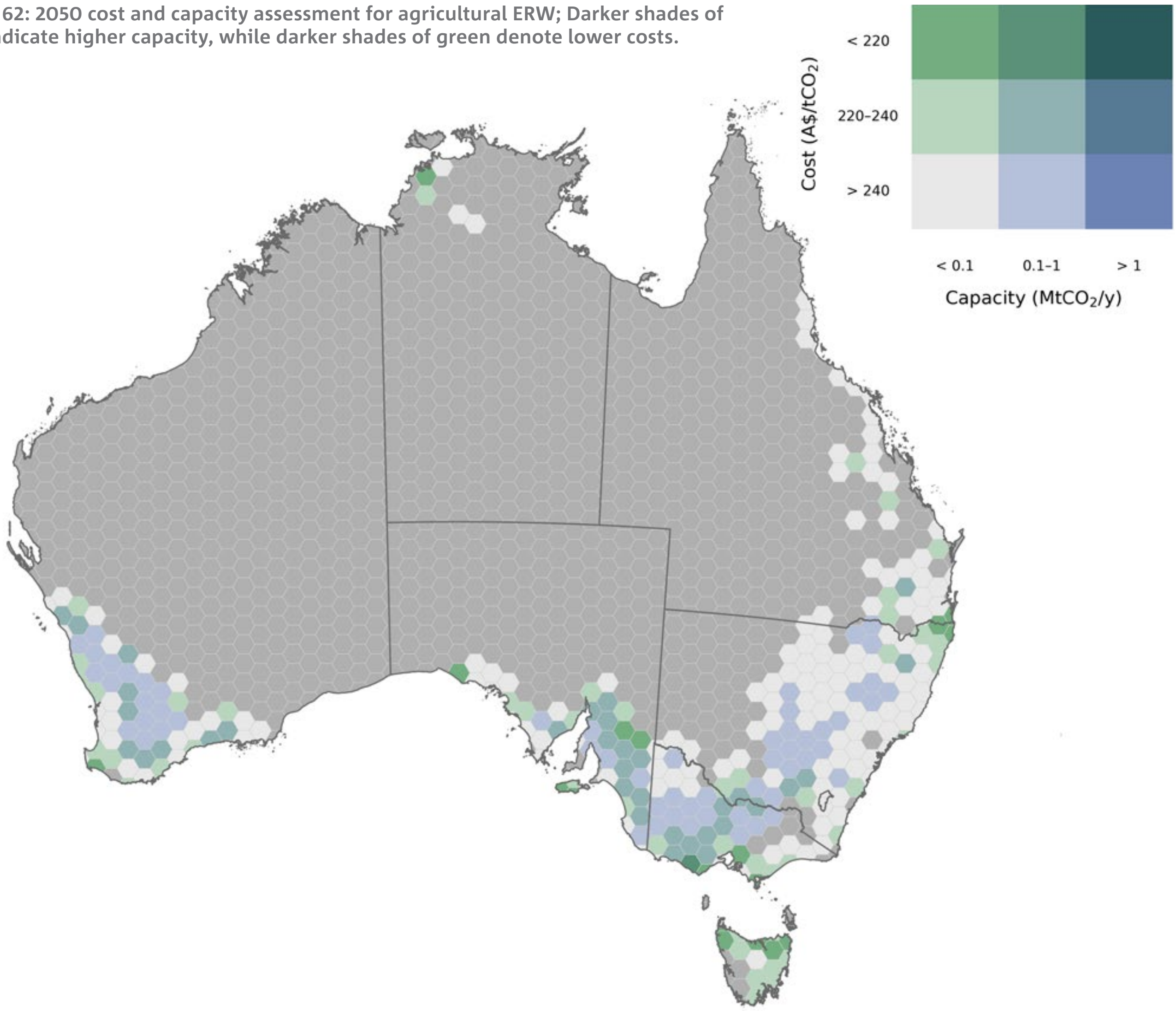
The 2050 results of realisable capacity and cost modelling for agricultural ERW in Australia are shown in Figure 62. While a conservative estimate, agricultural ERW would account for approximately 5% of Australia's current (2025) annual CO_2 emissions.[342] Realisable ERW potential was concentrated across Australia's agricultural land, with significant capacity across WA, SA, Victoria, Tasmania, NSW, Queensland and some capacity in the NT (see Figure 62). The capacity and levelised cost estimates both vary significantly across regions, driven by the regional cost and capacity inputs described in Section 8.3.

Figure 61: Agricultural ERW is examined in this section of the cost and capacity analysis.

CO_2 CAPTURE	CO_2 STORAGE				
	Geological storage		Mineral storage	Open environments	
Biologically captured during biomass growth	BiCR+S – fast pyrolysis to H_2 (geological storage) >1,000 years	BiCR+S – combustion (geological storage) >1,000 years	BiCR+S (mineral carbonation) >1,000 years	BiCR+S – slow pyrolysis to biochar 100–1,000 years	Conventional CDR 10–100 years
Geochemically bound in minerals				ERW >1,000 years	OAE >1,000 years
Chemically captured as gas	DAC+S (geological storage) >1,000 years		DAC+S (mineral carbonation) >1,000 years		

342 Australia's total CO_2 emissions data is sourced from: Department of Climate Change, Energy, the Environment and Water (2025) Quarterly update of Australia's National Greenhouse Gas Inventory: December 2024. <https://www.dcceew.gov.au/sites/default/files/documents/nggi-quarterly-update-december-2024.pdf>.

Figure 62: 2050 cost and capacity assessment for agricultural ERW; Darker shades of blue indicate higher capacity, while darker shades of green denote lower costs.



Areas with high capacity typically have significant agricultural land area while also being located near large quantities of suitable mafic rock feedstock, enabling low levelised costs due to cost-effective transport distances.

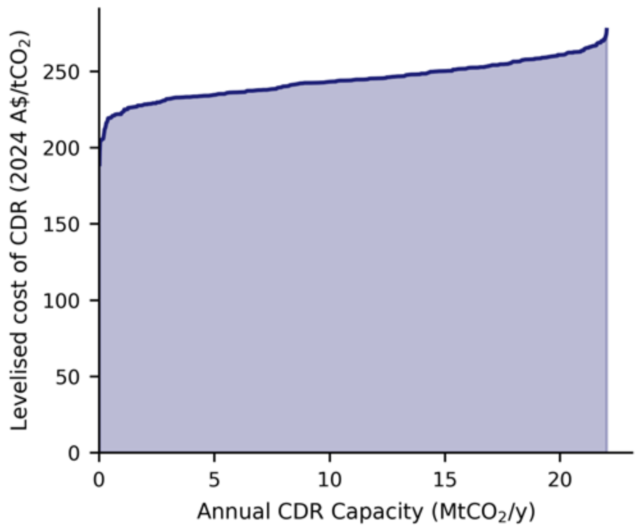
Figure 62 highlights regional cost and capacity insights that can be used to inform scale-up and demonstration projects. There are opportunities for low-cost trial projects in all states, with local climate and soil conditions that are not reflected in this analysis also likely to influence suitability. Significant capacity is identified in WA, SA, Victoria and NSW, aligned to the extensive agricultural land in these states co-located with mafic rock.

Importantly, only a portion of suitable agricultural land (5%) is used to estimate the realisable capacity in each region. Similarly, the quantity of quarried rock available for ERW is constrained (100 Mt of rocks per year). Relaxing each of these constraints could increase realisable capacity in new locations not shown on Figure 62.

As described in Section 8.1, the cost and capacity analysis has been combined into a supply curve for agricultural ERW in Australia. The levelised cost of deploying agricultural ERW to achieve the identified realisable capacity by 2050 varies across regions. Figure 63 presents the cumulative annual capacity of agricultural ERW, with this capacity sorted in order of increasing cost.

Cost differences in Figure 63 are driven by the inputs described in Section 8.3. In this case, variation is primarily driven by transport costs, a function of the distance between mafic rock sources and suitable agricultural land, as well as the quality of the road network linking them. This cost increase is compounded by the reduction in net carbon removal due to CO_2 emissions during transport.

Figure 63: Supply curve for agricultural ERW in 2050.



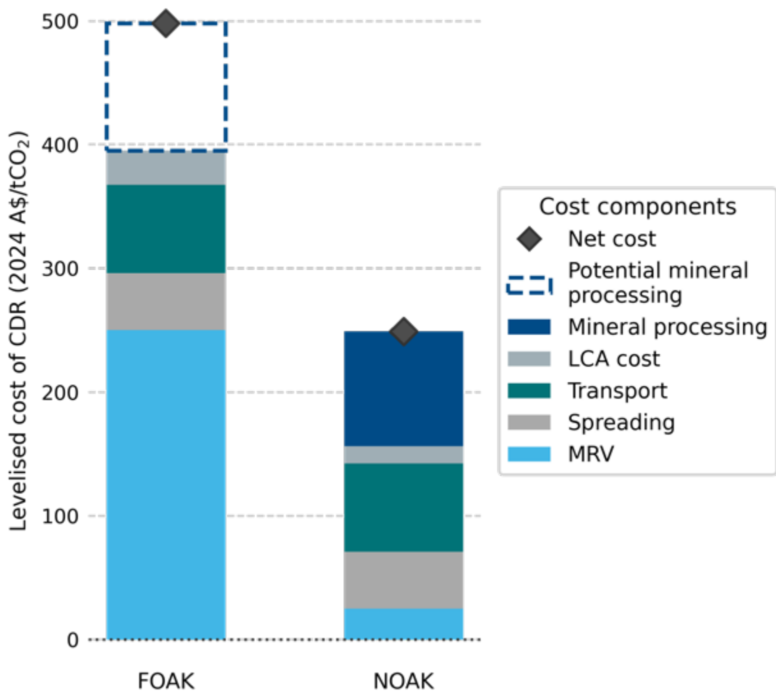
12.3 Levers to influence CDR cost

MRV costs, rock carbon removal potential, rock weathering rate and transport costs represent the largest components of ERW levelised cost, making them priority areas for further research and trials.

The modelled levelised costs of ERW are shown in Figure 64. Costs for both FOAK and NOAK projects highlight the potential for cost reductions. The inputs and assumptions underlying these levelised costs are provided in the *Australian CDR Roadmap – Modelling Appendix*. The costs reflect one possible combination of inputs, but as explained in Section 8.1, a number of inputs are varied in the regional analysis to understand the potential variation in cost across different regions. This variation explains the difference in cost results between Figure 63 and Figure 64.

Mineral processing costs are shown with a dashed outline in the FOAK scenario to reflect the possibility of cost savings by using byproduct material such as crusher dust from existing quarry operations. Limited availability of this byproduct makes it unlikely to be a viable source of supply in the NOAK scenario.

Figure 64: ERW levelised cost of CDR.



12.3.1 MRV costs

MRV costs are presently a major driver of the levelised cost for CDR via ERW. Data collection, model validation and RD&D into sensing technologies have the potential to reduce these costs.

MRV costs are currently the largest component of total levelised costs for CDR, with consultation indicating costs of A$200–300 per tCO_2 removed. MRV protocols are still under development, and for ERW specifically, the accumulation of field data over time will enable the development and calibration of predictive models. The NOAK scenario shown above reflects a cost target of A$25 per tCO_2 removed. This would see MRV costs for ERW reach similar levels to the MRV costs of other CDR approaches, but it is not clear if this target can be reached.

Existing protocols for ERW, such as the one developed by Isometric (described in detail in Section 3.2.3), rely heavily on direct field measurements. In the short term, this approach is a driver of high costs, as site heterogeneity necessitates oversampling to produce reliable estimates. However, these field measurements are critical in the early stages for building and calibrating accurate predictive models. Once sufficient data has been accumulated and models are fully developed, significant cost reductions are anticipated, as expensive field measurement will only be needed for randomised sampling.[343]

Advances in digitalisation and automation are also expected to further enhance modelling accuracy and reduce MRV costs. By leveraging historic datasets and applying machine learning (ML) and artificial intelligence (AI) techniques, models can be trained to predict carbon removal outcomes more efficiently. Additionally, the adoption of remote sensing technologies, including drones and satellites, can substantially reduce the need for manual sampling, further improving the scalability and affordability of MRV for ERW.[344]

12.3.2 Carbon removal potential of rock

Rock with a high carbon removal potential can support lower levelised cost of CDR.

The carbon removal potential of a rock refers to the amount of CO_2 that can be removed from the atmosphere per tonne of crushed rock applied to land, typically expressed in tCO_2 per tonne of rock. This metric is primarily determined by the rock's chemical composition and therefore varies across different types of mafic and ultramafic rocks. It is a key factor in determining the scale of ERW operations, as alongside the weathering rate, it enables project developers to estimate the quantity of material required to meet a given CO_2 removal target. Apart from the MRV cost, all ERW cost components are proportional to the total mass of rock applied. Using feedstocks with higher carbon removal potential reduces the volume that must be mined, processed, transported, and spread, thereby lowering overall costs per tonne of CO_2 removed. This modelling has assumed a carbon removal potential of 0.25 tCO_2 per tonne of rock.[345] The carbon removal potential and the rock weathering rate described below should be considered together when selecting an optimal feedstock for ERW.

12.3.3 Rock weathering rate

The levelised cost of CO_2 removal also depends on the annual rock weathering rate, as higher weathering rates lead to faster CO_2 removal. Improved understanding of the weathering rate can improve the efficiency of ERW projects in the long run.

The weathering of applied rock and the associated removal of CO_2 from the atmosphere occur over multiple years. This is not the case for the other CDR approaches considered in this Roadmap, where carbon removal takes place over much shorter timescales. The levelised cost and capacity of ERW have been adjusted into present value terms as described here. This accounts for the longer time period of removal for a given rock application and enables a like-for-like comparison with other CDR approaches.

343 Mercer L, Burke J, Rodway-Dyer S (2024) Towards improved cost estimates for monitoring, reporting and verification of carbon dioxide removal. Grantham Research Institute on Climate Change and the Environment, London. <https://www.lse.ac.uk/granthaminstitute/wp-content/uploads/2024/10/Towards-improved-cost-estimates-for-monitoring-reporting-and-verification-of-carbon-dioxide-removal-.pdf>.

344 Mercer L, Burke J, Rodway-Dyer S (2024) Towards improved cost estimates for monitoring, reporting and verification of carbon dioxide removal. Grantham Research Institute on Climate Change and the Environment, London. <https://www.lse.ac.uk/granthaminstitute/wp-content/uploads/2024/10/Towards-improved-cost-estimates-for-monitoring-reporting-and-verification-of-carbon-dioxide-removal-.pdf>.

345 Informed by stakeholder consultation and Beerling DJ, Kantzas EP, Lomas MR, Wade P, Eufrasio RM, Renforth P, Sarkar B, Andrews MG, James RH, Pearce CR, Mercure J-F, Pollitt H, Holden PB, Edwards NR, Khanna M, Koh L, Quegan S, Pidgeon NF, Janssens IA, Hansen J, Banwart SA (2020) Potential for large-scale CO_2 removal via enhanced rock weathering with croplands. Nature 583(7815), 242–248. <https://doi.org/10.1038/s41586-020-2448-9>.

When modelling the levelised cost of CDR via ERW for FOAK and NOAK projects, an annual weathering rate of 0.036 tCO_2 per tonne of mafic rock has been assumed.[346] Although actual annual weathering rates may vary depending on site-specific factors, this rate is regarded as a conservative estimate. Importantly, assuming higher weathering rates may risk overestimating carbon removal via ERW due to the inherent uncertainties associated with the weathering process. This can undermine the credibility of ERW if carbon credits are being incorrectly attributed.[347]

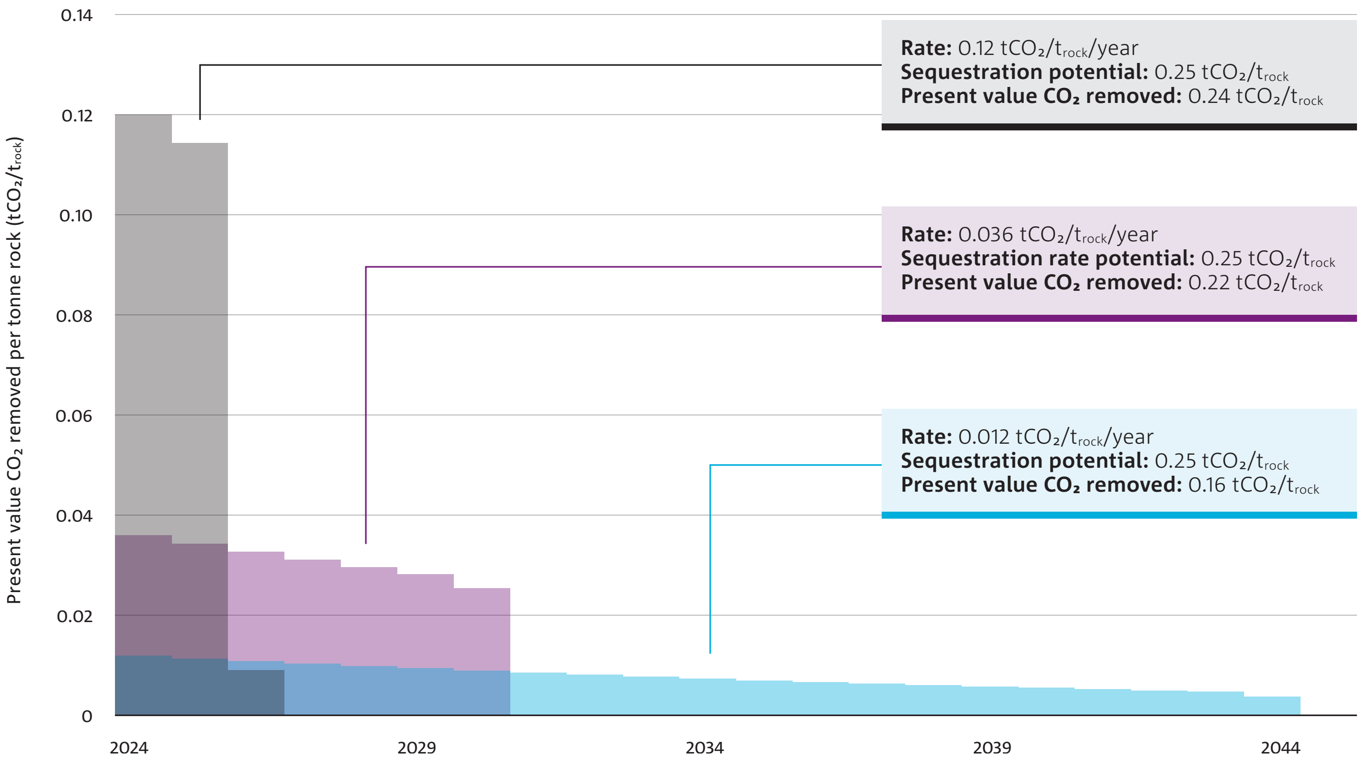
The duration of carbon removal is determined by both the annual rate of rock weathering and the maximum amount of CO_2 that can be removed per tonne of rock (i.e. the carbon removal potential). Assuming a constant carbon removal potential, a higher weathering rate will shorten the duration for a given application of rock by enabling the same amount of CO_2 to be removed from the atmosphere in a shorter period. This accelerates CO_2 removal, increases the present value of the total CO_2 removed and consequently reduces the levelised cost of CDR as shown in the equation below.

$$\textit{Levelised cost of CDR via ERW} \downarrow = \frac{\textit{Present value of costs}}{\textit{Present value of } CO_2 \textit{ removal} \uparrow}$$

The shaded areas in Figure 65 represent the present value of CO_2 removal for a range of weathering rates. The middle rate (in purple) sourced from stakeholder input has been used for estimating the levelised cost of CDR via ERW, with the low and high rates used to show uncertainties.

There are many drivers of weathering rate. Different rocks have different weathering rates, for example, mafic rocks generally have slower natural weathering rate than ultramafic rocks.[348] The type of soil and mineral, the pH level and water availability (driven by temperature and rainfall) can influence the pathway of soil carbon (Figure 23).[349] Increased level of comminution and adopting

Figure 65: Levelised rate of CO_2 removal.



346 Based on input by subject matter experts at CSIRO and stakeholder consultations.

347 Power IM, Hatten VNJ, Guo M, Schaffer ZR, Rausis K, Klyn-Hesselink H (2025) Are enhanced rock weathering rates overestimated? A few geochemical and mineralogical pitfalls. Frontiers in Climate 6, 1510747. <https://doi.org/10.3389/fclim.2024.1510747>.

348 Common Capital Pty Ltd (2023) Scaling atmospheric carbon dioxide removal in New South Wales. Report prepared for the NSW Office of Energy and Climate Change. <https://www.energy.nsw.gov.au/sites/default/files/2024-02/Common_Capital_Scaling_atmospheric_CDR_in_NSW_Final.pdf>.

349 In-field carbon dioxide removal via weathering of crushed basalt applied to acidic tropical agricultural soil. Science of the Total Environment 955, 176568. <https://doi.org/10.1016/j.scitotenv.2024.176568>. https://www.sciencedirect.com/science/article/pii/S004896972406724X?via%3Dihub - s0005

agricultural practices such as tilling, irrigation and reduced acidifying fertiliser usage can help increase the weathering rate and support carbon sequestration.[350] While the effect of each driver is generally understood, the interaction between them can have significant complexity and spatial variability. As a result, RD&D is still needed to further understand the geochemical and biogeochemical processes that affect the rock weathering rate and the fate of CO_2, and ultimately, CO_2 removal, generating knowledge and data that can be used to optimise the efficiency and cost requirements of ERW projects in the longer term.

Weathering of applied rock does not necessarily mean CDR is taking place.

For simplicity, this analysis has assumed that all weathering is caused by the reaction between the applied rock and carbonic acid and therefore leads to CO_2 removal. However, this may not hold true in all environments, particularly in acidic soils.[351]

Additional research is required to understand the relationship between weathering rate and CO_2 removal rate. Suitable soils for agricultural ERW operations need to maintain a level of alkalinity across its depth profile. In-field studies and modelling work have found that the conversion of atmospheric CO_2 into (bi)carbonate products is very low in acidic conditions. While adding ERW feedstock can increase the soil pH at the surface level (0–0.1 m), the increasing effect on soil pH at deeper levels is minimal, and the time required to achieve a sufficient pH level in deeper levels is uncertain.

Crop type and management practices should be considered in conjunction with ERW practices to maintain soil alkalinity across different levels. Proposed strategies include frequent (e.g. annual) application of crushed limestone and minimising the use of acidifying ammonium fertilisers.[352]

Climatic conditions also affect weathering and carbon removal rates.

Water is a critical resource for agricultural ERW operations as it is essential for the weathering process and the conversion of CO_2 into solid carbonates and water-soluble bicarbonates in soil. As a result, important factors for determining a suitable location for agricultural ERW include annual precipitation rates and water management practices utilised, such as irrigation. For example, areas that receive high annual rainfall or grow highly irrigated crops would provide favourable conditions for implementing agricultural ERW.[353]

Temperature also has an influence on the fate of CO_2 in soil as solid carbonates or water-soluble bicarbonates, although it is a less important factor compared to water availability. For example, increased temperatures enhance water loss via soil surface and plants, leaving the majority of captured atmospheric CO_2 to be solid carbonate products in soil, rather than soluble bicarbonate products.[354] Increased temperatures also enhance soil microbial activity, allowing for an acceleration in the biogeochemical cycling that could lead to the accumulation of inorganic carbon (e.g. carbonates and bicarbonates) at deeper soil levels, reducing the risk of carbon loss via CO_2 release.[355]

In general, high temperatures coupled with high rainfall create beneficial conditions for the soil to capture and convert atmospheric CO_2 into soluble bicarbonate products.[356] The predominantly dry and hot Australian climate may put some limitations on the proportion of soluble bicarbonates produced and transferred in run-offs to rivers and oceans, as opposed to solid carbonates stored in soil.

350 Mission Innovation Carbon Dioxide Removal (CDR) Mission (2024) Measurement, Reporting and Verification (MRV) for Carbon Dioxide Removal (CDR): Issues and Opportunities for International Harmonization of National Governments' CDR MRV Methodologies. Ministry of Economy, Trade and Industry (METI), Japan. <https://mission-innovation.net/wp-content/uploads/2024/12/2024-12_CDR-Mission-MRV-Report.pdf>.

351 In-field carbon dioxide removal via weathering of crushed basalt applied to acidic tropical agricultural soil. Science of the Total Environment 955, 176568. <https://doi.org/10.1016/j.scitotenv.2024.176568>. https://www.sciencedirect.com/science/article/pii/S004896972406724X?via%3Dihub - s0005

352 In-field carbon dioxide removal via weathering of crushed basalt applied to acidic tropical agricultural soil. Science of the Total Environment 955, 176568. <https://doi.org/10.1016/j.scitotenv.2024.176568>. https://www.sciencedirect.com/science/article/pii/S004896972406724X?via%3Dihub - s0005

353 Common Capital Pty Ltd (2023) Scaling atmospheric carbon dioxide removal in New South Wales. Report prepared for the NSW Office of Energy and Climate Change. <https://www.energy.nsw.gov.au/sites/default/files/2024-02/Common_Capital_Scaling_atmospheric_CDR_in_NSW_Final.pdf>.

354 Ferdush J, Paul V (2021) A review on the possible factors influencing soil inorganic carbon under elevated CO_2. Catena 204, 105434. <https://www.sciencegate.app/document/10.1016/j.catena.2021.105434>.

355 Ferdush J, Paul V (2021) A review on the possible factors influencing soil inorganic carbon under elevated CO_2. Catena 204, 105434. <https://www.sciencegate.app/document/10.1016/j.catena.2021.105434>.

356 Ferdush J, Paul V (2021) A review on the possible factors influencing soil inorganic carbon under elevated CO_2. Catena 204, 105434. <https://www.sciencegate.app/document/10.1016/j.catena.2021.105434>.

Other driving factors of mineral weathering such as soil properties, rock properties and agricultural practices can be partially optimised with human interventions to increase the weathering rate. For example, tilling the dispersed ground mineral layer to increase the contact area with CO_2 and prevent secondary or passivating layer formation outside the rock, which can slow down the weathering rate.[357]

12.3.4 Transport costs

In practice, transport costs are a major consideration for ERW and will depend on the distance between extraction sites and application sites.

Stakeholders have indicated that transport costs could represent a significant component of the total costs per tonne of carbon removal, but that there are opportunities to reduce this cost. This analysis assumes that rock extraction and processing occur at the same site, minimising the need for additional handling, with only the crushed rock transported to the application sites. The transport costs shown in Figure 64 correspond to a transport distance of 100 km between the extraction site and application sites. Transport costs would increase or decrease in line with this distance.

Other modes such as rail and sea freight may offer lower transport costs, especially over longer distances. The use of low or zero emission heavy vehicles may also reduce levelised costs. Emissions from conventional heavy vehicles used to transport crushed rock from quarries to application sites have been accounted for in the levelised cost calculation. They reduce the net carbon removal of the ERW project analysed, and result in the LCA cost shown in Figure 64.

12.4 Levers to influence CDR capacity

Assumptions related to quarrying activity, weathering rates, carbon removal potential and supply chains, are key levers to expanding the capacity of agricultural ERW beyond the projected realisable 22 $MtCO_2$/y potential in 2050.

Increasing the quantity of suitable mafic rock feedstock and agricultural land within cost-effective transport distances can increase the feasible scale of ERW deployment. As previously noted, however, not all ERW capacity should be pursued, given the trade-offs involved. This section explores the key levers that could influence ERW capacity, helping to inform more strategic and efficient deployment pathways.

12.4.1 Social acceptance for additional quarrying

Acceptable levels of quarrying activity will dictate Australia's capacity for ERW.

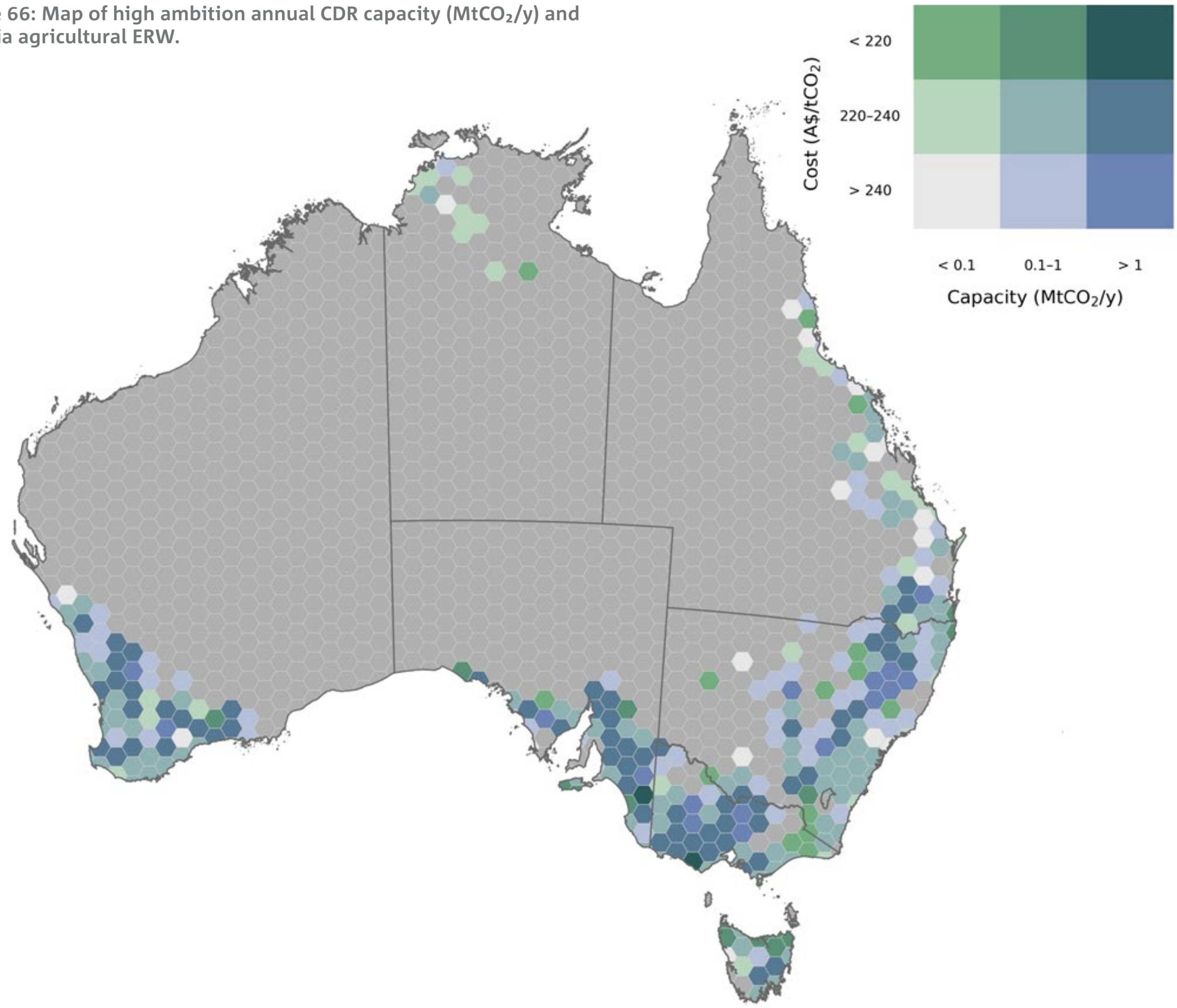
These results assume 100 Mt of additional quarrying activity per year to produce the crushed rock required for ERW. As mentioned in Section 8.3.7, this represents 50% of Australia's current quarry capacity for the production of construction materials. Social and environmental considerations will need to be weighed against the benefits of this CDR activity in deciding how much of this capacity should be realised.

Similar questions are being asked across the global community, with recent research considering the potential for ERW in the US.[358] This research considers scenarios where 1 and 2 Gt of rock are mined per year by 2050. Australia has sufficient mineral resources and agricultural area to operate at these rates and could achieve an annual carbon removal of 220 $MtCO_2$/y if 1 Gt of rock were mined per year, as shown in Figure 66. The constraints in this case are social and environmental rather than technical.

357 Common Capital Pty Ltd (2023) Scaling atmospheric carbon dioxide removal in New South Wales. Report prepared for the NSW Office of Energy and Climate Change. <https://www.energy.nsw.gov.au/sites/default/files/2024-02/Common_Capital_Scaling_atmospheric_CDR_in_NSW_Final.pdf>.

358 Beerling DJ, Kantzas EP, Lomas MR, Taylor LL, Zhang S, Kanzaki Y, Eufrasio RM, Renforth P, Mecure J-F, Pollitt H, Holden PB, Edwards NR, Koh L, Epihov DZ, Wolf A, Hansen JE, Banwart SA, Pidgeon NF, Reinhard CT, Planavsky NJ, Martin MV (2025) Transforming US agriculture for carbon removal with enhanced weathering. Nature 638(425–434).

Figure 66: Map of high ambition annual CDR capacity ($MtCO_2/y$) and cost via agricultural ERW.



12.4.2 Understanding drivers of weathering rate and carbon removal potential

Understanding the drivers of weathering rate and identifying rock material with high carbon removal potential will influence realisable capacity.

As described in Section 12.3.2, simple assumptions for the weathering rate and carbon removal potential have been applied at a national level in this realisable capacity analysis. In reality, these will vary significantly across regions (and even within individual paddocks). This could alter the realisable capacity and cost in different regions, with further research required to better understand these important variables.

12.4.3 Supply chain optimisation

Optimisation of supply chains and transport modes may increase realisable capacity and reduce levelised costs.

Transport of crushed rock is a significant component of levelised cost, and in turn reduces the capacity for ERW in Australia by constraining the amount of rock that can be cost effectively transported to suitable agricultural land. Refer to Section 12.3.4 for further discussion on the opportunities to reduce transport costs and increase CDR capacity.

12.5 Other considerations

Beyond capacity levers and considerations, the use of quarry byproducts, obtaining buy-in from the agricultural sector and understanding the relationship between weathering rate and carbon removal are relevant factors to consider when scaling up ERW.

12.5.1 Use of quarry byproducts

Notable cost reductions can be achieved in the FOAK scenario by making use of quarry byproducts, avoiding mining and mineral processing costs.

The mining and processing of mafic rock for application at ERW sites represents the second largest cost component in the FOAK scenario. Stakeholders consulted indicated that byproducts from existing quarries and overburden from operating mines could be sourced for early ERW deployment. In the FOAK scenario, the availability of such byproducts is expected to be sufficient, allowing mineral processing costs to be avoided and resulting in estimated cost savings of up to A$100 per tCO_2 removed as indicated by the dashed outline in Figure 64 above. In the NOAK scenario, it is assumed that newly mined rock would be required to meet the larger scale of operations. However, some ERW proponents may continue to secure quarry byproducts, offering potential to reduce the cost of rock procurement even at scale. In both FOAK and NOAK scenarios, the mining, crushing and grinding of rocks is assumed to use renewable electricity.

12.5.2 Obtaining buy-in from agricultural sector

ERW's potential can only be realised with buy-in from farmers and other primary industries.

While the other CDR approaches considered in this Roadmap involve megatonne-scale facilities, ERW is decentralised. Scaling ERW in Australia will rely on adoption by individual farmers and landowners, supported by companies who can provide suitable rock material and MRV services. Obtaining buy-in from farmers and landowners will require a clear understanding of the benefits that ERW could offer to the financial and environmental sustainability of farming operations. This goes beyond a potential share in carbon removal revenue to include broader co-benefits that ERW could offer, such as improved crop yields or the reduced need for acidifying fertilisers.

Characterising the mineral composition and mineralogy of rocks and quarry byproduct materials are necessary steps to determine suitable feedstock and agricultural management practices for different agricultural ERW operations. Rocks and byproduct materials for agricultural ERW need to have low heavy metal content to avoid leakage or damage to plant growth and soil health. Different minerals in rocks and byproduct materials release different amounts of nutrients at different rates as they weather. Many of these nutrients such as phosphorus and potassium are currently supplied via fertilisers.[359] For example, a US-based ERW study estimated that the weathering of basalts per round of rock application can partially[360] or fully replace phosphorus and potassium provided by fertilisers at an annual rate, depending on the source of basalt and crop type.[361] Phosphorus-containing minerals in basalts tend to be weathered faster than potassium-containing minerals, meaning the release of potassium might happen over a longer period of time compared to the annual timescale for phosphorus.[362] As a result, there need to be considerations for adapting fertiliser practices over the course of ERW implementation to avoid the oversupply of these elements which can impact plant ability to take up other nutrients, as well as optimise operating costs.

359 Lewis AL, Sarkar B, Wade P, Kemp SJ, Hodson ME, Taylor LL, Yeong KL, Davies K, Nelson PN, Bird MI, Kantola IB, Masters MD, DeLucia E, Leake JR, Banwart SA, Beerling DJ (2021) Effects of mineralogy, chemistry and physical properties of basalts on carbon capture potential and plant-nutrient element release via enhanced weathering. Applied Geochemistry 132, 105023. <https://eprints.whiterose.ac.uk/id/eprint/178259/1/1-s2.0-S0883292721001554-main.pdf>.

360 26% to 56% for phosphorus, 1% to 44% for potassium.

361 Lewis AL, Sarkar B, Wade P, Kemp SJ, Hodson ME, Taylor LL, Yeong KL, Davies K, Nelson PN, Bird MI, Kantola IB, Masters MD, DeLucia E, Leake JR, Banwart SA, Beerling DJ (2021) Effects of mineralogy, chemistry and physical properties of basalts on carbon capture potential and plant-nutrient element release via enhanced weathering. Applied Geochemistry 132, 105023. <https://eprints.whiterose.ac.uk/id/eprint/178259/1/1-s2.0-S0883292721001554-main.pdf>.

362 Lewis AL, Sarkar B, Wade P, Kemp SJ, Hodson ME, Taylor LL, Yeong KL, Davies K, Nelson PN, Bird MI, Kantola IB, Masters MD, DeLucia E, Leake JR, Banwart SA, Beerling DJ (2021) Effects of mineralogy, chemistry and physical properties of basalts on carbon capture potential and plant-nutrient element release via enhanced weathering. Applied Geochemistry 132, 105023. <https://eprints.whiterose.ac.uk/id/eprint/178259/1/1-s2.0-S0883292721001554-main.pdf>.

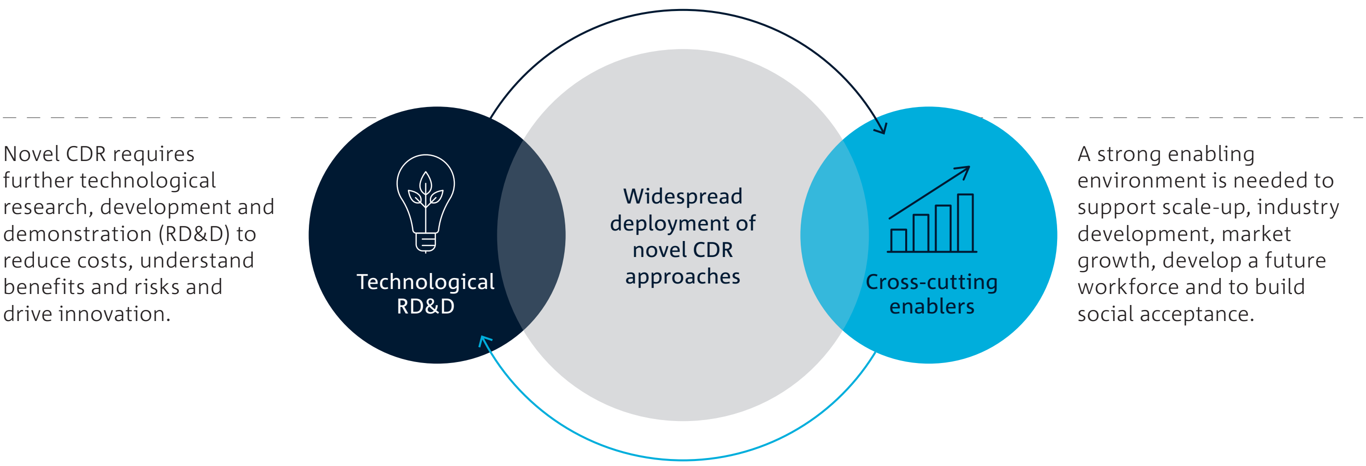
Part IV: Actions and recommendations

Australia has the potential to become a global leader in CDR, meeting and potentially exceeding its domestic CDR requirements of at least 133 Mt of CO_2-e removals by 2050 according to the CCA[363] (see Section 1.3), while also making meaningful contributions to international climate efforts. This opportunity is amplified by Australia's conventional CDR capacity, its enviable natural and energy resources, and its strong technical workforce. As both domestic and global carbon markets mature, the demand for billions of tonnes of high-quality removals is expected to surge. CDR therefore presents a long-term economic opportunity for Australia, specifically in exporting any excess production capacity beyond domestic requirements.

However, capturing this opportunity requires coordinated action. Scaling novel CDR in Australia requires funding, but funding relies on market development, including policy, incentives and engagement, which in turn depends on proven, cost-effective processes (see Figure 67). This dependency loop will necessitate deliberate and coordinated efforts to ensure that novel CDR will be available in the timeframes required to meet Australia's net zero target and its international commitments.

To accelerate the development of novel CDR in Australia and address this dependency loop, this section provides specific actions related to RD&D and scale-up to drive progress across the analysed CDR approaches within this Roadmap, followed by cross-cutting enablers, with specific recommendations and potential actions.

Figure 67: Dependency loop outlining the need for coordinated action across markets and technological RD&D.



13 RD&D and scale-up considerations

To support responsible and effective CDR scale-up, this section proposes a set of RD&D actions related to the four representative CDR approaches selected for cost and capacity analysis (Part III), considering specific capture and storage processes.

For each of the four approaches, a hypothetical scale-up pathway has been developed to explore actions, recognising that there are many ways to scale a given CDR approach. Additionally, each Australian state will have competitive advantages in certain CDR approaches, as such, the amount of focus required on each approach may differ based on environmental, social and regulatory environments. The scale-up pathway builds on current Australian and international technological developments, identifying key outcomes to inform RD&D, pilot, build, and scaling efforts from now to 2045 and beyond (see Figure 68). Given the importance of cross-cutting domestic market enablers to sustain a given approach (see Section 14), the actions focus specifically on achieving scale for the identified CDR approaches.

This pathway is intended as a structured framework that can be leveraged with other novel CDR approaches in future iterations of this Roadmap, particularly as additional approaches mature and more information and data is available. As such, this section concludes with a summary of other longer-term CDR pathways that have potential and require consideration in the future.

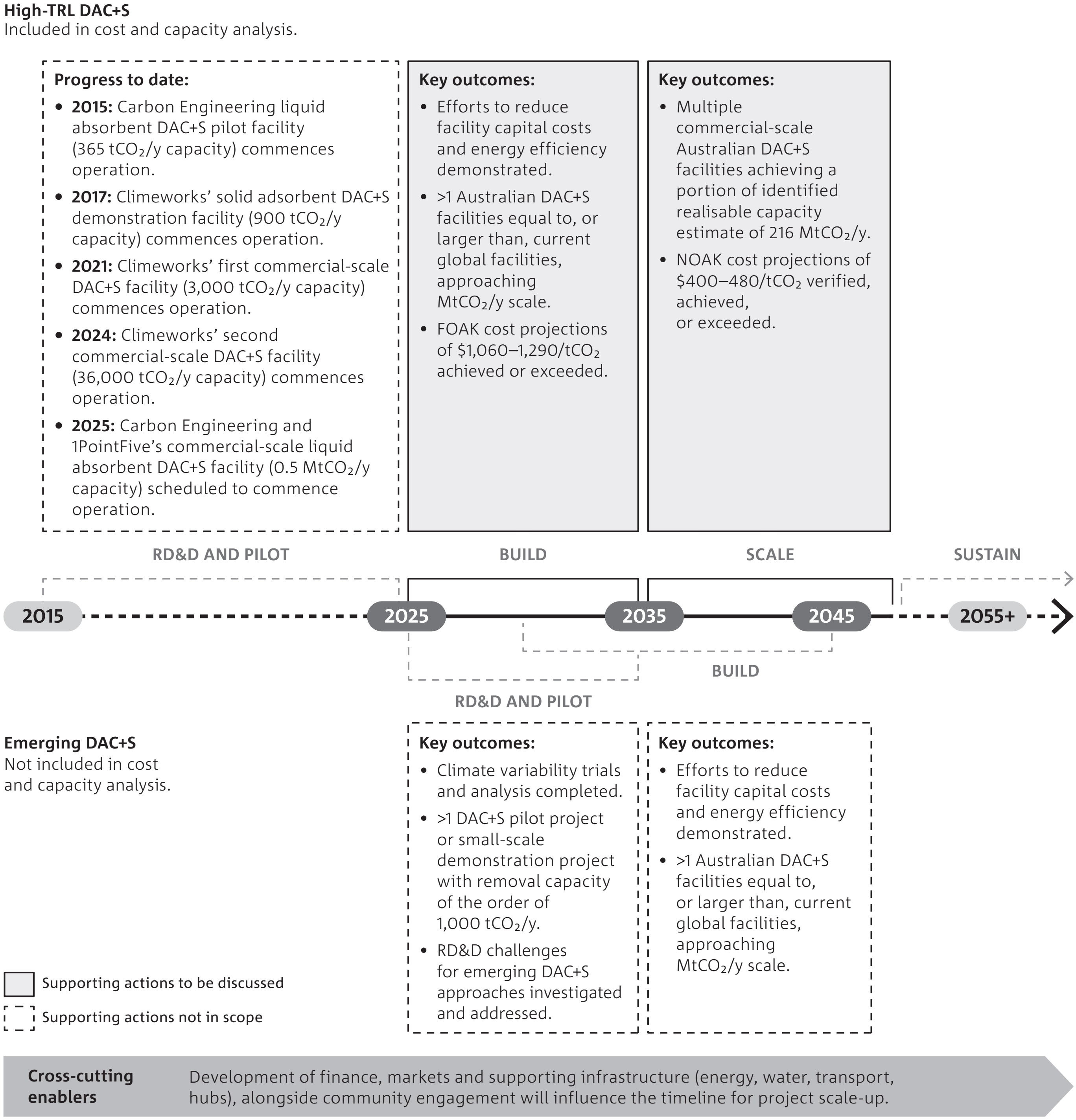
Figure 68: High-level summary of the scale-up pathways, including key outcomes by 2035 and 2045, for four representative CDR approaches considered in this Roadmap.

	2025 → 2035	2035 → 2045
DAC+S	• >1 large-scale high-TRL DAC+S facilities equal to, or larger than, current global facilities, with reduced costs and energy needs. • >1 pilot project or small-scale emerging DAC+S demonstration project. • Climate variability trials and analysis completed.	• Multiple commercial-scale high-TRL DAC+S facilities, with NOAK cost projections verified, achieved, or exceeded. • >1 emerging DAC+S facilities built equal to, or larger than, current global facilities, with reduced capital costs and energy efficiency demonstrated.
BiCR+S	• National biomass inventory developed, best practice in MRV and LCA established, and optimal sites identified. • Continued biochar market development. • High-durability biomass conversion processes integrated with CO_2 capture and storage processes and demonstrated at small-scale facilities.	• Increased carbon removal efficiency of slow pyrolysis (i.e. biochar) to maximise biomass resources. • >1 high-durability BiCR+S facilities approaching or exceeding megatonne-scale at cost parity with biochar.
OAE	• Site identification and feasibility analysis completed. • RD&D and trials for MRV of open system equilibration. • RD&D for efficient, low-cost and scalable process equipment. • >1 Australian pilot projects.	• At least 1 Australian OAE facility equal to, or larger than, currently planned global facilities. • Cost projections verified, achieved, or exceeded.
ERW	• Multiple pilot projects, with cost projection achieved or exceeded. • MRV framework established, combining on-field data with analytical models. • RD&D conducted to optimise carbon removal efficiency and inform rock material supply chain.	• Widespread commercial-scale ERW projects. • Cost projections verified, achieved or exceeded. • Rock mining and processing established as needed.
	Ongoing RD&D into additional alternative and emerging novel CDR approaches.	

13.1 DAC+S

Based on this Roadmap's analysis, Australia could capture and store up to 216 $MtCO_2$/y by 2050 via DAC+S. Given the maturity of these approaches, the main challenges are not in proving their feasibility, but in driving down capital costs and meeting their significant renewable energy demands.

Figure 69: Hypothetical scale-up pathway for high-TRL and emerging DAC+S approaches.



Note: The outcomes and timelines depicted in Figure 69 are designed to balance the current maturity of different DAC+S approaches in Australia with the rapid scale up needed to realise its full potential, recognising that there are multiple pathways to achieve scale. Due to the Roadmap's scope, this discussion focuses on supporting liquid and solid DAC+S approaches, however it is recognised that other emerging and alternative DAC+S approaches could also contribute to Australia's CDR portfolio.

The scale-up timelines and key outcomes for DAC+S shown in Figure 69 are divided into two streams. The first covers high-TRL DAC+S approaches based on solid and liquid DAC capture processes (see Section 4.1) and geological CO_2 storage (see Section 5.1). These approaches are supported by over ten years of global RD&D and pilot efforts, which can be leveraged to enable scaling up and commercial deployment. The second stream outlines timelines for emerging and alternative DAC+S approaches, which could benefit from the momentum of more mature DAC solutions.

The maturity of solid adsorbent and liquid absorbent DAC capture and geological CO_2 storage processes makes FOAK-scale facilities possible in Australia within the next decade (see Figure 69). Realising this depends on enablers like finance, infrastructure, and community engagement to provide capital, facilitate integration, and build social acceptance. These enablers will influence project deployment speed, with progress accelerating scale-up, but inaction risking delays (see Section 14 for details). Continued RD&D investment is essential to fully realise the potential of emerging and alternative DAC+S approaches, which include those using lower-TRL capture processes (see Table 5 in Section 4.1.2) or combined with mineral storage via in-situ and ex-situ mineral carbonation processes (see Section 7.1). While these approaches were not part of the cost and capacity analysis in this Roadmap, consultations indicate that several are in early development or pilot stages and could achieve notable cost reductions.

Actions to support scale up

> **Reduce capital costs:** Building FOAK solid adsorbent and liquid absorbent DAC+S facilities approaching the megatonne-scale will be contingent on breakthroughs that reduce their capital costs.

As mentioned in Section 9.4.3, facilities with high initial costs usually need high utilisation rates to operate efficiently, which requires a reliable, firmed electricity supply, adding to expenses. Innovations that cut capital costs for DAC+S facilities can unlock the potential for using cheaper renewable electricity, significantly reducing the levelised cost of CDR.

A mix of technical and non-technical factors can help lower FOAK capital costs, such as system design, integration, advanced materials, and external finance mechanisms (see Section 9.3). For instance, solid adsorbent DAC+S facility costs might be reduced with modular facility designs. Climeworks' Generation 3 DAC modules are prefabricated, modular cubes that have demonstrated a doubling of CO_2 capture capacity per module and a halving of energy consumption.[364] Their containerised design allows for both horizontal and vertical stacking, facilitating quicker deployment, reducing on-site construction, and lowering capital costs.

Potential actions:

- Focus RD&D into opportunities to reduce capital costs of DAC+S facilities, to facilitate cost-effective operation with low-cost variable renewable electricity.
- Consider modular facility designs when scaling solid adsorbent DAC+S facilities.
- Conduct independent LCA, climate sensitivity, and supply chain studies on the full DAC+S approach to determine cost-effective integration at commercial scale.[365]
- Develop a national database of RD&D gaps to accelerate DAC+S deployment by guiding researchers and funders toward the most urgent open questions.

363 Climate Change Authority (2024) Sector Pathways Review 2024. Commonwealth of Australia, Canberra. <https://www.climatechangeauthority.gov.au/sites/default/files/documents/2024-09/2024SectorPathwaysReview.pdf>.

364 Climeworks (2024) Next generation tech powers Climeworks' megaton leap. <https://climeworks.com/press-release/next-gen-tech-powers-climeworks-megaton-leap>.

365 RMI (2023) *The Applied Innovation Roadmap for Carbon Dioxide Removal (CDR)*. Rocky Mountain Institute, USA. <https://rmi.org/wp-content/uploads/dlm_uploads/2023/11/applied_innovation_roadmap_CDR.pdf>.

Conduct climate variability trials: There is a need for RD&D that trials DAC+S approaches across a range of geographic and climatic conditions to identify optimal temperature and humidity ranges for efficient operation.

As noted in this Roadmap, local ambient temperatures and relative humidity can influence system performance, water consumption, and energy requirements. Conducting climate variability trials to verify optimal operating conditions could help determine site feasibility for FOAK solid adsorbent and liquid absorbent DAC+S facilities. Additionally, there is an RD&D opportunity to develop process control systems that optimise operating conditions, reducing net costs and energy demands.

Potential actions:

- Identify optimal local climatic conditions and water requirements through diverse RD&D models and trials.
- Explore RD&D that optimises operating conditions, for example, developing tailored process control systems and algorithms.

Expand renewable energy capacity: To satisfy the substantial energy needs of large-scale DAC+S facilities, additional dedicated renewable infrastructure or integration with existing sources is necessary, ensuring other decarbonisation efforts remain unaffected. Simultaneously, RD&D efforts should focus on reducing the cost of renewable energy, given its major role in the overall cost of CDR.

To advance DAC+S from pilot to scale, new renewable energy infrastructure is needed to prevent renewable electricity from being diverted from Australia's decarbonising energy sector. This will require detailed, region-specific analyses to compare the costs and benefits of constructing new generation facilities against upgrading transmission networks or utilising excess grid electricity. A long-term strategy is needed to mitigate against potential renewable infrastructure gaps.

Enhancing DAC process energy efficiency lowers CDR costs. Optimising the operation of DAC+S plants through sequencing of regeneration cycles (i.e. prioritising times when renewable energy is abundant), using absorbents or adsorbents that regenerate at lower temperatures, or implementing electrical and thermal energy storage can improve cost-effectiveness and reduce energy consumption. Increased efficiency reduces dependence on renewable energy, lowering overall costs. Digital tools like AI/ML control models, energy management systems, and digital twins aid this optimisation.

Finally, for the liquid absorbent DAC process, creating cost-efficient high-temperature electric kilns could replace gas-fired systems, leading to reduced emissions and overall cost savings.

Potential actions:

- Develop process control systems that optimise the energy efficiency of DAC processes (e.g. regeneration sequencing).
- Develop digital tools for facility-level optimisation such as AI/ML models or digital twins.
- Optimise DAC adsorbents and absorbents to reduce the energy or temperature needed for regeneration.
- Consider additional energy sources and storage technologies beyond just solar, wind, and batteries.
- Perform regional energy evaluations and formulate a long-term plan for renewable energy integration.
- Advance the development of high temperature electric kilns for an electric DAC liquid adsorbent facility.
- Adopt industrial clusters to facilitate the use of potentially available resources and existing CCS infrastructure (see Section 14).

Reduce operational costs: There are opportunities to reduce other operating costs, such as sorbents and high temperature heat sources, through RD&D.

Replacing the adsorbent material represents a major operational expense in solid adsorbent DAC. Enhancing the durability of adsorbents can decrease the amount of material needed per tonne of CO_2 captured, thereby lowering costs. Furthermore, using inexpensive sorbents and optimising their performance, such as reaction kinetics and CO_2 capture efficiency, can further reduce overall operating expenses.

Operational costs for liquid absorbents may drop by using higher-performing, less corrosive absorbents. Liquid DAC processes rely on high-temperature heat, typically from gas-fired equipment. Cost-effective electric kilns could replace gas, reducing costs and cutting CO_2 emissions from natural gas, which leads to further net cost savings per tonne of CO_2 removed.

Potential actions:

- Explore RD&D into high capacity, low energy and durable adsorbents and absorbents.
- Advance the development of high temperature electric kilns for an electric liquid adsorbent DAC+S facility.

> **Verify geological storage:** The confirmed capacity for geological storage is limited, and it's necessary to confirm whether the sites identified in this analysis can reliably store the anticipated volumes of captured CO_2 durably. Additionally, increasing confidence in storage estimates for less developed sites could unlock more options for FOAK DAC+S projects that are also more cost-effective.

Determining the capacity of geological CO_2 storage is complex and often viewed as a trade-off between the theoretical maximum that can be stored and the confidence in that estimate. The method and data needed to estimate CO_2 storage capacity depend on the type, scale and detail of the chosen assessment. While the theoretical capacity of geological CO_2 storage is often very large, many sites may not be viable due to factors such as cost, infrastructure access, resource competition, and social acceptance.[366]

The key capacity outcomes here are based on geological storage sites that are either already operational for CCS projects or have been proven and advanced to a near-commercial stage. To enhance investor confidence and encourage sustainable funding in DAC+S facilities, it is crucial to improve the characterisation, modelling, and record-keeping of geological storage sites.

Potential actions:

- Enhance the classification of Australia's geological storage capacity to expand siting options for DAC+S.
- Create a comprehensive national registry of validated geological storage locations.
- Develop innovative approaches to monitoring, drilling, and asset management to reduce the cost of CO_2 storage and provide justification for long-term investment and public funding.[367]
- Strengthen social acceptance by implementing transparent monitoring systems, adopting long-term stewardship commitments and demonstrating environmental protection measures (see Section 14).
- Develop and optimise processes, models, and procedures to monitor and verify CO_2 migration and trapping.

Beyond 2050

Expanding DAC+S beyond 2050, from scaling to sustaining, is beyond this Roadmap's scope. Nonetheless, Figure 69 highlights key outcomes indicating Australia's preparedness to move into this phase. As noted in Section 1.4, Australia does not need to achieve all the capacity identified for DAC+S; a portfolio approach is advisable for a successful transition to net zero.

366 Bashir A, Ali M, Patil S, Aljawad MS, Mahmoud M, Al-Shehri D, Hoteit H, Kamal MS (2024) Comprehensive review of CO_2 geological storage: Exploring principles, mechanisms, and prospects. Earth-Science Reviews 249, 104672. <https://doi.org/10.1016/j.earscirev.2023.104672>.

367 CCUS SET-Plan (2021) CCUS Roadmap to 2030. European Strategic Energy Technology Plan, Brussels, Belgium. <https://www.ccus-setplan.eu/wp-content/uploads/2021/11/CCUS-SET-Plan_CCUS-Roadmap-2030.pdf>.

13.2 BiCR+S

Based on this Roadmap's analysis and depending on the approaches considered, Australia could have the capacity to capture and store up to 88 $MtCO_2/y$ in 2050 via BiCR+S. While slow pyrolysis to biochar can drive near-term carbon removal, large-scale commercial BiCR+S deployment will depend on Australia's ability to effectively allocate biomass resources and optimise supply chain logistics.

Figure 70: Hypothetical scale-up pathway for medium- and high-durability BiCR+S approaches.

Medium-durability BiCR+S
Not included in cost and capacity analysis; slow pyrolysis to biochar.

Progress to date:

- **2023:** Rainbow Bee Eater is certified by Puro.earth, with credits sold to Microsoft.
- **2023:** ~0.35 Mt of biochar is produced globally, a portion of this recognised as CDR.
- **2024:** Exomad Green reportedly has been removing 120,000 tCO_2/y via biochar, with two pyrolysis facilities operating.
- **2025:** Google agrees to purchase 0.1 Mt of CDR via slow pyrolysis to biochar from Varaha.
- **2025:** Biomass Projects, with support from Residual and Carbonfuture, commits to 0.5 Mt/y of CDR via slow pyrolysis to biochar by 2028.

RD&D AND PILOT

Key outcomes:

- Continued market development for market, supporting and expanding existing efforts.
- A national biomass inventory and allocation strategy established.
- Best practice in MRV and LCA established.
- Optimal sites identified through evidence-based supply chain logistics.

BUILD

Key outcomes:

- RD&D to improve carbon removal efficiency of slow pyrolysis conducted, supporting production scale-up and optimising biomass resources.

SCALE

SUSTAIN

2023 — 2025 — 2035 — 2045 — 2055+

High-durability BiCR+S
Included in cost and capacity analysis; fast pyrolysis to H_2 and combustion to electricity.

RD&D AND PILOT

Key outcomes:

- Biomass conversion processes successfully integrated with CO_2 capture and storage processes and demonstrated at small-scale (order of 1,000–10,000 tCO_2/y).
- A national biomass inventory and allocation strategy established.
- Optimal sites identified through evidence-based supply chain logistics.
- Best practice in MRV and LCA established.
- Efforts to reduce facility capital costs demonstrated.

BUILD

Key outcomes:

- >1 Australian BiCR+S facilities approaching or exceeding $MtCO_2/y$ scale.
- BiCR+S facilities demonstrate lower costs than high-quality biochar via slow pyrolysis (~\$333/tCO_2)

SCALE

SUSTAIN

Key outcomes:

- Multiple commercial-scale Australian BiCR+S facilities achieving a portion of identified realisable capacity estimate (88 $MtCO_2/y$).
- NOAK cost projections (\$140–260/tCO_2) verified, achieved or exceeded for BiCR+S facilities.

Supporting actions to be discussed

Supporting actions not in scope

Cross-cutting enablers Development of finance, markets and supporting infrastructure (energy, water, transport, hubs), alongside community engagement will influence the timeline for project scale-up.

Note: The outcomes and timelines depicted in Figure 70 are designed to balance the current maturity of different BiCR+S approaches in Australia with the rapid scale-up needed to realise their full potential, recognising that there are multiple pathways to achieve scale. While this discussion focuses on actions to support the BiCR+S approaches using fast pyrolysis to H_2 and combustion to electricity processes, other emerging and alternative BiCR+S approaches could also contribute to Australia's CDR portfolio.

The scale-up timelines and key outcomes for BiCR+S shown in Figure 70 are split into two streams. The first is centred on the medium-durability approach of slow pyrolysis to produce biochar. This approach is already proven at commercially significant scales and requires less small-scale testing or basic RD&D. For example, in WA, Biomass Projects, with support from Residual, are working on a commercial-scale biochar production facility that is projected to remove 500,000 tCO_2/y by 2028. Consequently, further commercial-scale deployment is possible in Australia in the next decade.

A prospective timeline for high-durability BiCR+S approaches using fast pyrolysis and combustion CO_2 capture processes and geological CO_2 storage processes is illustrated in the second stream of Figure 70. These individual processes are relatively mature when compared to other novel CDR processes, such as DAC. Nonetheless, deployment of BiCR+S at scale depends on successful integration of these capture and storage processes into a complete CDR approach. While global projects are testing this system integration, additional RD&D and engineering may be necessary before reaching megatonne-scale operations in Australia. Since slow pyrolysis is considered more established, its current average market price of A$270 per tCO_2 removed has been used as a benchmark for FOAK BiCR+S facilities utilising high-durability approaches. If these approaches can demonstrate, meet, or surpass this cost target, it could indicate their readiness for commercial-scale deployment and facilitate cost reductions toward the NOAK cost projections.

Importantly, slow pyrolysis to biochar is considered a medium-durability approach, with a storage timescale of centuries to millennia,[368] compared with high-durability CO_2 removal provided by fast pyrolysis to H_2 and combustion to electricity approaches. Slow pyrolysis to biochar also has a lower carbon capture efficiency (i.e. the percentage of carbon in biomass that can be durably captured, stored, or used) compared to the other BiCR+S approaches evaluated.

Slow pyrolysis for biochar generally captures and stores between 12–25% of the total biomass carbon, depending on the feedstock,[369] compared with up to 100% for other BiCR+S approaches. It is important to recognise that fast pyrolysis generates biochar along with concentrated CO_2, highlighting the ongoing importance of biochar as a storage medium. Furthermore, CDR through the production of biochar used as a soil amendment delivers co-benefits through reduced soil N_2O emissions, reduced fertiliser requirements, and enhanced soil properties, potentially making it easier and attractive to obtain social acceptance and scale up. While FOAK deployment is more feasible in the short term for slow pyrolysis producing biochar, support should also be given to alternative BiCR+S approaches due to their capacity for efficient biomass use and high-durability carbon removals.

A key challenge for all BiCR+S approaches is securing enough biomass and managing the costs of harvesting, processing, and transportation to BiCR+S facilities. Additionally, competition from other sectors for biomass complicates commercial deployment. For example, decarbonisation efforts could lead to increased competition for biomass resources from other sectors, such as low-carbon liquid fuel production, making efficient biomass use a priority. Therefore, by 2035, efforts will focus on confirming feedstock availability, optimising their allocation for BiCR+S approaches, and developing cost-effective, efficient supply chains.

Beyond technical feasibility, BiCR+S approaches require the support of cross-cutting enablers such as finance, markets, infrastructure, and community engagement. These must be developed at commercially relevant scales and costs. While advancements in these areas could speed up scaling, the absence of strategic action might cause substantial delays. For more details on these enablers, see Section 14.

368 Smith SM et al., (2024) The State of Carbon Dioxide Removal 2024 – 2nd Edition. <DOI:10.17605/OSF.IO/F85QJ>.

369 Pett-Ridge et al. (2023) Roads to removal: options for carbon dioxide removal in the United States. Lawrence Livermore National Laboratory. <https://www.osti.gov/biblio/2301853>.

Actions to support scale up

Develop a national biomass inventory and allocation strategy: Australia's ability to expand BiCR+S deployment depends on a better understanding of its biogenic feedstocks. This involves assessing their availability, alternative applications, and the potential environmental and economic effects of using them at commercial scales.

BiCR+S approaches can significantly influence land use and environmental health, potentially causing positive or negative effects. For instance, an unregulated rise in biomass demand might displace some food production activities. Therefore, implementing strict sustainability standards and establishing reliable methods to assess and report the impacts of BiCR+S value chains are essential. Additional details on possible actions are available in Section 8.4 of CSIRO's 2025 report: Opportunities and priorities for a low carbon liquid fuel industry in Australia.[370]

Potential actions:

- Use market sizing to estimate the demand and supply of primary and byproduct feedstocks and understand their applicability to BiCR+S approaches.
- Build on previous efforts (e.g. the Australian Biomass for Bioenergy Assessment, or ABBA, project) to create a comprehensive national biomass inventory to support BiCR+S approaches, ensuring data on location and availability are verified.
- Use land use modelling, such as CSIRO's Land Use Trade-Offs (LUTO) model, to examine land availability and competition between feedstock cultivation, agriculture, biodiversity, carbon removal and renewable energy.
- Determine accurate biomass pricing based on market demand, policy incentives, and local conditions and use this data to verify Australia's BiCR+S potential (see Section 14).
- Explore RD&D for new feedstocks and technologies.
- Establish clear standards for sustainability assessment and enhance support capabilities.

Implement cost-effective supply chain logistics: Transitioning BiCR+S approaches from pilot to build to scale will require an effective transport network. Optimal site selection will require an in-depth understanding of cost-effective supply chain logistics.

Transporting biomass to a biorefinery is a significant cost in BiCR+S approaches. Costs vary greatly based on the biomass feedstock type, its distance from the biorefinery, and the transportation method. This analysis assumes wet biomass transportation with drying at the BiCR+S facility. Future research could explore drying and densifying biomass before long-distance transport, as stakeholders have pointed out this could lower costs.

Biomass can be moved by road, rail, and sea; however, this analysis only considered road transport with cost data from CSIRO's TraNSIT tool. For larger quantities over longer distances, rail or shipping might be more economical. Regarding CO_2 transportation, pipelines could connect BiCR+S facilities to storage sites, but establishing new long-distance pipelines involves substantial regulatory and social acceptance hurdles.

While this Roadmap has focused on optimising transport setups for CO_2 removals, the best solutions could vary for BiCR+S approaches used with other industries, like low-carbon fuel production. Such industries may have unique processing needs, constraints, or infrastructure that affect supply chain logistics. Additionally, integrating low-carbon liquid fuel production with BiCR+S might be feasible to match the hydrogen-to-carbon ratio of various feedstocks.

Potential actions:

- Explore the role of feedstock drying and densification.
- Expand and explore tools such as CSIRO's TraNSIT model to map logistics pathways from feedstock sources to potential BiCR+S sites, analyse transport costs and emissions, and evaluate opportunities for co-location (see Section 14).
- Conduct techno-economic analysis to determine Australia's potential for CO_2 pipelines or explore the potential to reuse existing gas pipeline infrastructure.
- Consider opportunities to combine BiCR+S approaches with low carbon liquid fuel production.

370 O'Sullivan CA, Mishra A, Mueller S, Nadeem H, Flentje W (2024) Opportunities and Priorities for a Low Carbon Liquid Fuel Industry in Australia. CSIRO Towards Net Zero Mission, Australia. <https://www.csiro.au/-/media/Missions/TNZ/Opportunities-and-priorities-for-a-Low-Carbon-Liquid-Fuel-Industry.pdf>.

Optimise process design: Scaling BiCR+S approaches will require cost-effective process design. Priority should be given to RD&D efforts that unlock the potential of emerging and alternative BiCR+S approaches, enhance existing process efficiencies, or open up new revenue streams through byproducts.

RD&D to improve the carbon capture efficiency of BiCR+S approaches could reduce the amount of biomass required per tonne of CO_2 captured, lowering total system costs. RD&D aimed towards producing high carbon feedstocks,[371] advancing preprocessing steps[372] and tailoring conversion techniques to specific biomass chemistries,[373] could increase CO_2 yields.[374]

Emerging and alternative BiCR+S approaches, including those using BiCR capture processes not considered for cost and capacity analysis in this Roadmap (see Table 2 in Section 2.2.2), or combined with mineral storage via in-situ and ex-situ mineral carbonation processes (see Section 7.1), can benefit from ongoing RD&D support to enable pilots and demonstrations in Australia. They have the potential to reduce energy costs, improve the use of biomass resources, and better meet regional needs.

The byproducts of some BiCR+S approaches, such as H_2 and solid carbonates, can be used to generate additional project revenue. Optimising the production of these byproducts enables projects to develop synergistic, cost-efficient deployment opportunities. Placing BiCR+S facilities near potential consumers of these byproducts can enhance commercial viability.

Potential actions:

- Invest in RD&D for emerging and alternative BiCR+S approaches.
- Explore RD&D for commercially mature BiCR+S approaches, including the development of advanced pre-processing steps,[375] tailored conversion techniques or innovative heat transfer systems.
- Optimise the production and utilisation of BiCR+S byproducts, such as H_2, as an alternative revenue stream.

Verify geological storage: Developing and verifying geological storage sites could substantially increase Australia's future BiCR+S capacity.

As noted in Section 13.1, verified geological storage capacity is limited and improving confidence in storage estimates for less mature sites could unlock additional, more cost-effective options for FOAK/NOAK BiCR+S projects.

Potential actions:

- See Section 13.1 for a summary of potential actions.

Beyond 2050

Expanding BiCR+S beyond 2050 from scaling to sustaining is beyond this Roadmap's scope. Nonetheless, as illustrated in Figure 70, certain key outcomes could indicate Australia's preparedness to move into this phase. As noted in Section 1.4, Australia does not need to achieve all the identified BiCR+S capacity for a successful transition to net zero, and a portfolio strategy is advised.

371 Advanced Research Projects Agency - Energy. "Roots: Rhizosphere Observations Optimizing Terrestrial Sequestration." (December 2016) https://arpa-e.energy.gov/ technologies/programs/roots; Orr, Douglas J., Auderlan M. Pereira, Paula da Fonseca Pereira, Ítalo A. Pereira-Lima, Agustin Zsögön, and Wagner L. Araújo. "Engineering Photosynthesis: Progress and Perspectives." [In eng]. F1000Research 6 (October 2017) at p. 1891-91 (https://www.ncbi.nlm.nih.gov/pmc/articles/ PMC5658708/); South, Paul F., Amanda P. Cavanagh, Helen W. Liu, and Donald R. Ort. "Synthetic Glycolate Metabolism Pathways Stimulate Crop Growth and Productivity in the Field." Science 363, no. 6422 (January 2019) at p. eaat9077 (https:// science.sciencemag.org/content/363/6422/eaat9077)

372 Pett-Ridge et al. (2023) Roads to removal: options for carbon dioxide removal in the United States. Lawrence Livermore National Laboratory. <https://www.osti.gov/biblio/2301853>.

373 Zhao C, Ma Z, Huang C, Wen J, Hassan M. Editorial: From biomass to bio-energy and bio-chemicals: Pretreatment, thermochemical conversion, biochemical conversion and its bio-based applications. Front Bioeng Biotechnol. 2022 Oct 28;10:975171.

374 Pett-Ridge et al. (2023) Roads to removal: options for carbon dioxide removal in the United States. Lawrence Livermore National Laboratory. <https://www.osti.gov/biblio/2301853>; RMI (2023) The applied innovation roadmap for CDR. <https://rmi.org/insight/the-applied-innovation-roadmap-for-cdr/>.

375 Pett-Ridge et al. (2023) Roads to removal: options for carbon dioxide removal in the United States. Lawrence Livermore National Laboratory. <https://www.osti.gov/biblio/2301853>.

13.3 OAE

Australia has the potential to remove up to 7 $MtCO_2$/y in 2050 through OAE; however, determining the most technical, economical and environmentally suitable approaches and sites for large-scale deployment will require significant RD&D.

Figure 71: Hypothetical scale-up pathway for electrolytic OAE.

International progress:

- **2023:** Equatic operates two pilot facilities (100 $kgCO_2$/day capacity) in Los Angeles (US) and Singapore.
- **2024:** Equatic announces the scaling up of the Singaporean pilot to become a demonstration facility (3,650 tCO_2/y capacity), and announces the construction of a commercial-scale plant (109,500 tCO_2/y capacity) in Canada.
- **2025:** Captura operates a pilot facility (1,000 tCO_2/y capacity) in Hawaii (US). Ebb Carbon announces the scaling up of an electrodialytic OAE pilot facility from 100 to 1,000 tCO_2/y in Washington (US).

Key outcomes:

- Site identification and feasibility analysis completed.
- RD&D for MRV of open system equilibration progressed.
- RD&D for efficient, low-cost and scalable process equipment progressed.
- >1 Australian pilot projects (>3,000 tCO_2/y), potentially co-located with existing water processing infrastructure.

Key outcomes:

- At least 1 Australian OAE plant equal to, or larger than, currently planned global facilities (110 $ktCO_2$/y plant)
- FOAK cost projections of $670-890/$tCO_2$ verified and achieved or exceeded.

Key outcomes:

- Multiple commercial-scale Australian OAE facilities achieving a portion of identified realisable capacity estimate (7 $MtCO_2$/y).
- NOAK cost projections verified and achieved or exceeded ($80–140/$tCO_2$ when co-located with existing infrastructure, $210–390/$tCO_2$ when operating as a standalone plant).

RD&D AND PILOT | BUILD | SCALE | SUSTAIN

2023 | 2025 | 2035 | 2045 | 2055+

Cross-cutting enablers: Development of finance, markets and supporting infrastructure (energy, water, transport, hubs), alongside community engagement will influence the timeline for project scale-up.

Supporting actions to be discussed

Supporting actions not in scope

Note: The outcomes and timelines depicted in Figure 70 are designed to balance the current maturity of electrolytic OAE in Australia with the rapid scale-up needed to realise its full potential, recognising that there are multiple pathways to achieve scale. While this discussion focuses on actions to support electrolytic OAE, other emerging and alternative OAE approaches could also contribute to Australia's CDR portfolio.

The outcomes and timeline shown in Figure 71 highlight a specific electrochemical OAE approach, namely Equatic's closed loop electrolytic OAE approach, due to its relatively high TRL (see Section 3.1.1). This approach has already been demonstrated in the US with the capacity to remove 3,600 tCO_2/y.

The main challenges to scaling electrolytic OAE in Australia are technological and non-technological. Currently, there are no pilot projects. The focus until 2035 is to find suitable sites that are economically, technically, and environmentally viable for OAE facilities. Concurrently, RD&D efforts are needed to improve electrolyser efficiency, lower costs, and develop reliable MRV protocols. Addressing these issues could enable at least one commercial-scale electrolytic OAE facility by 2045. Regarding emerging and alternative OAE approaches (see Table 3 in Section 3.1.2), ongoing RD&D investment is essential to realise their full potential. These approaches were not part of the cost and capacity analysis in this Roadmap, and additional analysis is necessary to evaluate their technical feasibility and compare their potential to existing, more mature approaches.

Finally, scaling OAE will require support from a range of cross cutting enablers such as finance, markets, infrastructure, and community engagement, with more details discussed in Section 14. These cross-cutting enablers are critical not only to support the economic viability of OAE but also to ensure that the impacts on the environment and local communities are well understood, communicated and managed.

Actions to support scale up

> **Determine site feasibility:** This Roadmap's analysis indicates that cost reductions for electrolytic OAE facilities is possible by co-locating them with desalination or other coastal water treatment plants that have intake and outfall infrastructure. Additionally, environmental benefits and impacts will play a role in choosing the site.

Co-locating OAE facilities with existing desalination plants in Australia could significantly reduce implementation costs by sharing intake and outfall infrastructure. However, with few large-scale desalination facilities available, realisable capacity becomes constrained. In contrast, developing a large-scale standalone OAE facility would require significant civil works (i.e. dedicated ocean intake, screening, prefiltration, and outfall systems). A techno-economic analysis is necessary to better understand the economic trade-offs. See Section 14 for greater detail on co-located hubs and opportunities for shared infrastructure with other industrial sectors.

Assessing the technical feasibility of potential sites is essential for implementing OAE commercially. Further analysis is required to determine the optimal size of the OAE facility that can be integrated with existing desalination plants, especially to handle additional seawater intake. For example, an OAE facility designed to capture 1 Mt of CO_2 annually would require approximately 220 gigalitres (GL) of seawater intake per year. This volume accounts for about 65% of the Victoria Desalination Plant's current intake, which is 340 GL annually to produce 150 GL of drinking water.[376] There may be further opportunities to recirculate between an OAE facility and desalination plant to improve the desalination plant's water recovery rate.

In terms of environmental feasibility, it is important to understand and carefully monitor any effects on marine habitats at each scale-up phase, even with closed OAE systems. This includes potential co-benefits and impacts.

Potential actions:

- Conduct robust techno-economic analysis on all OAE site configurations.
- Assess the technical feasibility of co-locating OAE by engaging desalination plant operators and conducting system integration analysis and feasibility studies.
- Conduct LCA and environmental impact assessments to identify potential co-benefits or impacts that might influence site feasibility.
- Conduct detailed ocean mapping and biogeochemical modelling to identify areas where adding alkalinity would be most effective (i.e. CO_2 capture efficiency) and understand its impacts on ocean systems.[377]
- Assess other potential deployment sites such as wastewater facilities and rivers.[378]

376 Department of Energy, Environment and Climate Action (2024) Desalination Plant. Victorian Government, Melbourne, Australia. <https://www.water.vic.gov.au/water-sources/desalination/desalination-plant>.

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

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

Optimise electrolyser cost and performance: Electrolyser energy consumption is the main factor in operating costs, and efficiencies are nearing their physical limits. Reducing the capital and operational expenses of OAE facilities will require technological innovation.

Electrolysers represent the most capital-intensive equipment in the modelled electrolytic OAE approach. To enable cost-effective scaling of this approach, substantial cost reductions in electrolyser manufacturing are necessary, achieved through incremental design enhancements and mass production.

Another key RD&D focus is improving the durability of electrodes and electrolysers, especially given the corrosive operating environment. Enhancing component longevity can lower operating costs by decreasing replacement frequency and expenses.

Electrolyser operating costs are largely driven by the cost of electricity, which could be reduced through innovations in renewable energy generation, co-locating with existing industrial facilities like desalination or wastewater treatment plants, and improving electrolyser efficiency. Additionally, developing electrolysers that can be turned off during high electricity price periods and powered on when prices are lower will further lower operating expenses.

Lowering the cost of renewable electricity itself is an additional RD&D priority. For OAE to move from pilot projects to large-scale implementation, detailed site-specific analysis is essential. This should compare the costs and benefits of constructing new energy infrastructure against upgrading existing transmission lines, utilising surplus grid electricity, or co-locating with other industries to access their energy supply.

Potential actions:

- Conduct RD&D on electrolyser designs to reduce costs, facilitate mass production and improve durability.
- Improve electrolyser efficiency and design for flexible operation.
- Set site specific renewable energy targets and develop a strategy to meet these targets and enable FOAK OAE deployment.
- Consider additional energy sources and storage technologies beyond just solar, wind, and batteries.
- Co-locate OAE facilities to support efficient integration with existing electricity grid infrastructure in industrial areas.

Develop MRV for OAE: The MRV methodology for OAE operating in open water environments requires further RD&D to better measure and verify the total amount of CDR and the impact on the marine ecosystems.

The OAE approach modelled in this analysis is based on Equatic's closed CDR system, meaning CO_2 capture and storage happen within the OAE facility, and that the net amount of captured CO_2 can be easily and accurately measured. However, in other OAE approaches, CO_2 capture and storage happen outside of the OAE facility in an open environment and sometimes over long periods, making it less straightforward to measure and monitor the net amount of captured CO_2.

MRV methodologies also need to account for potential environmental impacts, such as changes to ocean alkalinity, potential acid leaks, and/or biogeochemical feedbacks, which can vary between approaches.

RD&D is needed to support the development of robust MRV methodologies, including setting tailored baselines for environmental impacts[379] and improving data availability through advanced observation and modelling tools.[380]

Potential actions:

- RD&D to support the development of robust MRV methodologies, including setting tailored baselines for environmental impacts for different OAE approaches.
- RD&D to advance ocean carbon models and monitoring tools.
- Support collaborations for knowledge exchange and improve data availability and accessibility.

Beyond 2050

Extending OAE beyond 2050 (from scale to sustain) is not covered in this Roadmap. Nonetheless, as illustrated in Figure 71, certain key outcomes could indicate Australia's preparedness for this transition. As noted in Section 1.4, Australia does not need to achieve all the identified OAE to enable a successful shift to net zero; a portfolio approach is advisable.

379 Oschlies A, Bach LT, Fennel K, Gattuso J-P, Mengis N (2025) Perspectives and challenges of marine carbon dioxide removal. Frontiers in Climate 6, 1506181. <https://doi.org/10.3389/fclim.2024.1506181>.

380 Oschlies A, Bach LT, Fennel K, Gattuso J-P, Mengis N (2025) Perspectives and challenges of marine carbon dioxide removal. Frontiers in Climate 6, 1506181. <https://doi.org/10.3389/fclim.2024.1506181>.

13.4 ERW

Based on this Roadmap's analysis, Australia might be able to capture and store up to 22 $MtCO_2$/y by 2050 using ERW, with projected costs ranging from A\$190 to A\$280 per tCO_2 removed. Key efforts required include advancing RD&D in weathering processes, developing reliable and scalable MRV methods, and improving feedstock supply chains and transportation. These initiatives are crucial for Australia to achieve part of this capacity and stay cost-competitive internationally.

Figure 72: Hypothetical scale-up pathway for ERW approaches.

International progress

- **2023–24:** Lithos signs offtake agreements to remove a total of 165,640 tCO_2 by 2028.
- **2024:** UNDO reports a cumulative capture of 63,136 tCO_2, and signs offtake agreement to remove 15,000 tCO_2.
- **2024-25:** Eion signs offtake agreements to remove a total of 86,707 tCO_2 by 2030.

Australian progress:

- **2018:** James Cook University five-year ERW field trial begins.
- **2023:** Carbonaught begins a pilot project in QLD (~2,000 tCO_2/y capacity).
- **2023:** Agseq is founded.
- **2023:** A study funded by the NSW Gov finds the State's CDR potential via agricultural ERW to be 0.07–0.31 $MtCO_2$/y.
- **2024:** Researchers from the Australian National University publish results from a 16-week lab trial (max. 32 $kgCO_2/t_{rock}$).

Key outcomes:

- Multiple Australian pilot projects across different locations, achieving or exceeding an aggregated CDR amount of 0.33 $MtCO_2$.
- FOAK cost projection of \$400–500/tCO_2 achieved or exceeded.
- A robust and verifiable MRV framework established, combining on-field data with analytical models.
- Advanced and scalable data collection and monitoring technologies adopted.
- RD&D to optimise carbon removal efficiency conducted.
- Modelling and planning of rock material supply chains (via quarries) and transport routes completed.

Key outcomes:

- Widespread commercial-scale Australian ERW projects, achieving or exceeding an aggregated CDR amount of 1 $MtCO_2$/y.
- NOAK cost projections (\$190–280/ tCO_2) verified, achieved or exceeded.
- For-purpose rock mining and processing established where needed.

Key outcomes:

- Widespread commercial-scale Australian ERW operations achieving a portion of identified realisable capacity estimate of 22 $MtCO_2$/y.
- Effective scaling up of rock material supply chains, especially for-purpose rock mining and processing activities in coordination with quarrying capacity.
- Transport emissions and costs reduced through investment in low- or zero- emission vehicles and optimised transport modes.

RD&D AND PILOT | BUILD | SCALE | SUSTAIN

2018 | 2025 | 2035 | 2045 | 2055+

Cross-cutting enablers: Development of finance, markets and supporting infrastructure (energy, water, transport, hubs), alongside community engagement will influence the timeline for project scale-up.

Supporting actions to be discussed

Supporting actions not in scope

Note: The outcomes and timelines depicted in Figure 72 are designed to balance the current maturity of ERW in Australia with the rapid scale up needed to realise its full potential, recognising that there are multiple pathways to achieve scale. While this discussion focuses on actions to support agricultural ERW, other emerging and alternative ERW approaches could also contribute to Australia's CDR portfolio.

Australia has abundant natural resources and agricultural land suitable for large-scale ERW deployment. Pilot projects have been conducted in Australia, albeit at smaller scales compared to global efforts. By 2035, Australia should deploy and scale multiple pilots across high-potential sites, aiming for at least 0.33 Mt of CDR during this phase. RD&D are needed to improve the process, develop a scalable MRV framework, and support project deployment across diverse environments. Data from varied climate and soil conditions will support the development and validation of MRV protocols.

During the next Build stage, Australia should focus on expanding pilot projects to achieve full commercial operation by 2045, while continuing to initiate new pilots at high-potential sites. Nationally, the goal for CDR through ERW should reach at least 1 $MtCO_2/y$. Improving cost efficiency and investing in dedicated rock mining and processing infrastructure are crucial for supporting greater project activity nationwide.

Finally, like other CDR methods, it is crucial to simultaneously develop and expand cross-cutting enablers such as finance, markets, infrastructure, and community engagement, as they are important for the commercial-scale implementation of ERW (see Section 14).

Actions to support scale up

Improve MRV: The MRV process for ERW approaches is challenging due to their open system nature. A combined approach that includes on-site sampling and modelling is likely required to estimate how much carbon is removed through mineral weathering process. As data availability, model precision and sensing technologies improve, the costs associated with MRV could decrease.

The development of robust and widely applicable MRV methodologies faces several limitations due to gaps in understanding and data regarding local weathering and carbon removal processes. Small-scale pilot projects primarily conduct MRV through numerical estimates of the net CO_2 removed, supported by on-site, manual sampling data, which is both costly and time-consuming.

For ERW to be ready for a Build phase by 2035 in Australia, the MRV methodology must be refined using empirical data and integrated analytical models. Pilot projects can validate the analytical model's accuracy by supplying extra data, helping to lessen the dependence of the MRV process on on-site, manual data collection, supporting the achievement of FOAK cost targets.

By 2045 when at least one project operates at commercial scale, the key outcome should be the demonstrated ability to achieve significant cost reductions in MRV and the ability to adapt developed MRV frameworks for other projects. The MRV cost target of A$25 per tCO_2 removed serves as an aspiration for NOAK projects.

Enhancing the efficiency and cost-effectiveness of data collection, along with increasing model accuracy, are central RD&D objectives to support ERW projects across their pilot, build and scaling phases. These objectives can be realised by adopting advanced remote sensing technologies and modelling methods. RD&D can also play a role in making relevant data publicly accessible and in supporting model development and progression, including utilising existing knowledge and frameworks. Such efforts could lower the costs for future ERW project developers.

Potential actions:

- Adopt advanced remote sensing technologies, including drones and satellites, to enable scalability of data collection across time and space and potential cost reductions.
- Integrate AI/ML techniques into the model development process to improve the model accuracy and reduce the requirement for on-field data input.
- Develop MRV methodologies that combine empirical data and models.
- Support public RD&D programs to build and update national databases on soil pH and carbon.
- Investigate the potential to adapt global MRV frameworks and models to regional contexts.

Optimise supply chains and the transport of materials: Expanding ERW projects necessitates diversifying material sources, such as dedicated mining or quarry byproducts, and optimising transportation to handle increased volumes with lower emissions, ultimately lowering total costs.

Small-scale pilot projects of ERW can utilise byproduct rocks from quarries, allowing projects to bypass the need to grind and crush these materials and save costs. However, as Australia transitions towards commercial deployment by 2045, establishing additional for-purpose rock mining and processing operations is likely necessary to meet the volume of rocks required, which would add to the overall project costs.

Ongoing strategic planning is essential for the rock materials supply chain. This involves balancing current quarry capacity and available supply with the new operations and infrastructure required to reduce disruptions during scaling-up, as well as optimising the distance between the rock source, processing facilities, and dispersion sites to reduce transport costs.

Furthermore, there is an opportunity to explore other modes of transport beyond the road freight option considered in this analysis, such as rail and sea freight, which can offer lower transport costs over longer distances. The use of low- or zero-emission heavy vehicles may also lead to reductions in net emissions, improved energy efficiency, and improvements in the net cost.

Potential actions:

- Gather data and model the current and projected capacity of rock quarries and other potential feedstocks.
- Conduct in-depth modelling activities of different supply and transport options.
- Invest in low- or zero-emission heavy vehicles to reduce emissions associated with transporting rock materials throughout the supply chain.

Optimise carbon removal efficiency: RD&D plays a crucial role in enhancing the understanding of the factors and interactions that influence weathering and carbon removal rates. This knowledge can guide decision-making and strategies to maximise the efficiency and cost-effectiveness of ERW projects.

Various factors influence weathering and the rate of carbon removal, including soil and rock properties, climate, and agricultural methods. For instance, different rock types need specific pH levels at the soil surface to weather effectively and exhibit different weathering rates. Mineral composition, soil pH at deeper layers, and water availability can all impact soil carbon pathways.

The geochemical and biogeochemical interactions among these factors can differ across space and time. Therefore, it is important to enhance understanding of these interactions both broadly and at specific ERW sites. This knowledge can guide the selection of rock types and operational practices to optimise carbon removal efficiency and cost-effectiveness.

Potential actions:

- RD&D to understand drivers of weathering and carbon removal rate, taking into account Australia's unique geographical and environmental landscape and climate.

Obtain buy-in from farmers and landowners: Gaining support from farmers and landowners is crucial for acquiring the large land areas needed to implement and expand ERW projects, as well as obtaining the necessary licenses. RD&D can play a key role by helping assess and demonstrate the co-benefits and impacts of ERW on soil and crop productivity.

Implementing and scaling up ERW requires a significant area of land and potential changes or adaptation to current land use and management practices. As a result, it is important to obtain buy-in and social acceptance to operate from farmers and landowners from early stages. This can be achieved through effective community engagement strategies (see Section 14).

Furthermore, the additional benefits of ERW for soil health and productivity, such as reducing soil acidification, supplying nutrients, supporting plant growth, and benefiting the broader soil ecosystem, can serve as a compelling reason for farmers and landowners to support and partner with ERW projects. While these benefits are generally recognised, they need to be demonstrated and quantified in various locations and over time, offering farmers and landowners clear and transparent data for informed decision-making. Simultaneously, any negative effects on soil and crop productivity should also be measured, evaluated, and addressed with appropriate mitigation strategies. Performing these assessments can boost stakeholder confidence and generate valuable data and insights to develop accurate MRV methodologies.

Agricultural practices like fertilisation, irrigation and tilling can alter soil pH and moisture, thereby affecting weathering and carbon removal rates. It's important to note that weathering of added rock does not always equate to CDR, particularly in acidic soils.

Potential actions:

- RD&D to demonstrate and quantify the co-benefits and impacts of ERW on soil and crop productivity, and devise adaptation or mitigation strategy where needed.

Beyond 2050

Scaling multiple ERW pilot and commercial projects beyond 2045 is outside this Roadmap's scope. However, as illustrated in Figure 72, certain key outcomes could indicate Australia's preparedness for this transition. As noted in Section 1.4, Australia does not need to achieve all the identified ERW capacity to enable a successful shift to net zero, and adopting a portfolio approach is recommended.

13.5 Other RD&D opportunities

The global CDR landscape is evolving rapidly, with a constant flow of scientific and technological breakthroughs. While this Roadmap has focused on four representative CDR approaches, there are broader CDR opportunities that require strategic support and sustained RD&D investment and could be valuable additions to future iterations of the Roadmap. Specifically, these areas include:

- **Unexplored capture and storage combinations:** A key example is the integration of mineral storage (or mineral carbonation) with different CO_2 capture processes. For example, the integration of mineral storage with DAC or BiCR both show promise but require continued RD&D and scale-up efforts (see Box 9).
- **Emerging and alternative CO_2 capture processes:** For each of the representative CDR approaches, there are emerging and alternative CO_2 capture processes that have the potential to improve CDR capacity and cost outcomes.
- **New capture and storage innovations:** The use of microalgae is gaining attention for CDR and has active Australian research efforts.[381] While algae can sequester large amounts of carbon and provide potential ecosystem co-benefits, further research is needed to demonstrate that intensive algal systems can be scaled reliably, economically, and provide durable CDR.

As with many CDR approaches, the investments in the examples and those detailed in the Roadmap can be optimised with other carbon management pathways. For instance, CCU options include mineral storage for durable building products, and DAC and microalgae are being scaled to support low-carbon fuel production.

Box 9: Mineral storage (mineral carbonation).

Mineral storage offers a promising pathway for durable CO_2 storage with identified Australian resources and market activity (see Section 7.1). Continued RD&D is essential in improving the commercial viability of mineral carbonation processes and supporting the integration with CO_2 capture processes. Priority areas include the following:[382]

- In-situ mineral carbonation:
  - Site evaluation: Characterise potential storage sites, assess risks, and quantify mineral storage potential.
  - Social acceptance and regulatory: Build public trust, engage local and Indigenous communities and seek necessary approvals.
  - Mineral reactivity and modelling: Understand reaction rates, volume changes, and quantification at the pore-scale.
  - CO_2 injectivity and engineering: Improve knowledge of CO_2 flow, injectivity, and reservoir design in Australian rocks.
  - Water and energy use: Assess water needs (including recycling options), and energy and environmental impacts.
- Ex-situ mineral carbonation:
  - Mineral reactivity and kinetics: Understanding and enhancement of reactivity (particularly less-reactive phases).
  - Integration: Explore synergies between DAC and accelerated mineral carbonation (AMC) processes, and explore systems integration with relevant industries.
  - pH swing: Investigate chemical processes to optimise carbonation efficiency.
  - Continuity: Ensure process reliability, particularly with renewable energy inputs.
  - Magnesium source: Determine optimal magnesium compounds for mineral carbonation.

381 CSIRO CarbonLock (2025) Microalgae gaining traction in carbon dioxide removal community. <https://research.csiro.au/carbonlock/microalgae-gaining-traction/>.

382 Stakeholder consultation

14 Cross-cutting enablers

Countries around the world are committed to reaching net zero emissions under the Paris Agreement, and Australia shares this goal.[383] Australia has already committed to incentivising the development of novel CDR as part of achieving this goal.[384] Incentivisation can occur through support for RD&D, and, as technologies mature, via carbon markets or other financial instruments. In the near term, the voluntary carbon market (VCM) is anticipated to play a catalysing role, providing early demand signals, mobilising private capital, and supporting uptake while compliance markets and international regulatory frameworks evolve. Australia has also agreed in principle to take a leading role in addressing domestic and international regulatory barriers that may hinder the uptake of novel CDR.[385] In line with the endorsement of these recommendations and opportunities, the details of this Roadmap and recommendations for next steps will help ensure the development, deployment, and scaling of novel CDR in Australia to support the transition to net zero and beyond.

Once international accounting methodologies are finalised, novel CDR could be integrated into Australia's national reporting frameworks and carbon markets. This integration could incentivise the uptake of novel CDR in Australia and accelerate trends already underway in the VCM.

Integrating novel CDR into Australia's national reporting and carbon market

The IPCC Task Force on National Greenhouse Gas Inventories is currently developing guidelines for accounting for CDR approaches, expected before the end of 2027, with active contributions from Australia. Once finalised, these guidelines will provide a clear international methodology to recognise emissions reductions from CDR towards United Nations Framework Convention on Climate Change (UNFCCC) and Paris Agreement mitigation targets.

In Australia, the *National Greenhouse and Energy Reporting Act 2007* (NGER Act) provides a robust legislative framework for domestic emissions measurement and reporting under the NGER Scheme. This framework is positioned to support Australia's adoption of the new IPCC guidance for CDR accounting methods and reflect the resulting emissions removal in the Australian National Greenhouse Gas Accounts (NGA, published by DCCEEW), including Australia's UNFCCC and Paris Agreement reporting commitments. For CDR activities not covered by NGER Scheme reporting, an alternative source of complete and consistent national activity data will be needed for this abatement to be included in the NGA.

The *National Greenhouse and Energy Reporting (Measurement) Determination 2008* (Measurement Determination) provides the methods and criteria for calculating GHG emissions and energy data under the NGER Act. The Measurement Determination has been updated annually since 2009 to reflect the best available science, technologies, practices and stakeholder feedback.

The Safeguard Mechanism is the Australian Government's policy for reducing emissions at Australia's largest industrial facilities. It sets legislated limits, known as baselines, on the net greenhouse gas emissions of covered Safeguard facilities. Covered facilities can reduce their net emissions by surrendering ACCUs, or Safeguard Mechanism Credits (SMCs) which are issued to facilities with emissions below baseline levels.

383 Department of Climate Change, Energy, the Environment and Water (2025) Australia's net zero plan. <https://www.dcceew.gov.au/sites/default/files/documents/net-zero-report.pdf>.

384 Department of Climate Change, Energy, the Environment and Water (2023) Annual climate change statement 2023. <https://www.dcceew.gov.au/sites/default/files/documents/annual-climate-change-statement-2023.pdf>; Department of Climate Change, Energy, the Environment and Water (2025) Australia's net zero plan. <https://www.dcceew.gov.au/sites/default/files/documents/net-zero-report.pdf>.

385 Department of Climate Change, Energy, the Environment and Water (2023) Annual climate change statement 2023. <https://www.dcceew.gov.au/sites/default/files/documents/annual-climate-change-statement-2023.pdf>.

Australia's carbon crediting system

The Australian Carbon Credit Unit (ACCU) Scheme, established under the Carbon Credits (*Carbon Farming Initiative) Act 2011* (CFI Act), allows project proponents to earn carbon credits for activities that reduce, avoid or sequester emissions. Projects registered under the ACCU Scheme are required to meet legislated integrity criteria known as the Offsets Integrity Standards.[386] These standards ensure carbon credits issued under the ACCU Scheme represent genuine emissions reductions that may be counted towards Australia's international emissions reduction obligations under the Paris Agreement.[387] Together with other provisions of the CFI Act, the Offsets Integrity Standards ensure that Australian carbon credits are high-integrity, based on durable emissions reductions that are additional, measurable and verifiable.

There are currently no ACCU methods for novel CDR approaches. However, the existing Scheme may provide a pathway once a CDR approach-specific IPCC methodology is developed and adopted by Australia. Once that occurs, development of a new method to allow for CDR approaches may be considered as part of the proponent-led method development process. Amendments to the CFI legislative framework may also be required to enable the development of ACCU methods for novel CDR approaches.

If new ACCU methods are developed for novel CDR approaches, these could be used in the same way as credits issued to other ACCU projects. For example, ACCUs can be sold to private sector buyers or the government to generate income and meet voluntary emissions reduction commitments, or they can be surrendered to meet compliance obligations under the Safeguard Mechanism.

The voluntary carbon market

The VCM allows companies, organisations and individuals to access credits for abatement, including from CDR, beyond official carbon crediting schemes (e.g. the ACCU Scheme). Currently, novel CDR credits can only be generated and traded within the VCM. There are currently no Australia-specific platforms for the domestic trading of these credits. However, novel CDR credits can be accessed through international marketplaces or directly from project developers.

Transparent participation in the VCM will be essential to support early innovation, build supply chains, and send clear market and demand signals for novel CDR development. The VCM can also attract investment into Australian CDR companies and serve as a gateway for access to international carbon markets. While the VCM may be important in generating early-stage demand for novel CDR in Australia, its credibility could be threatened by the presence of low integrity offsets, which could undermine trust in the marketplace for all forms of CDR.

A clear price premium is emerging for high-integrity CDR in the international VCM, showing market valuation of high durability removals, over lower-cost and lower-integrity conventional CDR.[388] Initiatives such as the Integrity Council for the VCM and the Voluntary Carbon Markets Integrity Initiative are promoting transparency regarding durability. Some standards bodies, such as Puro.earth, only certify durable CDR credits, whereas others, such as Isometric, classify credits based on their durability. Companies are increasingly requiring durability disclosure from credit suppliers. International frameworks, such as the Science-Based Targets initiative, emphasise the importance of companies using durable credits when accounting for these towards their net zero targets. For example, Google has pledged US$200 million to Frontier, an advance market commitment focusing on scalable, durable solutions.[389] This is also reflected in over US$120 million of investment in novel CDR companies in the second quarter of 2025.[390]

386 Department of Climate Change, Energy, the Environment and Water (2025) Australian Carbon Credit Unit (ACCU) Scheme. <https://www.dcceew.gov.au/climate-change/emissions-reduction/accu-scheme#toc_3>.

387 Emissions Reduction Assurance Committee (2021) Information paper: Committee considerations for interpreting the Emissions Reduction Fund's offsets integrity standards. Version 2.0. <https://www.dcceew.gov.au/sites/default/files/documents/erac-information-paper-offsets-integrity-standards.pdf>.

388 MSCI ESG Research. (2025). 2025 State of Integrity in the Global Carbon-Credit Market. September 2025. Retrieved from https://www.msci.com/downloads/web/msci-com/research-and-insights/paper/2025-state-of-integrity-in-the-global-carbon-credit-market/2025%20State%20of%20Integrity%20in%20the%20Global%20Carbon-Credit%20Market.pdf

389 Google (2024) 2024 Environmental Report. Google Sustainability, Mountain View, CA, USA. <https://sustainability.google/reports/google-2024-environmental-report/>.

390 CDR.fyi (2025) Durable CDR Market Update <https://www.cdr.fyi/blog/2025-q2-durable-cdr-market-update-biggest-quarter-ever>.

Together, this sends a strong signal that the market is willing to pay for high-durability approaches. Enhancing the transparency and accessibility of durability information could further boost trust in the VCM and allow projects with higher durability to attract a price premium.

Cross-cutting recommendations and potential actions to accelerate novel CDR in Australia

The goal of this section is to identify cross-cutting recommendations and potentially actionable steps to accelerate the development and deployment of novel CDR approaches in Australia. These actions are designed to be technology-agnostic and support the broad spectrum of novel CDR approaches (including land-based, mineralisation, and ocean-based solutions) across various stages of maturity. They are also not designed to be developed or implemented by one actor alone. A collaborative approach involving key stakeholders, including governments, industry, researchers and others, will be needed for success.

Importantly, these recommendations are not exhaustive nor prescriptive, but instead offer strategic, enabling actions informed by international best practices which are seen as best suited to an Australian context.

> **Recommendation 1:** Support the development of MRV across different novel CDR approaches.

Currently, MRV is decentralised and under-resourced, creating a financial burden for early-stage CDR developers. Some reports indicate that MRV accounts for 30–50% of the cost per tonne of CO_2 removed.[391] There is also limited consensus on requirements, assumptions and costs, contributing to the wide variation in credit prices and limiting proof-of-concept demonstrations of CDR capability. MRV development could help inform international policy that unlocks finance and market access for early-stage CDR projects and developers, as well as current IPCC efforts to develop internationally agreed methods for inclusion in National Accounts. It could also reduce financial burden for early adopters, de-risk project development, and enable credible carbon pricing. Together, these factors are likely to underpin market confidence and will be essential to scaling up novel CDR in the long-term.

Potential actions include the following:

- Engage in international efforts to develop agreed MRV methods as part of the Task Force on National Greenhouse Gas Inventories.
- Provide targeted funding support: Offer grants or RD&D funding to project developers to offset the high costs of developing MRV systems, particularly for early-stage CDR approaches.
- Streamline pilot project approvals: Create expedited approval pathways for pilot-scale projects that test and refine MRV methodologies. Enable iterative improvement processes to ensure MRV remains fit for purpose as approaches mature.
- Build digital MRV infrastructure: Develop national-scale, interoperable digital platforms for MRV, including geospatial mapping tools, open-access registries, and real-time tracking of carbon removals.
- Collaborate on MRV standards development: Partner with standards bodies, governments, research institutions, and private developers to co-develop or refine MRV frameworks (Box 10), ensuring methodologies are robust, scalable, and aligned with emerging international best practices and consistent at both a national and jurisdictional level.
- Engage with the VCM: Support pilot projects or deployments in the VCM that contribute to the shaping of internationally agreed MRV frameworks.

391 Amador G, Gilleo A, Lam M, Hatalsky L (2024) Establishing quality in carbon removal: A policy roadmap to strengthen carbon removal markets through monitoring, reporting and verification. Carbon Removal Alliance, USA. <https://a-us.storyblok.com/f/1020427/x/c9c4ac6f91/cra-mrv-policy-report_final.pdf>.

Box 10: Current global state of CDR MRV methodologies for novel CDR in the VCM.

In the VCM, MRV can be broken down into standards and methodologies. Standards outline how projects should be developed, implemented, monitored and verified. Methodologies refer to the detailed and specific set of technical procedures prescribed by a standard that a project must adhere to.

Figure 73 illustrates the complexity and disparity of MRV in the VCM. It only includes the novel CDR approaches analysed in this Roadmap and the MRV methodologies active or in development by the reporting platform CDR.fyi. Therefore, it should not be considered an exhaustive depiction of MRV in the VCM. Note, 'proprietary' is used to capture the MRV methodologies designed by private companies.

Figure 73: Selection of MRV methodologies developed by different standards/developers in the VCM across each novel CDR approach (current as of September 2025).

Methodologies/protocols

STANDARDS/DEVELOPERS					
PURO.EARTH	GOLD STANDARD	CARBON STANDARDS INTERNATIONAL	PROPRIETARY	ISOMETRIC	OTHERS
Puro Standard – Geologically Stored Carbon	Methodology for Biomass Fermentation with Carbon Capture and Storage (BFCCS)	European Biochar Certificate	CDR by DAC (Climeworks)	DAC v1.0	CCS Projects v1.1 (American Carbon Registry)
Puro Standard – Biochar		World Biochar Certificate	Permanent and Secure Geological Storage of CO_2 by In-situ Carbon Mineralisation (Carbfix)	Biochar Production and Storage v1.1	Methodology for project activities involving the capture, transport, and geological storage of CO_2 v1.1 (Global Carbon Council)
Puro Standard – Terrestrially Storage of Biomass		Global Artisan C-Sink Standard	CDR through Algal Biomass Burial (Brilliant Planet)	Biogenic Carbon Capture and Storage v1.1	Direct Air Capture and Storage (Nori) *
Puro Standard – Enhanced Rock Weathering		Global Rock C-Sink	Equatic's MRV Methodology	Ocean alkalinity enhancement from Coastal Outfalls v1.0	US and Canada Biochar Protocol v1.0 (CAR) *
			MRV Protocol for OAE mCDR by mineral addition v3.0 (Planetary) *	Electrolytic Seawater Mineralisation v1.0	
				Enhanced Weathering in Agriculture v1.1	

BiCR+S (biochar) BiCR+S (other) DAC+S ERW OAE * In development

Recommendation 2: Position the scaling of CDR and the need for a portfolio of approaches as a national strategic priority alongside emissions reduction.

In mid-2025, Australia published a definition for carbon management[392] which recognises CDR, in line with international countries and regions such as Canada[393] and the European Union.[394] This recognition highlights its importance, raises awareness, and lays the foundation for future action. It's important that CDR is positioned as a national strategic priority alongside expanding emissions reduction options. While responsibly scaling a range of CDR approaches in Australia is essential, it is recognised that CDR and emissions reduction approaches play different roles, but both are needed to reach net zero emissions. Diversifying carbon removal beyond land-based removals will strengthen Australia's path to net zero. Novel CDR approaches require a relatively smaller land footprint, particularly those using geological storage, compared to conventional CDR. Scaling up novel CDR approaches will require a maturing of the national dialogue, particularly a shift in how Australia thinks about and communicates climate goals.

Developing a unified national strategy could help elevate novel CDR as a priority, despite its complexity in terms of politics, economics, social, and environmental aspects. Bringing together government, industry and community stakeholders can help promote mainstream conversations around the need for CDR, coordinate efforts and form shared goals, and has the potential to send market signals and improve public and private investment. Potential actions could include the following:

- Develop a unified national narrative for novel CDR that aligns core principles, roles and goals.
- Establish joint committees or advisory boards to guide the deployment of novel CDR in Australia.
- Create open-access knowledge hubs or digital tools to increase awareness and urgency among key stakeholders about the potential of novel CDR.
- Regularly publish market insights and policy updates.
- Recognise that a portfolio of CDR approaches will be needed, and regionally, these will differ.
- Build cross-sector collaboration and awareness.
- Undertake research and mapping to understand future workforce, skills needs and opportunities associated with scaling novel CDR, with a particular focus on regional Australia.
- Include novel CDR in Australia's Integrated Assessment Modelling capability.
- Identify and communicate the opportunity that the novel CDR industry will bring for Australia.

Recommendation 3: Consider developing a target for novel CDR in Australia.

Establishing formalised national targets could drive the development of policies, funding mechanisms, and regulatory frameworks for novel CDR.[395] It could also provide clear investment signals to both public and private sectors, enabling more efficient and scalable deployment across national and state levels, and bring Australia in line with other nations, such as the UK.[396]

There are several actions that would need to occur prior to consideration of a target for novel CDR in Australia, including:

- Review Australia's realisable capacity for conventional CDR, and the need to balance land use and climate risk[397] in an emissions reduction economy.
- Establish a clear understanding of the difference between conventional CDR and novel CDR, particularly in terms of durability.[398]
- Explore the role of a time-increasing target that reflects the decrease in the cost and maturity of novel CDR approaches, and their current scale of deployment in Australia.

392 Department of Climate Change, Energy, Environment and Water (2025) Carbon Management for Tough Emissions. <https://www.dcceew.gov.au/climate-change/emissions-reduction/carbon-management-technologies>.

393 Natural Resources Canada (2023) Capturing the opportunity: a carbon management strategy for Canada. <https://natural-resources.canada.ca/sites/nrcan/files/energy/pdf/NRCan_CCMS_EN.pdf>.

394 European Commission (n.d.) Industrial carbon management. <https://energy.ec.europa.eu/topics/carbon-management-and-fossil-fuels/industrial-carbon-management_en>.

395 Climate Change Authority (2022) Review of International Offsets. Commonwealth of Australia, Canberra. <https://www.climatechangeauthority.gov.au/sites/default/files/Review%20of%20International%20Offsets%20-%20Report%20-%20August%202022.pdf>.

396 At least 5 Mt CO_2/year of novel removals by 2030, aiming at 23 Mt CO_2 by 2035 an 75-81 Mt CO_2 by 2050. See: Carbon Gap (2025) Carbon Removal in the United Kingdom – National Policy Overview. <https://tracker.carbongap.org/regional-analysis/national/united-kingdom/>.

397 Australian Climate Service (2025) Australia's national climate risk assessment 2025: an overview. <https://climateservice.maps.arcgis.com/sharing/rest/content/items/a088c56f21384881bb187d54e66b50b7/data>.

398 Currently under consideration in the EU through the proposed use of disaggregated targets.

Recommendation 4: Include novel CDR within an Australian Carbon market.

As Australia's climate policy evolves, the demand for carbon credits is likely to substantially rise. There is growing demand for high-integrity durable solutions reflecting the higher prices paid for these credits in the VCM. Bringing novel CDR into the Australian carbon market could enable Australia to extend the number of credits available over time and to validate, track, report, and, through price signals, incentivise durable removals consistent with UNFCCC- and Paris-aligned domestic and international reporting. Furthermore, if Australia were to elect to participate in Article 6.2, this could broaden export opportunities for Australian removals (see Box 11).

Australia will need a portfolio of novel and conventional CDR to reach its net zero targets in the near term.[399] Bringing novel CDR into existing or future compliance market mechanisms creates an opportunity to identify, recognise and value the inherent differences and benefits across novel and conventional approaches. This would enable the carbon market and future Australian Government policies to ensure that the necessary removals are available across the portfolio, provide incentives for different CDR approaches, and allow buyers to match purchases with their net emission reduction goals, particularly in hard-to-abate sectors.

Potential actions toward inclusion of novel CDR within an Australian carbon market include:

- Engage in international efforts to develop MRV methods as part of the IPCC Task Force on National Greenhouse Gas Inventories Report due in 2027.
- Consider how CDR approaches with differing levels of durability are valued.

Box 11: Australia's export potential.

The Paris Agreement allows for the trading of international carbon credits to help countries achieve their emissions reduction obligations. These credits, called Internationally Traded Mitigation Outcomes (ITMOs), can be exchanged between parties in accordance with Article 6 of the Paris Agreement.

As stated in its Net Zero Plan,[400] the Australian Government does not currently allow ITMOs to be used towards our national emissions reduction targets or for compliance purposes, including under the Safeguard Mechanism. This ensures Australian industries are focused on reducing emissions domestically and are well-positioned to capture the economic benefits of the transition to net zero.

Considering the significant capacity for CDR identified in this Roadmap, there could be an opportunity for Australia to realise export opportunities once a clear national strategy is established, novel CDR approaches are fully developed and international accounting methods for CDR are agreed. The VCM is already taking advantage of these opportunities, with Australian companies generating and exporting novel CDR credits overseas.

Recommendation 5: Continue building a strong science evidence base to support and optimise novel CDR deployments.

Although developing novel CDR is essential for achieving net zero, as discussed above, this cannot occur in isolation. Instead, it demands strong integration across multiple scientific disciplines to assess the effectiveness of novel CDR approaches under different warming scenarios and to identify synergies, co-benefits, trade-offs and potential adverse impacts on land, biodiversity, ecosystems, energy, materials, food and water resources. As science evolves, it will be crucial to assess the role of different novel CDR approaches in achieving both net zero and net-negative outcomes, and to understand how these approaches could interact with sectoral emissions reduction plans and the capacity of existing industries to achieve deep emissions reductions.

399 Department of Climate Change, Energy, the Environment and Water (2025) Net Zero Report. DCCEEW, Canberra, ACT. <https://www.dcceew.gov.au/sites/default/files/documents/net-zero-report.pdf>.

400 Department of Climate Change, Energy, the Environment and Water (2025) Net Zero Report. DCCEEW, Canberra, ACT. <https://www.dcceew.gov.au/sites/default/files/documents/net-zero-report.pdf>.

Potential actions toward continuing to build a strong science evidence base to support and optimise novel CDR deployments include:

- Develop a multidisciplinary national science advisory group for the development and deployment of novel CDR.
- Enhance international collaboration through partnerships with global research initiatives (e.g., Mission Innovation CDR Mission, IPCC, IEA).
- Fund inter/multidisciplinary research programs to explore performance, scalability, and sustainability of novel CDR approaches and portfolios under different warming scenarios and in various regions.
- Link research outputs to policy and market design so evidence directly informs regulations, standards, and incentives.

Recommendation 6: Accelerate investment in novel CDR along the innovation pathway.

Scaling novel CDR in Australia requires early and sustained mobilisation of both public and private capital. Most novel CDR approaches are at an early stage, demanding substantial upfront investments while facing uncertain revenue streams. The current policy and investment settings lack adequate incentives and risk-sharing mechanisms to support FOAK projects, integrate value chains, or enable long-term scale-up.

Advancing along the innovation pathway requires maintaining investor confidence at every stage through the TRL scale. This progression is complex, time-consuming, and often hindered by the fact that few funders, public or private, have the capacity or mandate to provide support across the full development lifecycle, even for the most promising CDR approaches. There is a clear and urgent need to accelerate investment in novel CDR along the innovation pathway, particularly for FOAK deployments, which is considered the '*Valley of Death*' for novel CDR.

Each step along the innovation pathway is unique, with its own challenges. Potential actions that may accelerate investment at different stages along the innovation pathway include:

Early-stage (research and concept development)

- Establish dedicated multi-year early-stage funding programs targeting funding for high-potential, under-researched approaches and gaps.
- Explore innovative approaches, such as RD&D tax incentives, public-private matched-funding programs, and joint funding calls between industry and research.
- Support continued engagement into global research networks such as the IEA and the Mission Innovation CDR Mission.
- Strengthen research collaborations between academia and industry, and science and engineering.
- Develop early-career researcher programs in novel CDR, such as CSIRO's CarbonLock Program nationally.

Mid-stage (prototype and pilots)

- Establish funding to provide public concessional capital, grants or pre-seed equity available for spinouts and startups, especially where private capital is not yet viable.
- Launch a national CDR accelerator program to fast-track the transition from research to pilot.[401]
- Develop pilot funding or blended finance models, build investor pipelines and facilitate academia industry linkages.
- Continue to tie Australia's efforts to global RD&D initiatives, to strengthen the case for domestic investment and coordination.
- Track existing funding and quantify future investment, and create a public registry of current financing to inform further investment, increase transparency and avoid duplication.

Late-stage (FOAK and scale-up)

- Public procurement of credits and advance market commitment options can help novel CDR developers access finance for FOAK projects.
- Consider Carbon Contracts for Difference (CCfDs) to provide price certainty and attract capital for FOAK deployments.
- Development of Public Private Partnerships (PPP) to share the risks associated with commencing FOAK projects, unlock funding, and accelerate deployment to the commercial scale.[402]
- Increase infrastructure readiness by ensuring access to grid connections, water supply, and transport links for pilot sites (e.g. using hubs and other suitable sites).
- Develop long-term offtake agreements to allow the transition to large-scale project finance and bring market confidence.

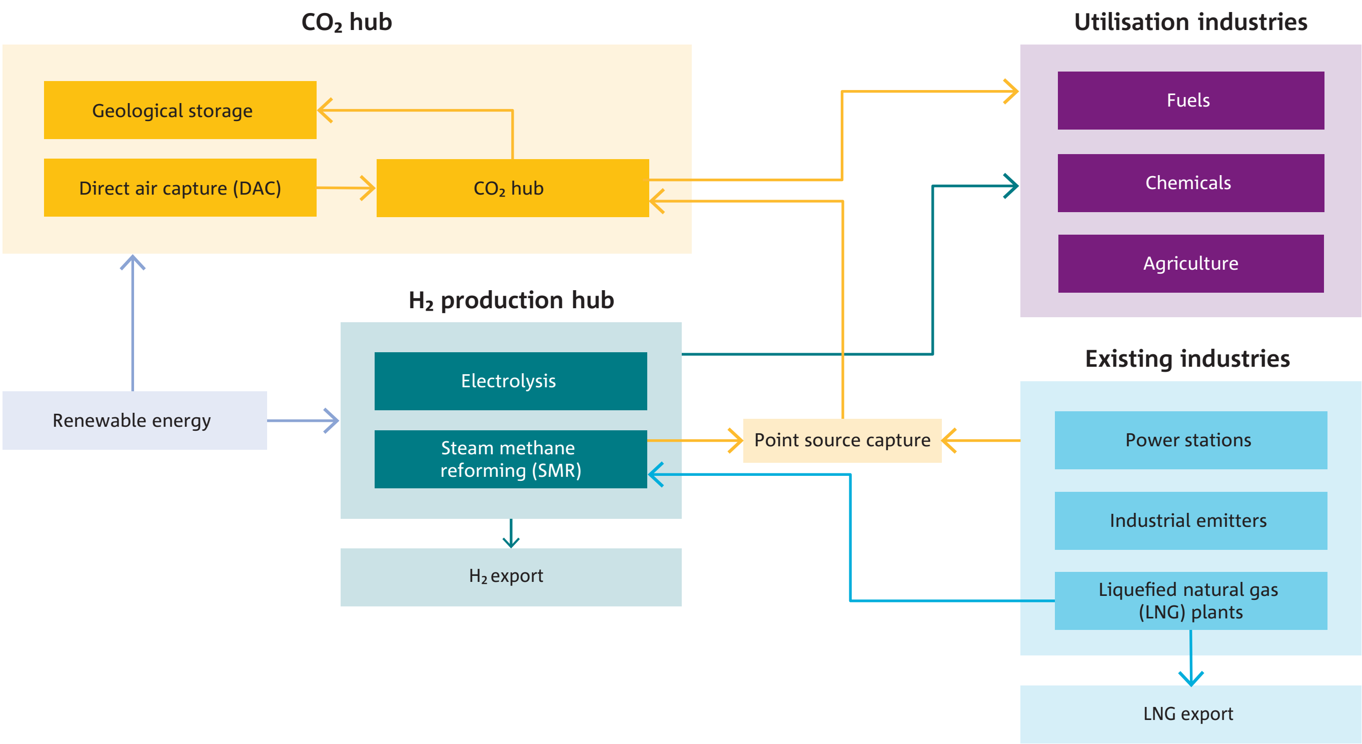
401 A potential model is the UK's CO_2RE initiative, which supports GGR demonstration projects across biochar, enhanced weathering, and more.
402 These include Co-funding, Concession/Contract and Risk-Sharing Models.

Recommendation 7: Leverage existing hub-based models and infrastructure.

Several CDR approaches demand substantial initial investment, access to CO_2 transport and storage facilities, and dependable, affordable energy. Implementing these approaches individually raises costs and hampers advancement. Hub-based models, which bring together multiple CDR projects and industries around shared infrastructure, present a more economical and lower-risk route to scale up. Industrial clusters can offer advantages such as pipelines, ports, power supply and skilled labour, while also facilitating synergies in feedstocks, waste heat utilisation and monitoring systems.

Early investment in shared-use infrastructure and planning coordination will be critical to realising these economies of scale across CDR and emissions reduction initiatives. In Australia, there is an opportunity to take advantage of existing and proposed CCS and hydrogen projects and industrial activity to support CDR scale-up. For example, AspiraDAC is a small-scale DAC project proposing to store captured CO_2 at the Moomba CCS storage site.[403] Alternatively, companies like Carbonaught are using basalt found in abundance near farmland in Brisbane as ERW feedstock with co-benefits for agriculture. Pilots have been strategically co-located in regions where agriculture and mining infrastructure exists to minimise costs and maximise impact.[404]

Figure 74: An example of CDR integration into a CCS hub focused on the storage of captured CO_2 from industrial processes as well as its utilisation to support emerging industries.



403 Geoscience Australia (2024) Carbon Capture and Storage. In Australia's Energy Commodity Resources 2024. Commonwealth of Australia, Canberra. <https://www.ga.gov.au/aecr2024/carbon-capture-and-storage>; AspiraDAC (2025) Modular, Scalable and Solar-Powered Direct Air Capture Technology. AspiraDAC Pty Ltd, Australia. <https://www.aspiradac.com/>.

404 Brisbane Economic Development Agency (2025) How Brisbane's Carbonaught is Changing the Forecast for Sustainable Farming. <https://choose.brisbane.qld.au/news/how-brisbanes-carbonaught-is-changing-the-forecast-for-sustainable-farming>; Carbonaught (2025) Selected Projects. <https://www.carbonaught.io/work>.

Hub-based models could facilitate the sharing of workforce capabilities, allow multiple industries to share transport and CO_2 infrastructure, and make commercial-scale CDR deployment more efficient and cost effective. While national level policy is needed to support novel CDR project deployment, project developers could begin feasibility studies now to accelerate and de-risk future implementation.

Potential actions that that allow existing hub-based models and infrastructure to leveraged include:

- Develop governance and funding models for shared infrastructure to enable multi-user access and reduce the investment burden on individual CDR developers. This could include funding early-stage infrastructure development for hubs (e.g. feasibility studies or front-end engineering design assessments).
- Develop a national CDR infrastructure blueprint that builds on existing national and jurisdictional plans and schemes to identify priority regions for shared infrastructure investment, including pipelines, ports, power supply, CO_2 storage, and quantify the co-benefits for co-located sectors.
- Support the co-location of CDR facilities with industries producing CO_2 streams or waste heat, such as ammonia, hydrogen or cement production, to reduce costs and improve overall carbon efficiency.
- Investigate co-benefits for other sectors through a hub-based model (e.g. agriculture), with emphasis on R&D into the quantitative co-benefits for co-located sectors.

Recommendation 8: Identify and coordinate cost-effective and zero-emission CDR supply chains.

The commercial deployment of novel CDR approaches will demand coordinated investment across transport, storage, energy and feedstock infrastructure. Existing systems such as CO_2 pipelines, renewable energy transmission, biomass logistics, and mineral supply are fragmented or not fully developed for novel CDR. Strategic planning is essential for decreasing per-tonne costs and assessing regional feasibility.

Deciding what mode of transport to use involves balancing transport costs, distances, available infrastructure, regulatory considerations, and the volume of CDR inputs or outputs to be moved. The process is straightforward when CDR capture and storage sites are located close together and near low-cost transport options. However, challenges arise when capture and storage sites are distant or when additional CDR inputs (e.g. biomass or silicate rocks) also need to be transported.

Furthermore, to qualify as a CDR approach, transport-related CO_2 emissions must be tracked and accounted for to ensure the entire value chain removes more CO_2 than it emits.[405] As a result, the methods to best mitigate or minimise scope 1, 2 and 3 emissions during project deployment and lifetime need to be considered.

Potential actions to identify and coordinate cost-effective and zero-emission CDR supply chains include:

- Implement decision-making tools to identify the most effective transport options.
- Establish consistent regulatory pathways for CO_2 transport and storage, including cross-jurisdictional permitting, long-term liability frameworks, and standards for infrastructure interoperability.
- Develop a national CDR infrastructure blueprint to identify priority regions for shared infrastructure investment.
- Invest in low- or zero-emissions heavy vehicle transport options to reduce emissions associated with transporting CDR inputs.
- Adopt a hub-based model (see Recommendation 7) that co-locates with clean energy industrial hubs.
- Utilise agreed full LCA frameworks (including upstream and downstream) to prioritise the lowest emission approach and ensure that projects are a net removal of atmospheric CO_2.

405 McQueen N, Kolosz B, Psarras P, McCormick C (n.d.) Analysis and quantification of negative emissions. In Carbon Dioxide Removal Primer. <https://cdrprimer.org/read/chapter-4>.

Recommendation 9: Foster social acceptance and awareness for novel CDR nationally and regionally.

Building public understanding and trust at both national and regional levels is essential for developing a domestic CDR industry. While national policies could support the responsible environmental and social deployment of novel CDR, community engagement and place-based initiatives will also play a key role in developing and maintaining support.

Engagement should be facilitated as dialogues and conversations that aim to understand the priorities, questions, concerns (and the reasons behind them) of key stakeholder groups. Insights and feedback solicited could then be reflected in Australia's RD&D and industry strategies, and broader CDR policy. CSIRO is leading efforts in this space, conducting an interview- and survey-based research study to identify social and ethical risks and inform responsible pathways for the development and deployment of novel CDR.[406]

Potential actions to support the development of acceptance include:

At the national level:

- Establish a national CDR awareness and education program.
- Develop a transparent CDR project registry including environmental and social impact assessments.
- Publicise high-integrity transparent MRV methods in line with agreed international standards and methods.
- Bring together community representatives through stakeholder forums.
- Early and continuous engagement.

At the regional level:

- Early and continuous engagement.
- Tailor outreach and develop communication tools.
- Establish community benefit sharing agreements.[407]
- Support regional skills development.
- Showcase pilot project or FOAK deployment.
- Increase engagement and access to scientific and technical experts.

Recommendation 10: Ensure CDR projects are developed in partnership with communities and Traditional Owners.

First Nations peoples have rights and interests recognised in over 50% of Australia's land mass.[408] To make CDR initiatives locally sustainable, socially responsible, and culturally respectful, it is crucial to embed community engagement at multiple levels into CDR planning and decision-making, as well as profit sharing.[409] CDR initiatives will need to ensure that the rights and interests of First Nations peoples related to land and sea are included in project processes.[410]

Tailoring engagement strategies to specific communities and regions is essential for ensuring that rights in relation to land and cultural heritage are implemented, and for building trust and securing meaningful support for CDR projects. Consent-based siting, including obtaining the Free, Prior, and Informed Consent (FPIC) from affected communities, will be critical to project deployment.

Ensuring First Nations experience, expertise and aspirations are incorporated in projects are essential for optimising environmental and community benefits of CDR projects and guiding the portfolio approach to both conventional and novel CDR approaches in a changing climate.

Although community engagement has faced challenges in the past, these experiences provide a solid foundation for responsibly scaling up new CDR strategies. As a result, Australia possesses mature social impact frameworks and expertise, including experience from the clean energy sector[411] and representative bodies such as the First Nations Engagement Working Group.[412]

406 Malakar Y, Brent K, Gardner J, Jeanneret T (n.d.) Responsible transition pathways for new carbon dioxide removal technologies. CSIRO CarbonLock Future Science Platform. <https://research.csiro.au/carbonlock/responsible-transition-pathways/>.

407 These could include a commitment to local employment outcomes, social and local procurement targets and/or community benefit funds.

408 National Indigenous Australians Agency (n.d.) Environment and land. <https://www.niaa.gov.au/our-work/environment-and-land>.

409 Ecotrust Canada (2023) Advancing Indigenous Protected and Conserved Areas (IPCAs) through carbon financing. Ecotrust Canada, Vancouver, BC. <https://ecotrust.ca/wp-content/uploads/2023/01/IPCAs-Through-Carbon-Financing_WEB.pdf>; Department of Climate Change, Energy, the Environment and Water (2024) The First Nations clean energy strategy 2024 – 2030. <https://www.energy.gov.au/sites/default/files/2024-12/First%20Nations%20Clean%20Energy%20Strategy.pdf>.

410 Department of Climate Change, Energy, the Environment and Water (2024) The First Nations clean energy strategy 2024 – 2030. <https://www.energy.gov.au/sites/default/files/2024-12/First%20Nations%20Clean%20Energy%20Strategy.pdf>.

411 Department of Climate Change, Energy, the Environment and Water (2024) The First Nations clean energy strategy 2024 – 2030. <https://www.energy.gov.au/sites/default/files/2024-12/First%20Nations%20Clean%20Energy%20Strategy.pdf>.

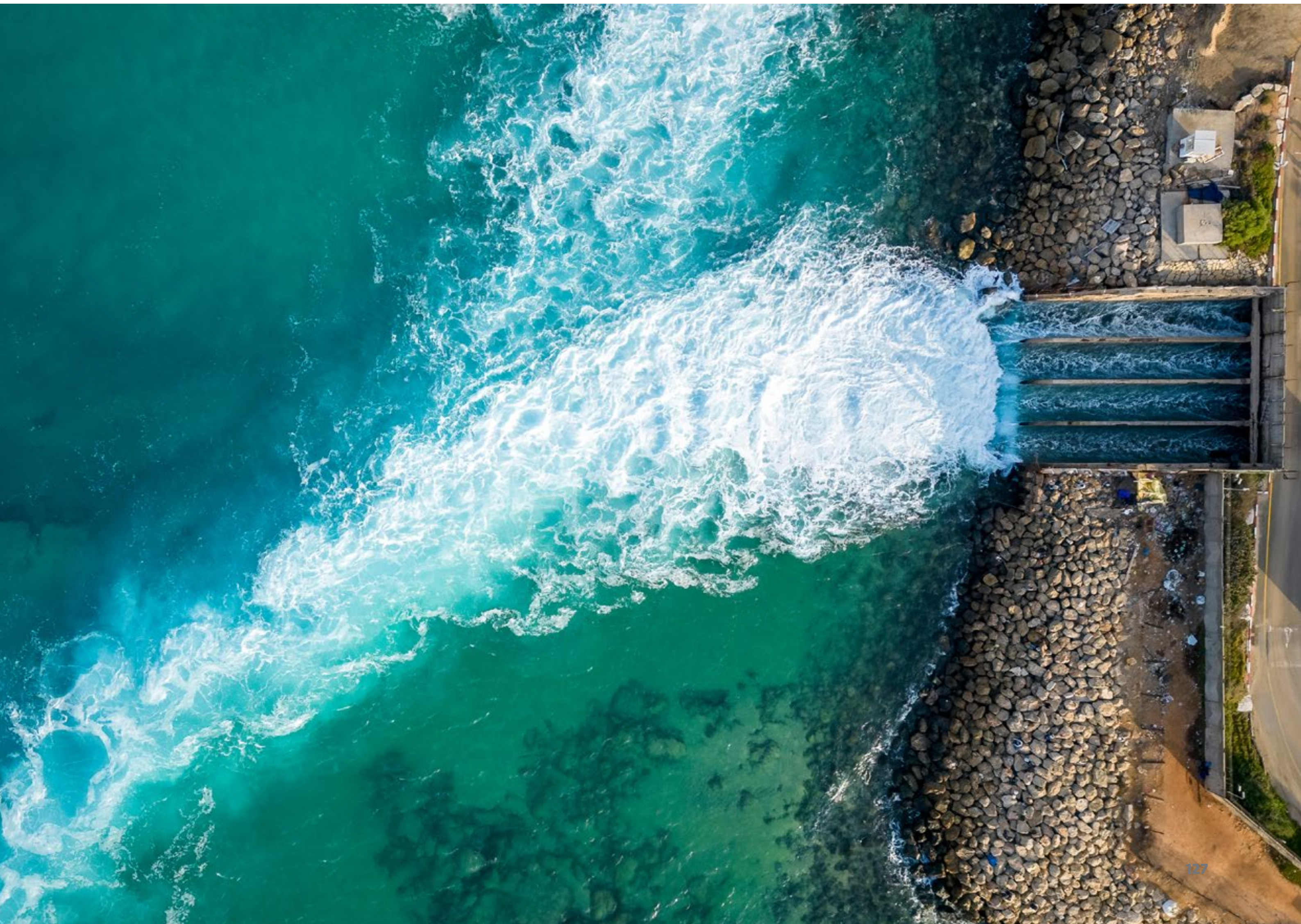
412 Department of Climate Change, Energy, the Environment and Water (n.d.) First Nations Engagement Working Group. <https://www.energy.gov.au/energy-and-climate-change-ministerial-council/working-groups/first-nations-engagement-working-group>.

15 Conclusion

CDR has been nationally recognised for its essential role in complementing deep emissions reductions to achieve net zero. Conventional CDR approaches are already delivering near-term removals and co-benefits to the nation. However, their limitations mean that novel CDR is anticipated to play an increasingly important role. Together, they will be critical to achieving net zero.

This Roadmap, for the first time, quantifies the capacity and cost of novel CDR in Australia. It provides the evidence base that helps identify regional opportunities and lays the foundation for deeper engagement and partnership with communities. The roadmap also provides detailed scale-up pathways and technology, research and cross-cutting actions that can bring down costs, address national challenges and risks, and maximise co-benefits. Deployed responsibly, novel CDR can deliver durable climate benefits, open new industries, and create regional economic opportunities.

Australia has the potential to leverage its rich natural and energy resources to develop novel CDR at scale. When combined with conventional CDR potential, Australia could surpass its projected national requirements with only a fraction of the capacity identified in this roadmap while positioning the nation to be leader in international markets. However, realising this capacity will require action and collaboration across government, industry, research and community to drive technological development and create the right conditions to scale novel CDR responsibly.



Appendix

A.1 Stakeholder engagement list

External consultations

- AgSeq
- Australian Government – Department of Climate Change, Energy, the Environment and Water
- Australian Industry Greenhouse Network
- Australian National University
- Carbon Market Institute
- Carbonaught
- CarbonRun
- Clean Energy Finance Corporation
- Elimini
- Equatic
- Geoscience Australia
- Google
- James Cook University
- Lawrence Livermore National Laboratory (LLNL)
- National Renewable Energy Laboratory (NREL)
- New South Wales Government
- Queensland Government
- South Australian Government
- Supercritical
- Treasury
- US Department of Energy
- University of Oxford
- University of Sheffield
- Victorian Government Department of Jobs, Skills, Industry and Regions (DJISR) – CarbonNet
- Western Australian Government
- Worley

CSIRO consultations

- Aaron Thornton
- Ali Kiani
- Amir Aryana
- Andrew Higgins
- Andrew Ross
- Anton Wasson
- Audrey Bester
- Elizabeth Shadwick
- Gregory Wilson
- Jenny Hayward
- Jim Austin
- John Gardner
- Karsten Michael
- Kerryn Brent
- Linda Stalker
- Louisa Warren
- Morgan Williams
- Paul Feron
- Pep Canadell
- Renee Birchall
- Ryan Gee
- Sam West
- Stuart Whitten
- Talia Jeanneret
- Terry Sparrow
- Tess Dance
- Thomas Jones
- Warren Flentje
- Yuwan Malakar

A.2 Glossary

Please note, definitions marked with a * have been directly sourced from the Carbon Dioxide Removal Mission's carbon management terminology document.[413]

TERM	DEFINITION
Absorption	The incorporation of a substance throughout another substance.
Accelerated mineral carbonation	A process that speeds up natural mineral reactions to durably store CO_2 in solid form.
Additionality	A measure of whether carbon removals would have occurred without deliberate intervention. Essential for validating carbon credits.
Adsorption	The adhesion of a substance onto the surface of another substance.
Afforestation	A conventional CDR activity where trees are planted on land that was not previously forested.
Agroforestry	A conventional CDR activity where trees and shrubs are integrated with agricultural land to enhance carbon removal and biodiversity.
Alkalinity	A measure of the capacity of water to neutralise acids, important in ocean-based CDR.
Amine-based materials	Chemical compounds used in solid adsorbent DAC to selectively capture CO_2 from air.
Article 6 (Paris Agreement)	Provisions allowing countries to trade carbon credits to meet climate targets.
Australian Carbon Credit Unit (ACCU)	A unit issued under the Australian Carbon Credit Unit Scheme, representing one tonne of verified CO_2 emissions reductions or CDR.
Battery energy storage system	Technology used to store electricity from renewable sources.
(Bi)carbonate Ions	Dissolved inorganic carbon that is found in oceans, forming part of the natural carbon cycle.
Biomass Carbon Removal (BiCR)	See BiCR+S
BiCR+S*	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.
Biochar*	A stable solid, rich in carbon that is made from organic waste material or biomass that is partially combusted in the presence of limited O2. Biochar may provide long-term CO_2 storage, potentially offering CDR.
Biological CO_2 capture	Refers to the capture of CO_2 during biomass growth. Plants and algae produce biomass via photosynthesis, which removes CO_2 from the atmosphere.
Biomass*	Plant (or animal) material that contains stored carbon, and can be used as fuel. Examples include wood and wood processing wastes, agricultural crops and residues, and organic waste.
Biomass conversion	Transforming biomass into energy or carbon storage products through processes like pyrolysis or combustion.
Calciner	A high-temperature device used to release CO_2 from capture compounds in some DAC processes.
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 credits	A carbon credit represents a reduction or removal of one tonne of CO_2-e that can be sold or traded, usually in voluntary or compliance carbon markets.

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TERM	DEFINITION
Carbon crops	Plants grown specifically for carbon removal purposes.
Carbon cycle	The natural circulation of carbon among the atmosphere, oceans, soil, and living organisms.
Carbon dioxide (CO_2)*	A colorless, odorless, naturally occurring gas made up of two oxygen atoms and one carbon atom. A byproduct of fossil fuel combustion and biomass burning, it is also emitted from land use changes and other industrial processes. It is the principal anthropogenic greenhouse gas that affects the Earth's radiative balance. It is the reference gas against which other greenhouse gases are measured, thus having a Global Warming Potential of 1.
Carbon dioxide leakage*	Unintended release of CO_2 out of a pre-defined containment. Containments can include both surface containers (e.g. compressors, pipelines or storage tanks on trucks, trains or ships) and subsurface containments (e.g. geological storage complex). Not to be confused with carbon leakage (in economics), which is the effect of carbon costs that cause companies or investors to move hydrocarbon production or other operations to jurisdictions with lower costs. The result is that emissions are not reduced; they are just emitted in a different location.
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 Farming Initiative (CFI) Act	Legislation governing carbon offset projects in Australia.
Carbon removal efficiency	The percentage of carbon in biomass or other feedstock that is durably captured and stored.
Carbon removal potential	The amount of CO_2 that can be removed per unit of material or process.
Carbon stocks	Natural reservoirs (e.g., forests, soils) that store carbon and help regulate atmospheric CO_2 levels.
Carbonate ions	Stable ions formed in ocean water that store CO_2 over long timescales.
Carbonic acid	A weak acid formed when CO_2 dissolves in water, central to weathering and ocean chemistry.
CO_2 equivalent (CO_2-e)	A metric measure to compare the emissions from non-CO_2 greenhouse gases on the basis of their global warming potential, by converting amounts of other non-CO_2 greenhouse gases to the equivalent amount of CO_2 with the same warming potential. Since no scalable techniques currently exist to remove non-CO_2 greenhouse gases from the atmosphere, all CDR is effectively measured in CO_2 terms, making CDR expressed in CO_2-e identical to CO_2.
CO_2 fluxes	The flow of CO_2 between the atmosphere and other systems, critical for measuring carbon removal.
CO_2 storage	The process of storing captured CO_2.
Commercial geological storage (SPE-SRMS definition)	Represents storage capacities in known and characterised formations where a viable development project exists, and the storage is economically feasible.
Conventional CDR*	CDR methods that are well established, already deployed at scale and widely reported by countries as part of land use, land-use change and forestry (LULUCF) activities. Often also referred to as 'Nature-based CDR'. The methods included in this group are afforestation/reforestation; agroforestry; forest management; soil carbon sequestration in croplands and grasslands; peatland and coastal wetland restoration; and sequestration in durable wood products.
Decarbonisation*	The reduction of carbon emissions from energy systems, industries, and transport to mitigate climate change.
Deployment*	Activities with the objective to achieve large-scale operation and commercialisation of technologies, as opposed to activity intending to improve innovation or technological development through RD&D.
Digital Twin	A virtual model of a physical system used for simulation and optimisation.
Direct air capture (DAC)*	A process that captures CO_2 directly from ambient air using chemical processes.
Direct air capture and storage (DAC+S)*	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.
Discount rate	A rate used to convert future costs or benefits into present value, reflecting time preference.

TERM	DEFINITION
Durability	The length of time CO_2 remains sequestered without re-entering the atmosphere; a key factor in evaluating CDR effectiveness.
Eddy covariance	A technique for measuring gas exchanges between ecosystems and the atmosphere.
Electrochemical cell	A device that uses electricity to drive chemical reactions, used in ocean alkalinity enhancement.
Electrolytic OAE	An ocean alkalinity enhancement method using electrolysis to increase seawater's CO_2 absorption capacity.
Emission factor	Factors that are used to convert a unit of activity into its emissions equivalent, for the purpose of estimating greenhouse gas emissions. See: Australian National Greenhouse Accounts Factors
Emissions Reductions*	Actions taken to decrease the amount of greenhouse gases released into the atmosphere.
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.
Firming	Techniques to ensure reliable electricity supply from variable renewable sources.
First-of-a-kind (FOAK)	A first-generation commercial scale facility, typically following smaller scale pilot and demonstration facilities.
Free, prior and informed consent (FPIC)	A principle ensuring Indigenous communities consent to projects affecting their land or rights.
Gasification	Gasification is the process of decomposing biomass into syngas, which comprises carbon monoxide, H_2, CO_2 and a small amount of methane.
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.
Gigatonne (Gt)*	One billion tonnes = 1 000 000 000 tonnes.
Greenhouse gases (GHGs)*	Gases such as CO_2, CH_4, and N_2O that trap heat in the atmosphere and contribute to global warming.
Hard-to-abate emissions	Emissions from sectors that are difficult to decarbonise, such as aviation, cement, and steel production.
Hub-based model	A deployment strategy where multiple CDR projects share infrastructure and resources.
Hydrocarbons	Organic compounds made up only of hydrogen and carbon atoms.
Hydrothermal liquefaction	Hydrothermal liquefaction is a thermochemical process that converts biomass into liquid fuels at moderate temperatures and operating pressures.
Inorganic carbon	Carbon stored as carbonate or bicarbonate ions.
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.
Integrity Council for the Voluntary Carbon Market (ICVCM)	An organisation developing standards for high-integrity carbon credits.
ISO 14064/65/66	International standards for quantifying, verifying, and reporting greenhouse gas emissions and removals.
Leakage	The unintended release of stored CO_2 back into the atmosphere, undermining the effectiveness of CDR.
Levelised cost of CDR	The average cost per tonne of CO_2 removed, accounting for capital, operational, and other costs over the project lifetime.
Life cycle analysis (LCA)	Assessment of environmental impacts associated with all stages of a product or process.

TERM	DEFINITION
Liquid absorbent DAC	DAC process using liquid chemicals to absorb CO_2 from air and regenerate them for reuse.
Measurement, reporting and verification (MRV)*	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.
Mineral carbonation*	Carbon mineralisation processes mimic and accelerate natural rock weathering or hydrothermal processes in which CO_2 -reactive minerals in rocks (or alkaline waste material) react with CO_2 from the atmosphere or a concentrated CO_2 source to produce carbonate minerals that are either stored in the soil and/or ocean (e.g., ocean alkalinity enhancement), long-lived products (e.g., ex-situ carbon mineralisation) or underground in mafic- or ultramafic formations (e.g., in-situ carbon mineralisation). 'Enhanced rock weathering' and 'enhanced weathering' are used synonymously.
Nationally Determined Contribution (NDC)	Australia's Nationally Determined Contribution (NDC) sets overarching national targets and outlines Australia's official climate action plan under the Paris Agreement.
Net-negative emissions	Conditions where annual rates of greenhouse gas removal are greater than residual greenhouse gas emissions.
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.
Nth-of-a-Kind (NOAK)	A commercial scale facility that incrementally improves on multiple previous generations of similar facilities.
Novel CDR	Technological solutions that deliberately remove CO_2 from the atmosphere and durably store it in natural carbon reservoirs (e.g., geological, terrestrial, or ocean), or in long-lived products.
Ocean alkalinity enhancement (OAE)	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.
Organic carbon	Carbon stored in living biomass, soil carbon or biochar.
Permanence*	See 'durability'
Photosynthesis	The biological process by which plants absorb CO_2 and convert it into biomass.
Prospective geological storage (SPE-SRMS definition)	Refers to storage resources that are not yet identified. These are estimates of storable quantities in geologic formations that have not yet been discovered or characterised.
Pyrolysis	Thermal decomposition of biomass in the absence of oxygen to produce biochar and other byproducts including bio-oil and pyrolysis gas/syngas.
Reforestation	Replanting trees in areas that were previously deforested to restore carbon sinks.
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.
Renewable energy zone (REZ)	Designated areas for renewable energy development to support grid decarbonisation.
Safeguard Mechanism	An Australian policy that sets emissions limits for large industrial facilities.
Soil carbon sequestration*	Occurs through direct and indirect fixation of atmospheric CO_2. Direct soil carbon sequestration occurs by inorganic chemical reactions that convert CO_2 into soil inorganic carbon compounds such as calcium and magnesium carbonates. Direct plant carbon sequestration occurs as plants photosynthesise atmospheric CO_2 into plant biomass. Subsequently, some of this plant biomass is indirectly sequestered as soil organic carbon (SOC) during decomposition processes. Worldwide, SOC in the top 1 meter of soil comprises about 3/4 of the earth's terrestrial carbon.

TERM	DEFINITION
Solid adsorbent DAC	DAC process using solid materials to adsorb CO_2 from air and release it upon regeneration.
SPE-SRMS	A classification system for CO_2 storage resources developed by the Society of Petroleum Engineers.
Storage reversal	The release of previously stored CO_2 due to environmental or human disturbances.
Sub-commercial geological storage (SPE-SRMS definition)	These are discovered but not yet commercially viable resources.
Syngas	A mixture of gases including CO and H_2 produced during biomass conversion.
Technology readiness level (TRL)	A scale used to assess the maturity of different technologies ranging from 1 to 9, with 9 indicating full commercial readiness.
Thermochemical	Processes involving heat and chemical reactions, used in biomass conversion for CDR.
Voluntary carbon market (VCM)	A market where companies voluntarily buy carbon credits to offset emissions.
Voluntary Carbon Markets Integrity Initiative (VCMI)	A body providing guidance on the credible use of carbon credits.
Variable renewable energy (VRE)	Energy (commonly electrical energy) generated intermittently by renewable technologies that depend on environmental conditions, e.g. solar or wind.

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