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Scaling atmospheric carbon dioxide removal in New South Wales

NSW Office of Energy and Climate Change

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This report was produced for the NSW Government Office of Energy and Climate Change by Common Capital Pty Limited Common Capital).

Key takeaways

Box 1.1 Key takeaways for NSW policymakers

- NSW will need to remove and durably store megatonnes of CO_2 from the atmosphere each year by 2050 to reach a state of net zero.
- The methods reviewed in this paper – direct air capture and mine-site enhanced weathering – can reliably capture and store atmospheric CO_2 with high measurement certainty and durability. However, they are at early stages and are currently high cost. Methods assessed in this report include direct air capture and enhanced weathering.
- Scaled deployment is required to drive learning curves that unlock step change cost reductions. Modelled scenarios of scaled-up deployment suggest major cost reductions are possible from >AUD1000/tonne today to ~AUD100/tonne at multi-megatonne scale in NSW. However, these reductions are not guaranteed; they require the right enabling setting.
- NSW has strong potential to deploy these technologies at large scales due to the NSW resource profile and industrial capability. This means NSW could approach the export of atmospheric CO_2 removal services to other jurisdictions, for example selling removal credits, as a strategic industry.
- Policy intervention can remove barriers and unlock scale in the timeframe required. Major areas for consideration include R&D investment, project finance, revenue streams, social licence, governance structures, information barriers, infrastructure requirements, direct industry experience and measurement, reporting and verification (MRV) standards and frameworks.
- Policy intervention is required in this decade so that CDR can be ready for scaled deployment from 2030.

Executive summary

Urgent emissions reduction is needed to avoid dangerous climate change. But emissions reduction alone is no longer enough. According to the Intergovernmental Panel on Climate Change (IPCC), limiting climate change to below 2°C is now only possible by combining both emissions reduction and the removal of some of the CO_2 that's already in the atmosphere.

The Intergovernmental Panel on Climate Change (IPCC) defines CDR as:

> *Human activities capturing CO_2 from the atmosphere and storing it durably in geological, land or ocean reservoirs, or in products. This includes human enhancement of natural removal processes, but excludes natural uptake not caused directly by human activities* [1].

There are two components of this definition **(1) capturing CO_2 from the atmosphere *and* (2) storing the CO_2 durably** in geological, land or ocean reservoirs or long-lived products.

Atmospheric CDR is often confused with:

- **Carbon capture and storage** (CCS) of point source emissions. This is emissions avoidance – capturing additional emissions before they go into the atmosphere, rather than removing them from the atmosphere.
- **Carbon capture and utilisation** (CCU), particularly of fuels, where the captured carbon is re-released. This is also emissions avoidance – the use of captured carbon for fuels, supplants the use of fossil fuels and associated emissions. It is not carbon removal as the carbon has not been durably stored.

Carbon removal in NSW

The amount of atmospheric CDR NSW requires will change over time. Drivers include the need to scale up deployment over time, the volume required to balance residual emissions to achieve net zero, contributing to the global requirement to deliver up to 15 gigatonnes of net negative emissions annually [2] and opportunities for NSW to export surpluses of CDR to jurisdictions with restricted capability to scale atmospheric CDR.

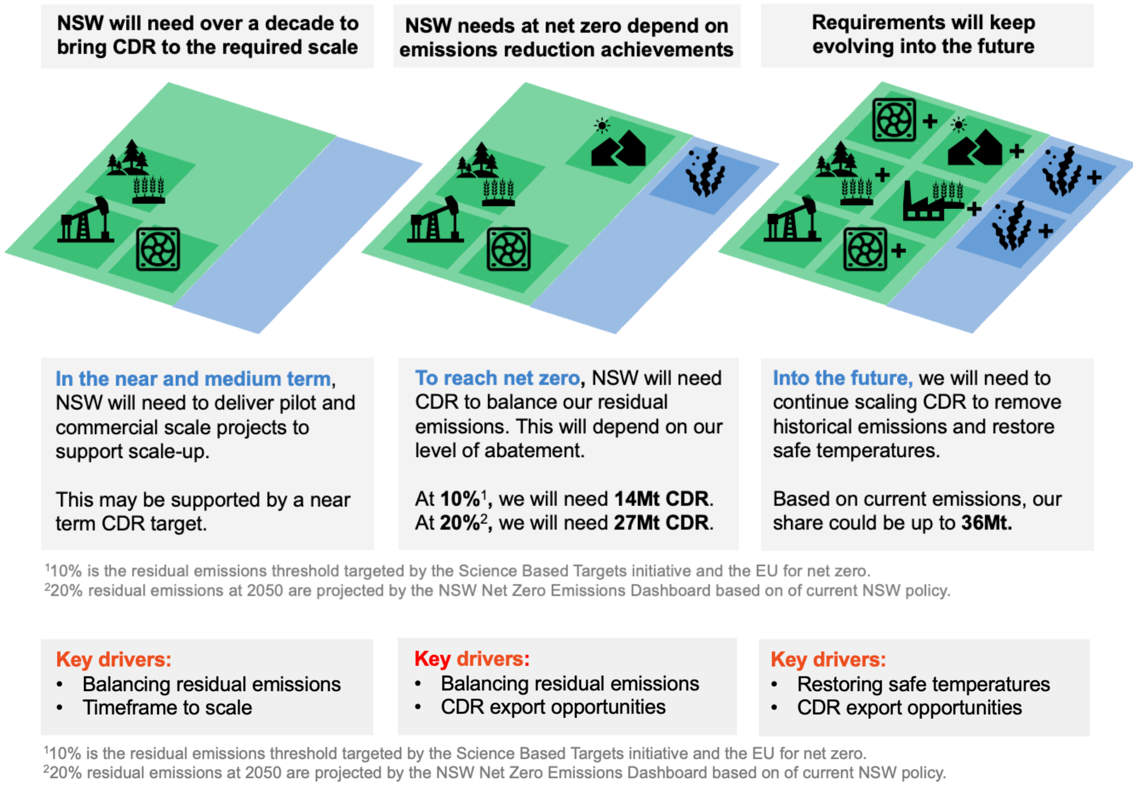

Figure 1: Near term, net zero and future CDR scenarios for NSW

Based on these dynamics, NSW will require megatonne scale CDR by the latter half of this century. A strategy is required to deliver to this scale in order to mitigate significant transition risk to NSW, including potentially higher risk to the small number of NSW industries that represent difficult-to-decarbonise emissions. If NSW does not deliver scaled carbon removal, it may be exposed to potentially volatile inter-jurisdictional carbon removal purchase at potentially significant cost. But if NSW establishes a scalable carbon removal industry, carbon removal moves from a cost captured by other jurisdictions to a source of value that contributes to NSW gross state product and sovereign capability.

Our project

This project sought to investigate the feasibility of different methods to deliver measurable, durable removals at scale in NSW. There are many atmospheric carbon removal methods which can produce a net negative emissions outcome. We focused on the potential of direct air capture and storage (DACCS) and enhanced weathering in NSW. We also conducted a higher-level review of the potential of biomass carbon removal and storage (BiCRS).

Our methodology comprised extensive domestic and international interviews across CDR start-ups, financiers, academics, relevant industry actors, philanthropy and NGOs, literature reviews, as well as economic and removal potential modelling.

Overview of key findings

We found NSW has significant potential to deliver large scale carbon removal due to an abundance of many key resources required as well as NSW industrial capabilities. However, carbon removal methods with strong durability and measurability certainty are currently expensive. To improve understanding of potential NSW pathways, we conducted techno-economic modelling for DACCS and enhanced weathering to understand the cost driver and CDR potential dynamics in NSW.

Our approach to modelling was to ground analysis in a known site so that assumptions and constraints could be tested using characteristics of a real-world setting, rather than purely theoretical top-down estimates. We then extrapolated that theoretical potential to begin estimating further potential sites. We note, additional work would be required to further refine total potential estimates for NSW with greater accuracy. However, from this analysis, we found the critical information for policymakers is not the total theoretical potential of NSW, but rather a grounded understanding of example site potentials.

Enhanced weathering potential

NSW has the key foundations required to scale mine-site enhanced weathering: an abundance of suitable minerals, such as multiple major deposits of serpentinite and a world-leading mining industry, including plans for new mines that co-locate with suitable mineralogy.

Enhanced weathering is a geochemical process using the natural process of the earth's slow carbon cycle. It involves the weathering of minerals with CO_2 from the atmosphere, which converts the CO_2 into carbonates or bicarbonates. We conducted modelling on two NSW mine site enhanced weathering ("mineral carbonation") implementation options:

- Mechanical acceleration where ground minerals are mechanically agitated ('tilled') to maximise exposure to air and increase weathering rates
- Enclosed facility weathering, where ground minerals are spread in a humidified enclosed facility to increase weathering rates; fully weathered minerals are then returned to mine tailing pits for storage

These options can be **integrated** into existing or new commercial mines in that produce suitable tailings, or the minerals may be **purpose mined** for CDR. Both processes involve thermal activation of the minerals to increase weathering rates. As this is an energy intensive process, our modelling includes deployment of additional renewable energy to meet this demand.

Mine site implementation options were selected for modelling as the minerals remain at site, making it easier to assess capture rates compared to agricultural and coastal enhanced weathering options where weathering inputs and captured carbon are dispersed by natural systems.

Key factors influencing cost and potential for mine site implementation options are:

The required minerals for enhanced weathering can be purpose-mined or sourced as waste products (mine tailings) from other mining operations.
NSW has existing reserves of ultramafic mine tailings and production is likely to increase in future due to the colocation of ultramafic rocks with metals like nickel and cobalt.

Different kinds of rocks have different reactivity potentials based on their exact mineral composition. Ultramafic rocks weather at faster rates than mafic rocks, e.g. basalt.
NSW has significant reserves of ultramafic rock in the Great Serpentine Belt, Coolac Serpenetine Belt and Gordonbrook Serpentine belt.

Some enhanced weathering approaches require significant energy for thermal activation – heating the rocks to increase their reactivity.
NSW has a strong renewable resource base and is comparatively well-placed to deliver these energy needs.

Implementation options use different approaches to accelerate the weathering process, e.g. mechanically agitating the minerals or spreading them thinly to maximise air exposure.
Both processes could be integrated into the mining process circuit at existing or future mining operations at NSW sites.

Figure 2: Factors influencing cost and capture potential of enhanced weathering

We modelled multiple mine-site enhanced weathering options across these levers to understand the order of magnitude potential in NSW and major cost drivers.

Overall, we found that:

- mine-site enhanced weathering has a **unique ability to achieve scale quickly** and without reliance on learning curves. The process can integrate operating mines already operating and producing and storing suitable rocks at a major scale. Further, it does not require novel technologies that have significant learning curves to ascend as it can use existing technologies that have already achieved mass adoption.
- optimising the weathering reaction is key to cost effectiveness. Higher rates of weathering means a greater volume of CO_2 is captured.
- upfront capex investments in technologies that materially increase weathering rates are cost effective to deploy on reactive rock as they support the sequestration of a much greater volume of CO_2. This makes the additional investment highly productive.
- due to upfront capex requirements, an incentive framework is needed to incentivise integration into new or existing mines in NSW.

As outlined in Figure 3 below, individual sites in NSW may have the ability to achieve megatonne scale CDR (between 0.07 and 1.24Mt CO_2 per annum) if technology is used that maximises CO_2 capture from the rocks. The scale of carbon removal achieved varies widely across implementation options. Likewise, costs vary significantly based on implementation option, with significant ranges based on optimisation achieved. Mine-site integration CDR yields costs as low as $79/tonne CO_2, whereas purpose-mining options remain higher than $100/tonne CO_2. Major cost drivers include energy use, capital expenditure for higher intervention processes such as building mine-site enclosed facilities to optimally store weathering rocks.

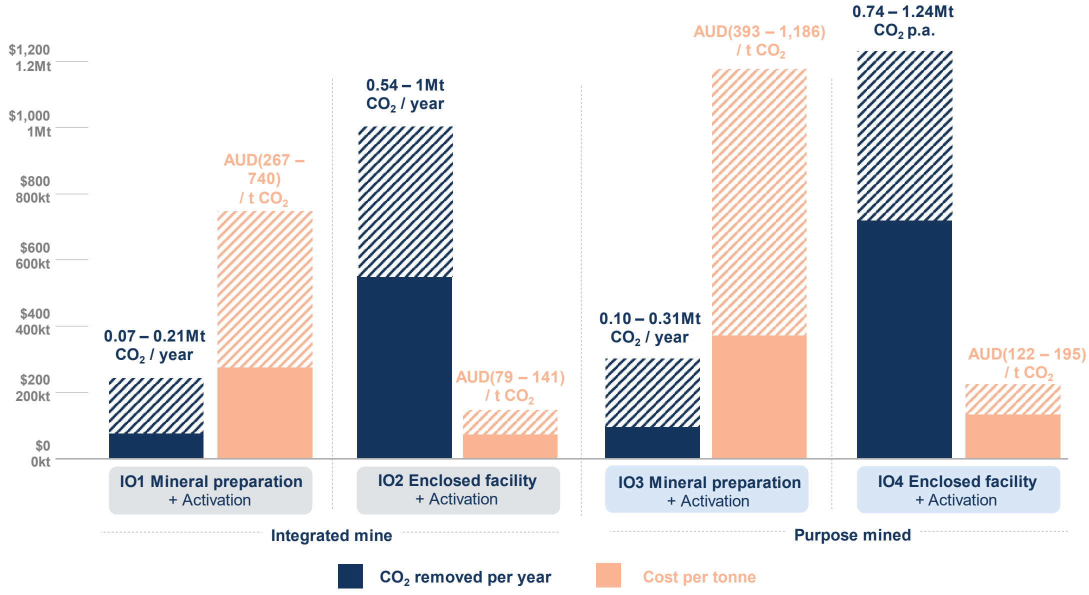

Figure 3: Cost per tonne and capture rate of enhanced weathering implementation options

While NSW has extensive mineral deposits that are likely suitable, the physical rate limiter on NSW potential is likely to be the specific mineralogy and accessibility of suitable minerals. Further work in mineralogy testing would be needed to further assess total physical potential.

We also found implementing this process in NSW could have significant macroeconomic benefits for NSW. If implemented at a single suitable mine site, a mine scale enhanced weathering project as shown in Figure 3 above will cost between $1.6 and 4.4 billion over the mine lifetime. This expenditure will stimulate a total of between $4.6 and $13 billion of activity across the broader economy. We also estimate between 1,900 and 7,900 jobs will be required in the construction phase of mine-site EW at scale, and 200-660 ongoing jobs generated to manage the process over the life of the mine.

The social licence of mine-site EW is tied closely to mining social licence and benefits from the existing mining regulatory framework in NSW. Mines purpose-built for carbon removal would not require the chemical processes that can cause negative ecosystem outcomes in standard mining operations, but like any new mining project would likely have other environmental impacts, for example biodiversity impacts, habitat loss, and amenity impacts for local communities.

Direct air capture and carbon storage potential

NSW has the key components required to scale DACCS: capacity to deliver abundant, cost-competitive renewable energy, significant land mass to scale capture facilities, potential geological storage sites and suitable mineralogy for carbon mineralisation as a storage pathway.

DACCS is a cyclic process that removes carbon dioxide directly from ambient air using a solid or liquid compound that is then regenerated, releasing the CO_2 for storage. DACCS represents a diverse category of technologies and the explosion of DACCS start-ups has yielded high innovation across the category. We identified 60 capture start-ups internationally with over 15 unique technology approaches between them, and over 20 storage-based start-ups. This means there is no single answer to what scaled deployed looks like and how costs will come down with scale. There is high variability across many system components that drive costs. Key areas of variability and NSW considerations include:

- **Capture agents**, including dozens of different types of solid sorbents and liquid solvents. Some agents are low-tech and readily available common minerals for example limestone or silicates while others require chemical manufacturing for example metal organic frameworks (MOFs), zeolites and polymers. This means NSW could be an importer of capture agents, or invest in the scaled manufacturing of capture agents, both to serve domestic DACCS and as an export opportunity (analogous to NSW chemical exports).
- **Modularity versus large industrial scale plants.** Many new DACCS start-ups have adopted a modular approach to capture units, rather than large traditional industrial plants. Many modular-based start-ups intend to manufacture their capture units locally near deployment locations. This is to add local economic benefits to support social licence and to avoid transport costs of bulky units. Manufacturing facilities must be large to achieve the required economies of scale to bring costs down. This means that attracting DACCS deployment in NSW create new manufacturing jobs in the NSW economy.
- **Energy requirements.** DAC processes typically require industrial quantities of input energy for air handling and/or capture agent regeneration through separating the CO_2 from the capture agent into a concentrated form. Energy consumption varies between options across each stage, but the high energy demand is common to all DAC start-ups we reviewed. During consultation we found NSW leadership in renewables was a major driver of NSW appeal to Australian and international DACCs companies.
- **CO_2 storage pathways.** Injection into geological formations and carbon mineralisation are the two overarching pathways to store captured atmospheric CO_2. Start-ups typically focus on capture, with intention to partner with storage providers. NSW is likely to be able to service both these variations, with at least one likely geological storage site under exploration and several other potential sites not yet explored. Further, NSW has large mineral deposits suitable for mineralisation storage pathways, including carbon utilisation storage. Northern NSW is also in proximity to the Queensland Surat Basin CTSCo storage site. It may be feasible to pipe CO_2 captured in NSW to this location as CO_2 piping was not found to be a major cost driver.

We modelled DACCS in NSW at various scales to understand the learning curve dynamics and to assess the order of magnitude potential in NSW. To account for the diversity of DACCS options, we modelled two archetypal DAC capture deployment options with different cost drivers and deployment scenarios:

- A low-tech sorbent that is already low cost and requires high heat zero emissions technology for regeneration, deployed at a location requiring offsite energy.
- A high-tech sorbent which is currently at very high lab-scale costs, requiring low heat for regeneration, deployed a location allowing 24/5 behind the meter solar and battery storage.

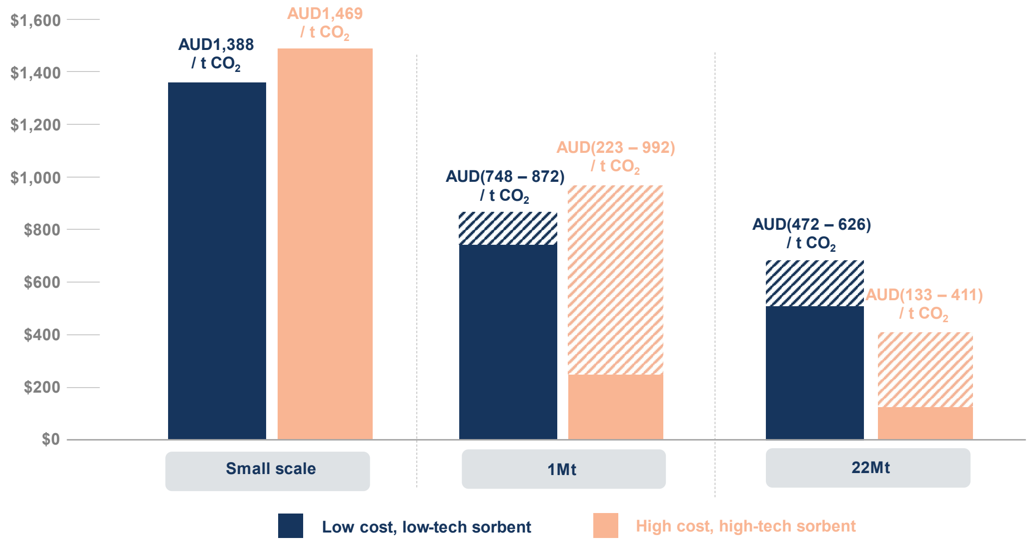

Figure 4 below illustrates the range of marginal costs per tonne of CO_2 removed for each option at three different scales.

Figure 4: Cost per tonne of two modelled implementation options across different scales

The figure illustrates how scale has a major impact on costs and how cost reductions vary between implementation and within each implementation option. For the two modelled scenarios in the NSW geographic context, we found that:

- Cost drivers and learning curves vary based on the implementation option – major cost drivers include the cost of sorbents/solvents, the manufacturing cost of the DAC unit/facility, energy and operations and maintenance costs.
- The low-cost, low-tech option is cheaper to deliver small scales, but faces energy cost floors unless it can piggyback off technology breakthroughs in industrial decarbonisation and access low-cost renewable energy.
- The high-tech option has the potential to reach lower costs at larger scales, if the sorbent durability and production costs are able follow typical industrial chemical learning curves.
- There are high levels of uncertainty in these costs currently resulting in large ranges of potential future prices.
- There are pathways for NSW to achieve a scale where it can independently bring costs down without reliance on other jurisdictions to achieve economies of scale
- Some major costs – like energy, plant, operations and maintenance – can only come down through local scale.
- Other inputs (for example modular components and some sorbents) can see cost reductions when produced at scale – either locally or imported (with different economic benefits for NSW).

Given the abundance of resources and landmass in NSW, the raw physical rate limiter on NSW DACCS potential is likely carbon storage. Further work is needed to conduct comprehensive geological assessments of NSW total potential. Supply chain constraints such as deployment rate or available renewable energy generation are expected to constrain DACCS before physical rate limiters are reached.

We also found implementing this process in NSW could have significant macroeconomic benefits for NSW. Deployment at the largest modelled NSW scale (22Mt, reflecting 15% of current emissions) would require $2.5-11 billion in direct investment resulting in a total of $3.5-40 billion benefit to the broader economy. This includes 1,200-12,000 jobs during construction and 5,000-90,000 ongoing jobs. The range encompasses the breadth of options modelled.

Extensive work will be required to build and earn general public and community social licence. There are also gaps in regulatory frameworks required for DACCS to operate, in particular NSW does not have a geological sequestration regulatory framework.

Both the mine-site EW and DACCS options modelled in this paper have extensive energy requirements – approximately 2,000GWh/yr per Mt of CDR for DACCS and between 1,000 and 8,000GWh/yr per Mt of CDR from EW, with per tonne energy use varying significantly based on the efficiency of the weathering reaction. This additional energy will need to be supplied by additional renewable capacity to balance delivery of net negative CDR with ongoing decarbonisation of current demand and additional increased demand across the energy transition, for example green hydrogen.

We identified nine key barriers to support NSW policymaking

In our carbon potential and economic assessments, we identified the likely physical rate limiters for methods in NSW. However, when taking a systems perspective, the real rate limiters are more likely to be economic, social, governance, information availability and industry capability barries and constraints. We examined nine key barriers representing these limiters.

Challenges accessing the quantum of **R&D investment** needed to develop tech
Challenges accessing **project finance** to meet up front capital expenditure needs
Lack of long term, stable **revenue streams** to unlock investment
Challenges building and maintaining industry, method and site-level **social license**
Insufficient **governance structures**, e.g. regulatory, legislative and planning barriers
Information barriers, i.e. lack of precompetitive information around NSW potential
Infrastructure requirements across entire CDR value chains
Lack of **direct industry experience** in engineering, trades and peripheral industry
Lack of established **MRV standards and frameworks**

Figure 5: Barriers to scaled deployment of CDR

NSW has a strong track record of acting on many of these barriers in analogous industries, such as in relation to the energy transition. There is significant potential for NSW policy interventions to address these barriers and begin unlocking the pathway to scaled deployment. From consultation, we heard that local conditions are critical for success and start-ups are looking to site in jurisdictions that are creating these conditions. A key role for the NSW government is creating the local conditions necessary for successful deployment while safeguarding the interests of NSW communities.

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Background

Project background and objectives

Common Capital was engaged by the Office of Energy and Climate Change to deliver research into carbon dioxide removal opportunities in NSW.

The objective of this project is to understand the feasibility of deployment, relative carbon abatement potential, and economic costs and opportunities of large-scale carbon dioxide removal in NSW's geographic and industrial context.

CDR is a new field. Technologies to remove atmospheric carbon dioxide, their potentials and their costs are all evolving rapidly. While our analysis provides potential and cost numbers, there is significant uncertainty about how these will change in the future. Further, information on NSW physical characteristics (particularly geological characteristics) is disparate and requires further investigation to support a firm estimate of total theoretical potential. Therefore, modelling results are indications only. The value of modelling is to analyse indicative carbon removal potential and cost ranges, and the cost and opportunity levers jurisdictions like NSW can act on to drive deployment and cost reductions through scale.

Method scope

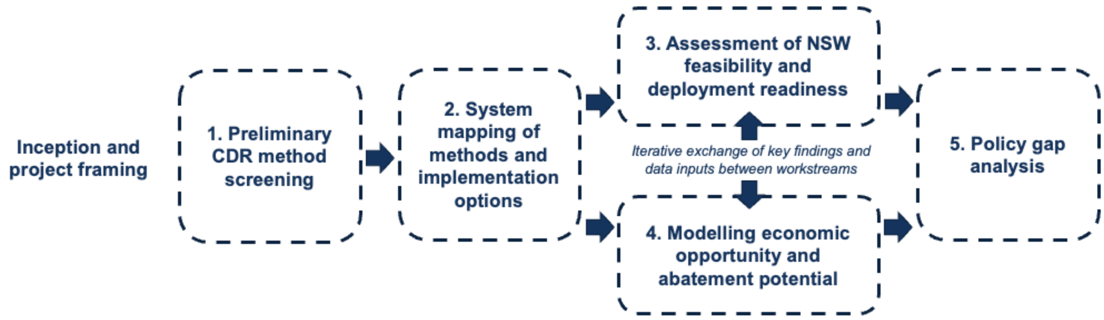
We have considered two broad CDR methods, enhanced weathering and direct air capture with carbon storage (DACCS) in detail, supported by quantitative modelling of costs and potentials. These methods were agreed as initial priority focus areas for this work with the Department.

We have conducted a further desktop and qualitative review of biomass carbon removal and storage (BiCRS).

Other land-based methods (afforestation/reforestation, soil carbon), biochar, and deep ocean-based methods (ocean fertilisation, ocean alkalinity enhancement) were out of scope for this research.

Methodology

We designed a foresight-led, mixed method research approach to deliver advice and policy insights that can drive market transformation.



The major workstreams for this research were:

- Preliminary method screening to define and identify methods for review, including review of research literature and detailed screening and assessment of over 200 CDR startups.
- System mapping of methods and implementation options under investigation to provide a consistent framework for subsequent analysis.
- Qualitative assessment of deployment feasibility in NSW, supported by further desktop research and over 25 interviews with subject matter experts, including international leaders in CDR deployment, CDR-focussed philanthropy and venture capital, major incumbents in domestic supply chains relevant to CDR, and a range of supply chain, social licence and governance experts. Interviewees are quoted throughout the report in italics but quotes are not attributed to protect anonymity.
- Quantitative modelling of carbon removal potentials, costs, and economic opportunity in NSW, applying the principles of life-cycle assessment and to understand place-based potentials and costs in NSW.
- Policy gap analysis, drawing on findings of previous streams to identify barriers to scaled deployment and frame policy problems and principles to support prioritisation of future NSW government policy in CDR.

This research was supported by workshops held across workstreams with both our consortium partners at the Climate Recovery Institute, expert advisors from Lawrence Livermore National Labs in the US, and representatives from the Office of Energy and Climate Change at key stages of the project.

Acknowledgements

Common Capital would like to thank our consortium partners at the Climate Recovery Institute (CRI), a CDR-focussed not-for-profit organisation. CRI experts contributed to advisory workshops and provided cross-disciplinary scientific and governance subject matter advice to support this research.

We are very grateful to Lawrence Livermore National Labs in the United States, recognised global leaders in CDR, for their generous advisory support during this research.

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Section 1: Understanding the carbon removal challenge

This section provides background on atmospheric CDR, why it is needed and methods that can be used to remove carbon from the atmosphere.

Key takeaways for NSW policymakers

- IPCC modelling tells us emissions reduction alone will not be enough to keep global warming below 2°C. Globally, gigatonnes of CO_2 must be removed from the atmosphere each year from the 2030s. This is called atmospheric carbon dioxide removal (CDR).
- NSW may require between 14Mt and 27Mt of atmospheric CDR in 2050 to achieve net zero.
- There is low literacy around the difference between atmospheric CDR and point source carbon capture and storage (CCS).

Atmospheric carbon dioxide removal is an additional requirement

Why do we need atmospheric CDR?

Urgent emissions reduction is needed to avoid dangerous climate change. But emissions reduction alone is no longer enough. Avoiding dangerous climate change is now only possible by combing both emissions reduction **and the removal of CO_2 that's already in the atmosphere.** Atmospheric carbon dioxide removal (CDR)[1] is the subject of this report.

Pathways to limit warming to below 2°C require removing hundreds of billions of tonnes of CO_2 from the atmosphere throughout this century [3] – a median 220Gt by 2100 with no overshoot, a median 360Gt in scenarios where we initially exceed 1.5°C, or up to 660Gt at high estimates [4] [5] – in addition to urgent deep emissions reduction.

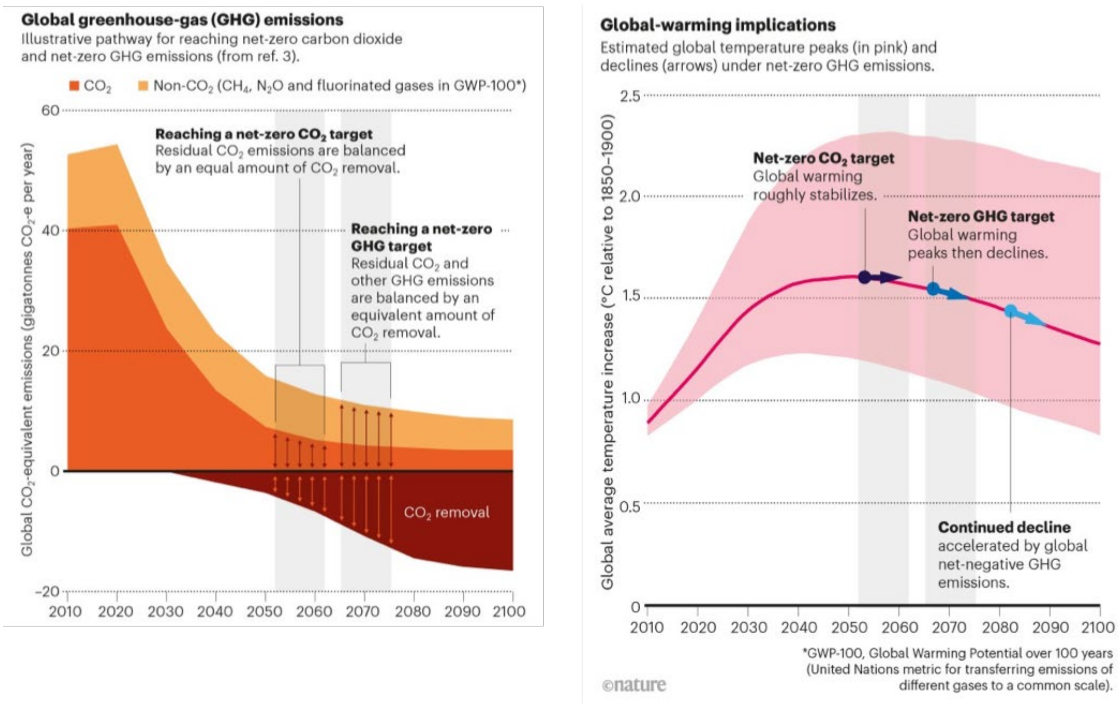


Figure 6: Carbon dioxide removal is needed both to (1) balance residual emissions to reach net zero, left, and (2) help manage any temperature overshoot beyond 1.5 or 2C, right [6]

[1] Also commonly referred to referred to as carbon removal, greenhouse gas removal (GGR) and negative emissions technologies (NETs). This report uses CDR and carbon removal.

Atmospheric CDR is not a substitute for emissions reduction

Atmospheric carbon removal is needed in addition to emissions reduction. The IPCC pathways that model steep emission reductions across sectors already require billions of tonnes of CDR annually into the future. Any delay to emissions reductions will further compound the scale of the CDR challenge. As outlined in Figure 7, the IPCC models that we will breach safe temperatures and restore them using CDR. Restoration of safe temperatures is a critically important role for CDR.

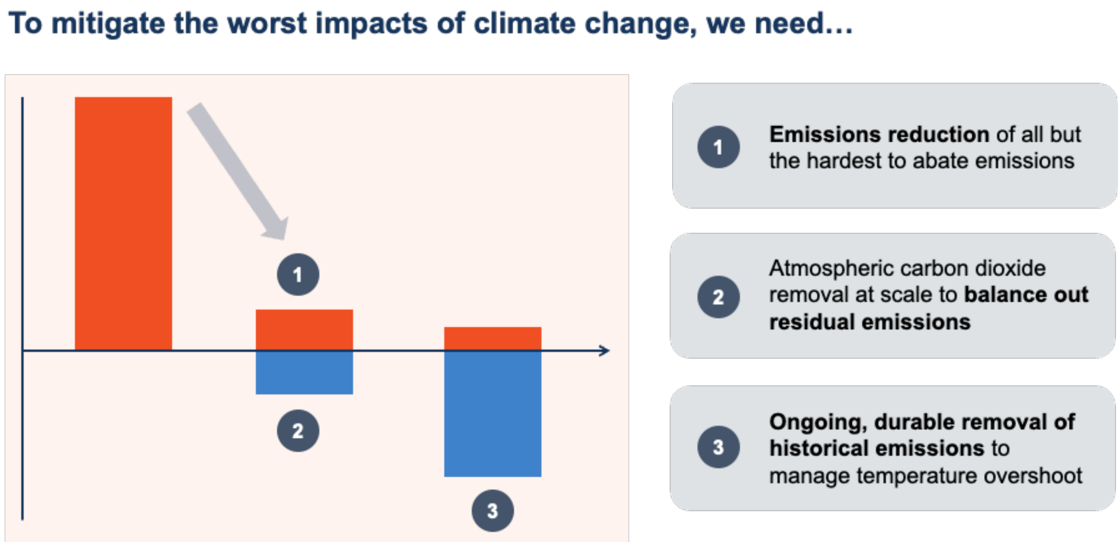


Figure 7: CDR is needed - in addition to emissions reduction - to balance residual emissions and manage temperature overshoot

How much atmospheric CDR might NSW require?

The amount of carbon removal NSW needs to deliver to balance out residual emissions depends on the rate of decarbonisation. With current policy, NSW is presently forecast to have 27Mt residual emissions by 2050 – requiring **27Mt** of CDR per annum [6]. If we increase our rate of decarbonisation, our net zero requirements decrease – for example, if we reach the 10% residual emissions threshold targeted by the EU, we will need **14Mt** of CDR per annum [7] [8] to reach a state of net zero. It will take time for NSW to scale up CDR to reach these levels. NSW may set policies such as targets in the near-medium term to drive scale-up.

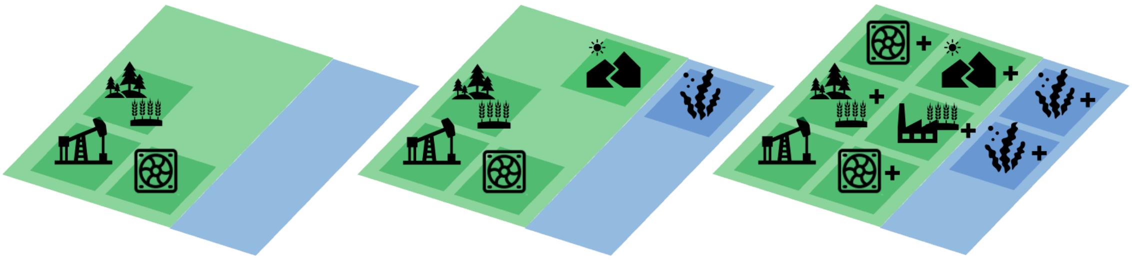
Beyond net zero, NSW may also contribute to the global need to reach net negative emissions by drawing down historical emissions. In 2020, Australia produced 1.1% of global emissions [9], with NSW contributing approximately a quarter [10]. As an example, if the IPCC's upper estimated 660Gt global removal requirement[2] were attributed proportionally based on that reference year, NSW's ongoing target would be approximately **36Mt** per annum.

[2] There is significant variation in modelled estimates of CDR required to manage temperature overshoot into the future due to high levels of uncertainty in future temperature pathways [213]. These estimates are dependent on our global rate of decarbonisation (i.e., how much carbon dioxide and other GHGs we continue to emit before reaching net zero), what level of residual emissions CDR has to neutralise, and what level of confidence we want to have in our temperature trajectory.

NSW will need over a decade to bring CDR to the required scale

NSW needs at net zero depend on emissions reduction achievements

Requirements will keep evolving into the future



In the near and medium term, NSW will need to deliver pilot and commercial scale projects to support scale-up.

This may be supported by a near term CDR target.

Key drivers:
- Balancing residual emissions
- Timeframe to scale

At net zero, NSW will need CDR to balance our residual emissions. This will depend on our level of abatement.

At **10%**[1], we will need **14Mt CDR**.
At **20%**[2], we will need **27Mt CDR**.

Key drivers:
- Balancing residual emissions
- CDR export opportunities

Into the future, we will need to continue scaling CDR to remove historical emissions and restore safe temperatures.

Based on current emissions, our share could be up to **36Mt.**

Key drivers:
- Restoring safe temperatures
- CDR export opportunities

[1]10% is the residual emissions threshold targeted by the Science Based Targets initiative and the EU for net zero.
[2]20% residual emissions at 2050 are projected by the NSW Net Zero Emissions Dashboard based on of current NSW policy.

Figure 8: Potential near term, net zero and future CDR scenarios for NSW

NSW can either deliver this carbon removal at home or procure it from other jurisdictions – carbon removal at an ongoing cost that leaves NSW without the macroeconomic benefits of delivering this new industry. Conversely, if we deliver in excess of our own requirements, there will likely be export opportunities as many jurisdictions are constrained in delivering their own CDR due to relatively small landmass and resource bases. Exports of CDR as a service beyond our requirements can contribute to NSW gross state product and sovereign capability.

Box 1.1: How are other jurisdictions setting targets for CDR?

The EU is considering splitting their Nationally Determined Contribution (NDC) for net emissions reduction into separate reduction and removal targets [7].

The UK has set a near-term target of 5Mt CDR – across methods including land-based CDR, bioenergy with carbon capture and storage and direct air capture – by 2030 [3].

California has set a 20Mt carbon removal target for 2030, and a longer term 100Mt target for their net zero deadline in 2045 [6].

Most jurisdictions globally will require CDR both to neutralise residual emissions and to contribute to net negative emissions for restoring safe temperatures. The scale of the task means that most jurisdictions will have to make a contribution – it is not a 'winner takes all' dynamic.

The 2023 State of Carbon Removal report [3] provides an excellent overview of key concepts and is recommended as further background to understand the basis for atmospheric CDR.

What is atmospheric carbon dioxide removal?

The Intergovernmental Panel on Climate Change (IPCC) defines CDR as:

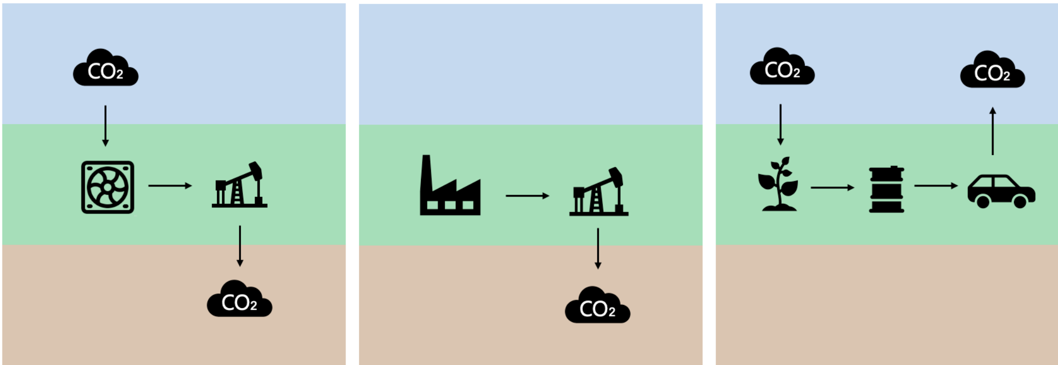
> *Human activities capturing CO_2 from the atmosphere and storing it durably in geological, land or ocean reservoirs, or in products. This includes human enhancement of natural removal processes, but excludes natural uptake not caused directly by human activities* [1].

This means that for a process to achieve atmospheric carbon removal, it must achieve two things: **(1) capturing CO_2 from the atmosphere** ***and*** **(2) storing the CO_2 durably** in geological, land or ocean reservoirs or long-lived products.

Atmospheric CDR is often confused with CCS and CCU

Atmospheric CDR is often confused with:

- **Carbon capture and storage** (CCS) of point source emissions. This is emissions avoidance – capturing additional emissions before they go into the atmosphere, rather than removing them from the atmosphere.
- **Carbon capture and utilisation** (CCU), particularly of fuels, where the captured carbon is re-released. This is also emissions avoidance – the use of captured carbon for fuels, supplants the use of fossil fuels and associated emissions. It is not carbon removal as the carbon has not been durably stored.



Carbon is captured from the atmosphere and stored durably underground.	Carbon is captured from the flue stack of a power station and stored durably underground.	Carbon is captured from the atmosphere and converted to fuel, but re-released during use.
This is CDR – durable storage of atmospheric carbon.	**This is CCS, not CDR** – the carbon is not from the atmosphere.	**This is CCU, not CDR** – the carbon is not stored durably.

Figure 9: Distinguishing CDR, CCS and CCU

CCS and CCU can be key parts of sectoral emissions reduction pathways as tools to avoid adding additional emissions to the atmosphere, particularly industry pathways such as cement and steel. These sectoral emissions avoidance strategies are different from atmospheric carbon removal.

There isn't an existing sector responsible for atmospheric CDR

We typically approach climate change mitigation through a sectoral lens, focusing on emissions reduction pathways suitable for the emissions profile of each sector. The responsibility for atmospheric carbon removal, on the other hand, does not reside in a single sector[3].

From a sectoral lens, atmospheric carbon removal is most akin to the waste management industry. The waste management industry is responsible for preventing negative impacts from waste products such as sewage and municipal waste. If left unmanaged sewage and waste cand (and used to) have significant negative public health impacts on communities. The waste management and water sanitation industries were created to address this and are funded through governments in the interest of the public good.

The volume of atmospheric carbon removal needed means it may also be thought of as a new industry providing a public good service of atmospheric sanitation.

Many actors in government, industry and civil society don't understand the need for and nature of atmospheric CDR

Through consultation, we found that most actors across government, industry and civil society do not understand atmospheric CDR. In particular:

- the need for atmospheric CDR is not well known in NSW. The need for atmospheric carbon removal at a global level has only emerged due to delays to achieving emissions reduction. Knowledge is still immature because it is relatively recent.
- the conflation of atmospheric carbon removal with CCS and CCU (particularly CCS) creates a misunderstanding about what atmospheric CDR is (i.e., it is not understood that the CO_2 must be removed from the **atmosphere** and durably stored).
- some climate change professionals struggle to understand atmospheric CDR due to existing knowledge of CCS and CCU. This is due to some crossovers between technical concepts in these different mechanisms. As a result, professionals may misunderstand atmospheric CDR as familiar concepts CCS and CCU, which is a barrier to building atmospheric CDR knowledge.

The social licence implications of this are discussed in Section 3.

[3] Some methods to remove carbon from the atmosphere can involve capabilities in existing sectors like agriculture (for example, soil carbon), power generation (like bioenergy with carbon capture and storage) and DACCS (through carbon storage in long-lived products like concrete).

There are many ways to remove carbon dioxide from the atmosphere

The earth system has naturally been removing carbon from the atmosphere for billions of years and storing it – both organically (in soils and biomass) and inorganically (in geological formations and oceans). While organic carbon can cycle relatively quickly, natural storage of stable inorganic carbon in the slow carbon cycle takes millennia.

Many CDR methods build on the earth's natural processes to remove carbon from the atmosphere – but reduce the time from millennia to days, weeks, or months. Methods must be resilient to the impacts of climate change (for example, resilient to fire and flood), able to be delivered at industrial scale, techno-economically viable over the long-term and deliverable with high confidence in the measured carbon benefit.

CDR methods capture and store atmospheric carbon using different mechanisms:

- **Biological** mechanisms use photosynthesis to capture carbon in growing biomass or in organic matter in soil, which is stored in situ as part of the fast carbon cycle or converted to other forms for more durable storage (discussed further in Section 2).
- **Geological** mechanisms accelerate the natural weathering of rocks with CO_2 and water to mineralise carbon, i.e., store it in carbonate minerals.
- **Chemical** mechanisms use manufactured chemical materials to capture CO_2.

The major methods to capture CO_2 by leveraging these processes are depicted in Figure 10.

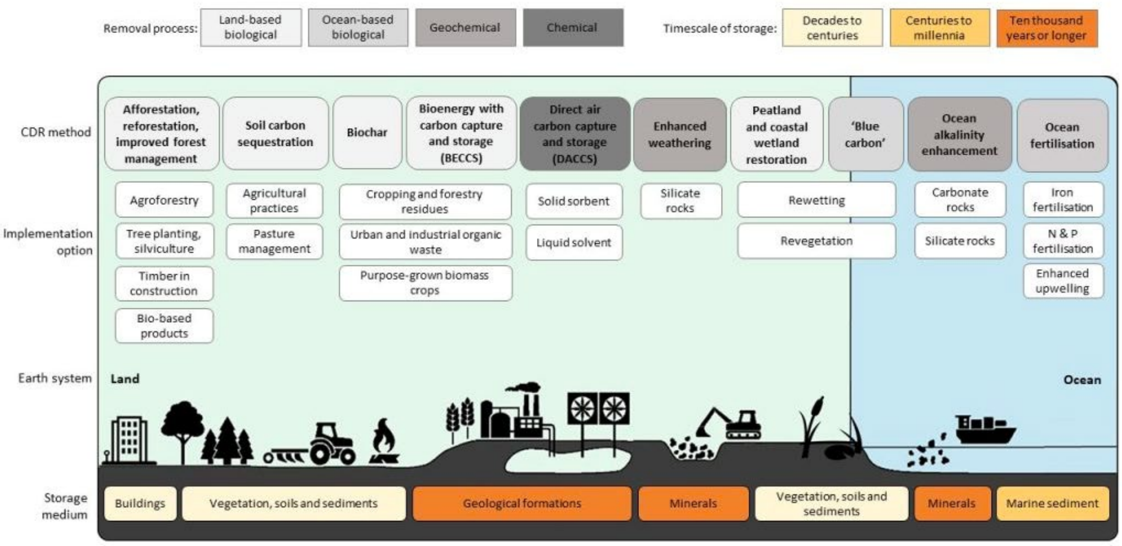


Figure 10: Major CDR methods and implementation options [11]

CDR methods and implementation options

The CDR taxonomy is evolving, spurred on by technological innovation. While the IPCC and Figure 10 above refer to bioenergy with carbon capture and storage (BECCS) at method level, in this paper, we use biomass carbon removal and storage (BiCRS) – an umbrella method that includes BECCS, biochar, long-lived wood and bio-based products and emerging implementation options like bio-oil (see Section 2).

These methods are not homogenous. Under each CDR method are different implementation options, representing the many different ways CDR can be deployed. We have identified well over 200 different companies working to achieve CDR across 12 methods. Solely within the umbrella method of direct air carbon capture and storage (DACCS) – which uses chemical capture agents to cyclically remove carbon from ambient air – we have identified upwards of 15 unique implementation options for capturing CO_2 and over 5 different technologies for storing the captured CO_2.

Methods are not single technologies, but end-to-end systems to deliver the capture and storage of CO_2. While it's easy to think of CDR in terms of technologies – like a single machine to deliver DACCS, for example – these methods and implementation options should be assessed and compared as systems. CDR can only deliver genuine removal if the entire system – including embodied emissions, energy, and transport requirements – delivers net negative emissions. Assessing CDR on the basis of individual technologies in isolation risks perverse outcomes, for example, where these systems emit more along their supply chains than they capture and store. Energy-intensive CDR methods like those reviewed in this paper will require the deployment of significant new renewables to meet their energy needs without compromising their CDR potential.

Not all storage pathways are equal. There is a growing consensus in climate science that for carbon removals to balance emissions they must be like-for-like with the emissions being neutralised [12]. As most human-induced emissions are from the slow carbon cycle – the burning of fossil fuels – these emissions need to be balanced by removals that return carbon dioxide to this cycle, storing it underground or in inorganic mineral form for thousands of years. While removals of shorter duration like reforestation will help mitigate near term climate impacts, the majority of CDR must store carbon over geological timescales. Re-released emissions from low durability methods will need to be replaced at the end of their permanence period to maintain the CDR benefit. However, land-based methods often have significant environmental and social co-benefits that higher permanence geological storage pathways may not. Accounting frameworks and funding mechanisms are needed to value these co-benefits while also recognising different timescales of removal.

Recommended resources for additional information on CDR methods include the CDR Primer and Section 12.3 of Chapter 12 of the IPCC Working Group III 6th Assessment Report.

The role of this report is to lay a foundation for NSW to design policy

This report provides NSW policymakers an overview of some of the key considerations regarding CDR in NSW based on the methods reviewed. This report looks at DACCS and enhanced weathering in depth (supported by modelling). Further, it provides a discussion of BiCRS. These methods are outlined in Section 2.

In this Section, we have outlined the key CDR concepts and why CDR is relevant for NSW. The remainder of the report explores different areas of CDR:

- Section 2 provides an introduction to the methods we reviewed, with short technology profiles and a review of the alignment of NSW resources with the method.
- Section 3 discusses thematic supply chain and social licence considerations for policy design, as well specific considerations for different methods.
- Section 4 focuses on the economic dynamics of CDR on both the supply and demand side. We explore the NSW CDR potential of different options and understand how cost drivers change between different implementation options and at different scales.
- Section 5 synthesises major barriers to scaling CDR in NSW to provide policymakers with an overview of different areas they may seek to target with policy intervention.

common capital

Section 2: A review of methods in the NSW geographic setting

This Section provides an overview of CDR methods and their alignment with the NSW resource profile. We reviewed DACCS and enhanced weathering in detail and BiCRS at a higher level.

Overview

Key takeaways for NSW policy makers

- NSW has significant reserves of required minerals for enhanced weathering, particularly ultramafic rock deposits and potential ultramafic mine tailings.
- NSW has strong land and storage resources (geological storage and mineralisation) to support DACCS deployment.
- NSW has significant volumes of waste feedstocks for BiCRS processes - particularly cropping waste.

Enhanced weathering

What is enhanced weathering?

Enhanced weathering (EW) is an atmospheric CDR method that accelerates the natural processes of the slow carbon cycle. Many rocks naturally contain minerals – namely calcium and magnesium – that capture CO_2. This occurs when CO_2 and water combine and come into contact with calcium and magnesium, converting the CO_2 into inorganic carbon through a geochemical reaction [13] [14]. The CO_2 changes from an atmospheric gas to bicarbonates or carbonates. This carbon is stored as a dissolved ion or solid for potentially millions of years in soils, oceans and crust.

The rocks that contain the magnesium and calcium minerals that create the basis for this reaction are called **mafic or ultramafic silicate rocks** (see Appendix A for more). These reactions can take place wherever all three ingredients are present - CO_2, water and mafic or ultramafic rocks.

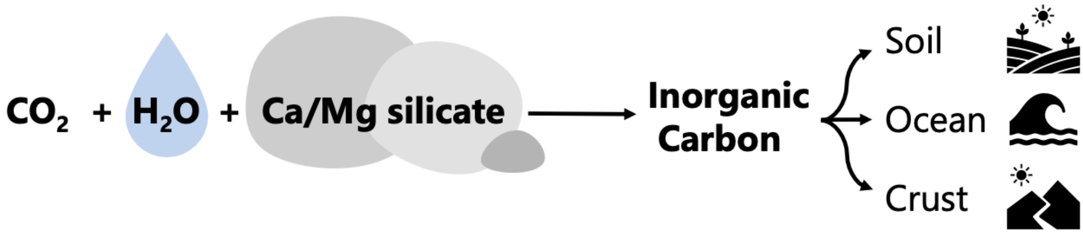


Figure 11: Carbon removal via rock weathering

Each year, natural weathering pulls down 1 Gt CO_2 from the atmosphere without intervention, just from the rocks that are on the surface of the earth [15] [16]. There is also an abundance of these rocks below the Earth's surface that can be exhumed and weathered. If these rocks are then crushed to very small sizes (roughly similar to a powder), they will react and capture CO_2 much faster than the natural process [14] [17]. Considering industry already exhumes and crushes millions of tonnes of these rocks each year when mining minerals like nickel, this method has high potential.

EW is appealing because it captures and stores CO_2 in one pathway and uses abundant, relatively cheap inputs. Additionally, its applications may have potential agricultural and environmental co-benefits. Innovation is focused on improving MRV accuracy, accelerating the reaction, and limiting the energy required to grind, transport, and activate the carbonation reaction.

Enhanced weathering is also commonly referred to as accelerated rock weathering. In engineering-based systems, enhanced weathering processes are typically referred to as mineral carbonation or carbon mineralisation.

How is enhanced weathering implemented?

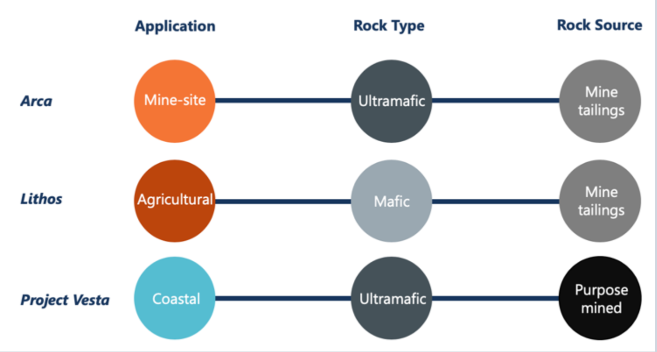
EW can be implemented in different ways, depending on where the rocks are weathered (at mine-site, on agricultural fields, or on the coast), what rocks are used (mafic or ultramafic), and how the rocks are sourced (purpose-mined or mine tailings).

- **Mine-site EW (most commonly referred to as mineral carbonation)** is where the ground rocks are weathered at the mine site where they were exhumed, such as in sealed tailings pits. These **ultramafic rocks** may be mine tailings or waste rock which are produced as a by-product of the extraction of certain metals, such as nickel. Mine tailings are already crushed to a very small size in the normal operation of the mine, meaning that no further crushing is likely required, reducing energy and cost requirements – these rocks are already ready to weather if exposed to CO_2 and water. Alternatively, highly reactive rock can be purpose mined and ground to maximise the carbon removal potential. Rocks can also be prepared to increase reactivity , such as through thermal processing. As this process can be energy intensive, many mine site options would require renewable energy to avoid increasing emissions.
- **Agricultural EW** is where the silicate rocks are distributed over agricultural land. As the rocks weather, they release nutrients that can increase the growth of the crops and improve the health of the soil. Agricultural EW usually requires the use of **mafic rocks** because ultramafic rocks often contain heavy metals that are toxic to plants.
- **Coastal EW** is where the silicate or ultramafic rocks (for example olivine) are distributed over beaches. The wave action accelerates the weathering to increase carbon capture.

See Appendix A for more detail on the implementation options of EW.

There are a number of enhanced weathering businesses around the world in different stages of development, including **Carbonaught** in Australia. Box 2.1 outlines three well known EW start-ups, each with millions of dollars in funding.

Box 2.1: EW deployment case studies



Arca (Canada) uses ultramafic tailings from nickel mines to capture atmospheric CO_2. They also have proprietary techniques that are integrated into mining process circuits to accelerate the reaction to over 5× the natural weathering rate.

Lithos (US) distributes mafic mine tailings over agricultural land. They have found that their process both captures CO_2 and increases crop yield.

Project Vesta (US) is testing the application of ultramafic rocks to coastal beaches. The wave action increases the rate of CO_2 sequestration.

NSW has a high potential for enhanced weathering based on its resource profile

The CO_2 removal potential of EW in NSW is not limited by the volume of appropriate rocks, with the capacity to store hundreds of years of emissions from NSW within one particularly suitable ultramafic deposit [18]. Instead, the CO_2 removal is likely to be limited by the mining of these rocks. Current ongoing production of mafic and ultramafic rocks is unable to support significant CDR, although there are likely reserves of mafic and ultramafic mine tailings from existing mining in mafic and ultramafic geology in NSW that would be suitable inputs into EW applications. As mine tailing data is not publicly available in NSW, further work is required to estimate the abatement potential of these resources. Utilisation of suitable mafic and ultramafic deposits could see EW comfortably reaching megatonne scale of annual CO_2 removal in the future[4].

NSW has a strong minerals resource profile for EW. The table below provides an overview of NSW resources, with the key uncertainties that illustrate that further work on NSW tailings and deposits are required to further understand the scale of potential EW in NSW.

Table 1: NSW alignment with enhanced weathering resource requirements

NSW resource	Uncertainties
NSW has significant ultramafic deposits. These include the Great Serpentinite Belt, the Coolac Serpentinite Belt and the Gordonbrook Serpentinite Belt [19] [20] [21]. The ultramafic resources in the Great Serpentinite Belt alone have the capacity to store hundreds of years of emissions produced by NSW [18]. Therefore, mining of these deposits can realistically reach annual **CO_2 capture on the megatonne scale.**	Public data of the mineralogy of ultramafic deposits is very limited – further surveying of the mineralogy and deposit size is important to assess the potential for EW. This not only includes assessing whether rock is ultramafic, mafic or otherwise, but also the specific mineralogy, as different minerals have very different carbon capture rates and potentials (see Appendix A for details).
NSW may have existing reserves of mafic and ultramafic mine tailings. Previous mining in mafic and ultramafic geology throughout NSW suggests that legacy mines may have existing reserves of mafic and ultramafic tailings. There is also potential for mafic mine tailings at the 15 operational gold mines and 12 operational copper mines across NSW, as these metals are often located in mafic geology [22]. Testing the reactivity of tailings from existing and future mines, particularly copper and gold mines, could reveal a source of **megatonne scale CO_2**	There is little public data regarding reserves of mafic and ultramafic tailings. A survey of tailings from existing mines in regions of mafic and ultramafic geology could reveal a supply of pre-ground mafic and ultramafic rocks that could contribute to megatonne scale CDR. Within the copper and gold mine tailings, the potential reactivity has not been tested. Characterisation of these tailings would allow for an accurate identification of CDR potential.

[4] See modelling results in Section 4.

capture each year by itself, as many of these mines produce 10s to 100s of Mt of mine tailings each year.	
Future ultramafic tailing production is likely to increase. Important metals to the energy transition and the NSW Minerals Strategy such as nickel, cobalt and platinum-group elements (PGEs) have a number of deposits in NSW. They are typically located in ultramafic geology [22] [23],which means these critical minerals often co-locate with the minerals required for enhanced weathering. The Broken Hill PGE deposit and the Sunrise Nickel-Cobalt-Scandium deposit are two examples that are both under development and would produce significant amounts of ultramafic tailings each year [23]. [24] [25]	It is not known how many NSW mines of these characteristics will ultimately go ahead. Further work would be required to explore how to adequately incentivise incorporation of EW to these mine sites. Further, characterisation of the potential mineralogy of the future mine tailings would allow for much more precise estimates of EW potential.
Purpose-mined mafic rocks: Mafic rocks, such as basalt, are currently produced at a rate that supports small-scale carbon capture. Hard rock quarries such as Ardmore Park Quarry, Oberon Quarry and Boral Peats Ridge Quarry are a source of basalt.	The reactivity of the hard rock products at NSW sites do not appear to be publicly known, as the basalt is mixed in with non-mafic material. There is also limited information on NSW basalt deposits to support future purpose-mining of mafic rocks.

Three key areas of uncertainty could be investigated to further refine NSW potential:

Overall availability of suitable rocks in NSW: The relevant information on suitable rocks is currently disparate and there are gaps in knowledge of total rock availability. This includes the size of underground deposits and above-ground reserves of mine tailings.

Further precision on the mineralogy and elemental composition of deposits: The precise mineralogy and elemental composition of a rock determines its CDR potential – specifically how much CO_2 it can capture, and how quickly it can do it. Without this information, it is difficult to assess the potential scale of EW in NSW, as the supply of appropriate rocks is likely to be the limiting factor to scalability. Please see Appendix A for more on the characterisation of rock deposits.

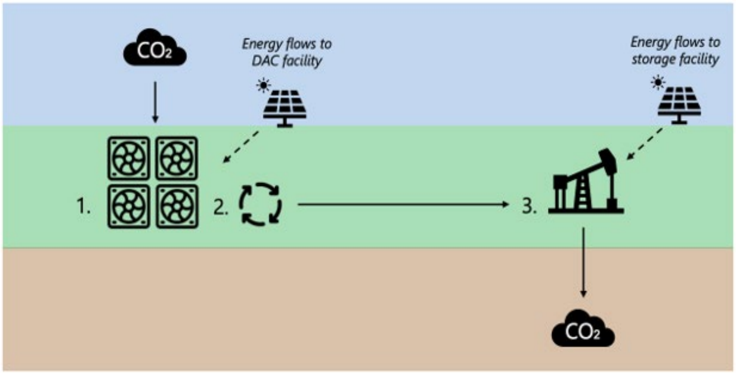
EW CO_2 sequestration rates in NSW conditions: The rate at which EW captures CO_2 is dependent on factors such as pH, temperature, and water availability. This means that the rate of CO_2 sequestration in NSW will be different to the rest of the world, and therefore, studies around the world cannot be relied on for an estimate of carbon capture potential in NSW. NSW must assess the weathering rate of mafic and ultramafic rocks at mine-sites, agricultural fields and beaches in NSW. It should be noted that this factor is marginally less important in mine-site EW, as the conditions can be more precisely controlled and measured in the closed system.

A more detailed review of enhanced weathering can be found at Appendix A.

Direct air capture and carbon storage

What is direct air capture?

Direct air capture and carbon storage (DACCS) is a cyclic process that removes CO_2 directly from ambient air [26] [27] [28]. Air is brought into contact with a capture agent which pulls down CO_2 molecules from the atmosphere. The capture agent is then regenerated using a process that releases the captured CO_2 for durable storage underground or in long-lived carbon products. The capture agent can be repeatedly re-used and regenerated.



As of 2022 there were 18 small-scale DAC plants worldwide, capturing almost 0.01 Mt CO_2/year. However, this is expected to scale up significantly. The US Regional Direct Air Capture Hubs policy provided US$3.5bn in incentives for 4 1MT capacity DACCS hubs [29]. The first large-scale DAC plant is expected to be operational in the US in the mid-2020s [28].

1. **Capture**: Ambient air passes through the unit and the CO_2 is captured.
2. **Regeneration**: A regeneration process separates a pure stream of CO_2 from the sorbent.
3. **Storage**: The CO_2 is stored – in this example, compressed and piped underground, where it is stored in a geological reservoir.

Figure 12: Direct air capture and carbon storage

DACCS has low physical resource requirements compared to other CDR methods as the capture agent is cyclically regenerated [27], and DACCS carbon capture takes place in closed systems, giving them high measurability certainty and the ability to reach industrial scale.

However, DACCS typically has high energy requirements to move air through the capture unit and regenerate the capture agent and requires the building or manufacturing of new facilities.

How is direct air capture implemented?

There is wide variation in DACCS approaches. Key points of variation across capture include:

- the **capture agent** – for example, solid amine sorbents, liquid hydroxide solvents, zeolites [30], lime [31], electrocapture agents [32] and metal-organic frameworks (MOFs) [33]. The nature of the agent, the regeneration process and the environment (impurities, dust, moisture, temperature) will determine the longevity of the particular capture agent (how many times it can be regenerated before being replaced).
- the use of air handling to accelerate airflow over the capture agent.
- how the capture agent is **regenerated;** most DACCS technologies use a temperature-swing process to release CO_2 [34]. Emerging approaches include electro swing (an electric current [35]), moisture-swing (change in humidity [36]) and reaction-swing (a chemical reaction).

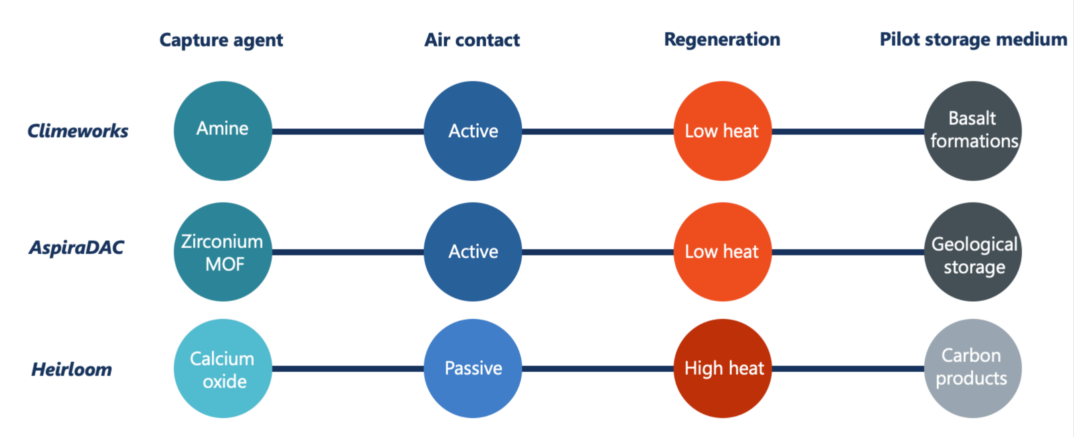
There are different potential storage pathways for CO_2 captured by DACCS systems:

- **Geological injection** of compressed CO_2 into sedimentary formations like depleted oil and gas reservoirs, deep saline aquifers, and coal beds [37] below 800m where it is trapped in a supercritical, liquid-like state [37]
- **In-situ mineralisation** where CO_2 and water are injected into mafic and ultramafic rock formations where they react to form carbonates [38] – the same chemical mechanism by which enhanced weathering captures ambient CO_2.
- **Mineralisation and use** in long-lived products including cement, building materials and fertiliser, where CO_2 is reacted with forms of calcium and magnesium within industrial waste or suitably reactive mafic and ultramafic silicate to form usable products. Mineralisation does not require an off-taker, it may also be stored at sites such as mine tailing pits (ex situ).

These diverse implementation options have bespoke deployment setting requirements. A future of scaled deployment is unlikely to be dominated by a single 'silver bullet' DACCS technology, but rather a range of technologies tailored to different deployment settings. The development of multiple implementation options in a range of geographies will be critical to reaching net zero climate goals [34].

Box 2.2: DACCS deployment example

Climeworks operates the world's first large-scale pilot plant in Iceland, Orca, at 4,000t per annum [39]. Climeworks use a functionalised amine sorbent regenerated in a vacuum at 80-100 degrees C, with electricity for the air contactor and heat for regeneration using geothermal energy [40]. CO_2 captured is injected into basalt formations for mineralisation by their storage partner Carbfix [39]. Climeworks is currently developing a second facility (36,000t). Their process is compared with two other well known DAC companies below:



NSW meets the physical parameters for successful deployment of DACCS

An assessment of the key physical parameters for DACCS systems suggest NSW is well-placed to deploy these technologies.

Table 2: NSW alignment with DACCS physical parameters

NSW parameters	Uncertainties
NSW has a strong physical resource base to produce capture agents – for example, the lime- and zircon-based capture agents described in the case studies above. NSW produces more than 4Mt limestone annually [47]; Australia has domestic production of >560kt zircon, with deposits in the Murray Basin and Western NSW [48].	Exact resource volumes required to produce high tech capture agents are uncertain as these are currently only produced in small quantities. However, these physical resource requirements are not expected to be a limiting factor.
NSW's climate and water profile are different to many early deployments of DACCS, for example, in Europe and the US. capture agents can be sensitive to both humidity and temperature and some processes, for example, those that prefer humidity [49]will likely see lower capture rates in parts of NSW. However, there are innovations in technology for a range of climates (notably the AspiraDAC/SGG MOF, which have been optimised for NSW climactic conditions). Geological injection of CO_2	Exactly what impact climate has on capture rates is highly specific to individual capture agents. Scales of required water use and water production are similarly technology-specific and current areas of innovation. Due to the variation across DACCS, water and climactic parameters are not expected to be a significant limitation.

may require water extraction to manage reservoir pressure (enhanced water recovery) which may provide a water input for co-located DACCS facilities.	
NSW has the landmass to facilitate scaled deployment. DACCS has significant land requirements including large-scale renewable energy needs. While this may compete with other land uses, DACCS can be deployed on otherwise unproductive (i.e. non-agricultural) land; some implementation options may be co-located with agriculture. NSW has a large, sparsely populated landmass relative to many other international jurisdictions.	The exact land requirements for DACCS vary based on different implementation options. Section 4 of this report includes modelled land requirements for two options.
NSW has identified Mt scale storage pathways. Preliminary estimates of NSW geological storage in the Darling Basin range from 69 – 1,331Mt (p50 value 555Mt, under further investigation) [50]. NSW has strong resources for ex-situ mineralisation, and Mt scale per annum mineralisation opportunities using coal ash, cement waste and iron and steel slag (see Appendix B).	Additional potential geological storage sites in the Darling, Oxley and Gunnedah Basins have yet to be explored and may be additional suitable storage.

We identified two key technical needs to advance DACCS in NSW:

- Incentives to support technology developers to design NSW-suitable solutions. NSW needs solutions that suit NSW water specific resource base, geography and climactic requirements, for example, water-generating DACCS processes, processes tolerant of high ambient temperatures, and processes tolerant of low ambient humidity. While there is a lot of international investment in R&D globally, NSW needs solutions that are geographically optimal. This means either supporting the R&D directly or providing other incentives that encourage technology developers to start piloting solutions in NSW.
- Investigation and public pre-competitive information on storage pathways, including deep saline aquifers, suitable in-situ mineral formations (for example, basalt formations) and ultramafic mineral availability for ex situ mineralisation. There is interest in NSW for deployment because of our renewable potential, however there is limited awareness about whether there are suitable storage pathways. Greater investigation into storage and public availability of precompetitive information may encourage companies to consider NSW as a deployment option.

Biomass carbon removal and storage

What is BiCRS?

Biomass carbon removal and storage (BiCRS) refers to processes that use biomass to remove CO_2 from the atmosphere and store it durably underground or in long-lived products.

Many BiCRS options are at high technology readiness levels, largely attributable to the simplicity of the photosynthesis capture process. There have also been large-scale demonstrations of many of conversion and storage processes [51], including large-scale CCS at commercial bioenergy facilities. BiCRS often uses waste feedstocks that would have decomposed/burned, removing carbon from the fast carbon cycle. Whereas natural methods like afforestation/reforestation and blue carbon see decreasing rates of carbon capture as ecosystems reach maturity and growth of biomass slows, BiCRS can deliver consistent removals as the biomass is harvested allowing for ongoing growth.

Box 2.3: BECCS and BiCRS

BiCRS includes the better-known BECCS – bioenergy with carbon capture and storage. BiCRS is an umbrella term that also captures a broader set of biomass-based CDR processes like the production of biochar, bio-oil and long-lived wood products, all of which remove carbon in biomass for storage but not all of which produce energy or fuels.

How is BiCRS implemented?

BiCRS captures a diverse group of implementation options. It includes biofuels and bioenergy pathways like ethanol production with underground storage of captured CO_2, use of long-lived wood products for example, oriented strand board, conversion into bio-oil for geological injection.

While BiCRS includes the production of biochar, this implementation option is out of scope for this report.

BiCRS processes can use diverse feedstocks, including purpose-grown crops or forestry inputs or agricultural, forestry, and municipal wastes. These typically undergo transformation into a new product – biochemical (fermentation), thermochemical (gasification, pyrolysis) or manufacturing (to produce wood products) – which store carbon in forms like biochar, bio-oil or wood or separate CO_2, for example, pure CO_2 in the fermentation process, for subsequent storage [52].

These processes may produce biofuels, for example, syngas, ethanol and hydrogen. Any utilisation that causes carbon re-release (for example, combustion of ethanol) is not CDR, but supports emissions avoidance as a fossil fuels replacement. If point source capture and storage is to be applied to those secondary emissions, the stored CO_2 is CDR, as it originally came from the atmosphere.

Box 2.4: BiCRS case studies

Charm Industrial is a US company that collect corn stover (agricultural residue) which is converted by fast pyrolysis into stable, carbon-rich bio-oil [53]. The bio-oil is injected into geological formations where it sinks and solidifies. Charm has removed over 6,000 tonnes of carbon for buyers including Stripe, Shopify and Microsoft [54].

Drax use energy-dense compressed wood pellets as fuel in boilers to produce high pressure steam and turn electricity-generating turbines [55]. Solvents isolate pure CO_2 from the flue gases, which are transported by pipeline for geological storage. Drax are substantial generators of energy – generating 15TWh of power of the UK's total 335TWh demand [56] – and have signed a memorandum of understanding to deliver two million tonnes of paid carbon removal to Respira International [57]. Drax plans to deliver 8m tonnes of CDR a year by 2030, meeting 25 – 40% of the UK's removals target [58].

The **Illinois Basin Decatur Project** is a bioenergy with CCS BiCRS project at an Archer Daniels Midland ethanol plant. CO_2 emissions from ethanol fermentation are captured by an amine sorbent and transported by pipeline for geological injection. As of 2021, the project had stored over 1Mt of carbon in the basin [59].

Our report only considers BiCRS with waste feedstocks

This report only considers the deployment of waste-based BiCRS projects – for example, utilisation of agricultural residues, rather than purpose grown biomass crops. Using purpose grown biomass for BiCRS at mass scale risks driving competition with food and fibre for land, and water and indirect land use change, which may inadvertently lead to net positive systems emissions and perverse ecosystem outcomes [60]. Because of these risks, large-scale purpose grown BiCRS is expected to face major hurdles in achieving social licence to operate.

There is potential to grow biomass for BiCRS on non-arable land using non-food crops like *miscanthus* [61] and woody biomass crops, for example mallees and acacias, as is being trialled under the Biomass for Bioenergy project by the NSW Department of Primary Industries [62]. Careful regulation is required to ensure this does not drive indirect land use change by encouraging production (and displacing food production) on arable land.

Biomass availability is the key rate limiter

Feedstock availability is the key constraint to scaling BiCRS. Waste-based biomass places hard limits on CDR potential due to waste availability. NSW has strong biomass availability, as identified under the Australian Biomass for Bioenergy Assessment (ABBA) study [63].

The largest source of biomass waste in the state is agricultural cropping waste (12.2M dry tonnes) – a popular feedstock for BiCRS processes – with considerable secondary volumes of organic waste (municipal solid waste, commercial and industrial waste and construction and demolition wastes, for example, wood, 6.59M DT). NSW has smaller volumes of forestry (2.2M DT), livestock (manure, 1.26M) and horticulture waste (0.16Mt). However, biomass waste is by nature distributed and expensive to transport. The economic implications of this are discussed further in Section 4.

Section 3: Understanding methods in their operational and social contexts

This section considers opportunities and barriers to deployment in NSW's operational and social contexts, including supply chain requirements and alignment with NSW capabilities and key components of social licence.

Bioenergy interviewees suggested potential underestimation in self-reported agricultural ABBA data. Therefore, these may be a conservative estimate of NSW biomass availability.

Key takeaways for NSW policy makers

- Scaled CDR in NSW will require new supply chains. NSW has a strong enabling foundation to deliver, and specific capabilities in mining and energy to support deployment.
- The industrial and resource needs of CDR align with NSW capability and ambitions for future industries in NSW, including advanced manufacturing and the future of mining.
- There is opportunity for NSW to coordinate logistics and siting and streamline regulatory frameworks to enable scaled deployment.
- Large-scale deployment will need to be supported by communication and governance and engagement frameworks to build social licence in NSW - for CDR as a whole, and across method, actor and community level.

Scaled deployment of CDR will need large new supply chains

If we are to meet Paris temperature goals, a new global CDR industry is required that is capable of storing as much carbon annually as the entire transport sector emits today. This will need entirely new supply chains, underpinned by the enabling infrastructure and regulatory processes – and they will need to be built quickly to support scaled deployment from 2030.

To meet this demand with DACCS, for example, it would require deploying thousands of capture units. But it will also require factories to build those units, chemical manufacturing of the required sorbents and solvents, operations and maintenance, new renewables and transmission infrastructure, and CO_2 pipelines and storage facilities.

Orchestration is critical for these puzzle pieces to come together in the timescale needed. Haphazard deployment risks delays and bottlenecks as some parts of the supply chain grow faster than others. Strategic coordination is needed across the ecosystem to ensure that the supply chains and infrastructure to support new projects are delivered where they are required.

What do these supply chains look like?

Potential supply chain operational components for implementation options under each method are outlined below. Supply chains vary significantly across implementation options.

Table 3: Components of CDR supply chains

DACCS	EW	BiCRS

Resource extraction Facility manufacturing Capture agent manufacturing Transport to site Construction Renewable energy, transmission and storage Site-level O&M CO_2 piping Geological storage infrastructure, for example, compression and injection wells Mineralisation processes. infrastructure (as per EW) Product utilisation MRV services	Resource extraction (purpose-mined or waste) On-site transport and handling infrastructure Minerals transport infrastructure Minerals processing Renewable energy, transmission and storage Industrial heating Industrial-scale chemical reactions Mine tailing rover infrastructure Transport to storage or use site Application at site Product utilisation MRV services	Facility manufacturing Capture agent manufacturing (if relevant, for example bioenergy with CCS) Production and sourcing of biomass (municipal, agriculture, forestry) Biomass processing Transport: biomass from sourcing to conversion Conversion, for example, biochemical, gasification, pyrolysis Transport: carbon from conversion to storage Storage infrastructure, for example, injection wells Product utilisation MRV services

NSW has strong potential to deliver CDR supply chains

NSW has a strong enabling foundation to build these supply chains. NSW has a highly skilled workforce, knowledge and skills base, strong public and private infrastructure, robust financial institutions and funding mechanisms for major projects, and strong central planning and regulation. Furthermore, we have identified significant overlap between CDR supply chain needs and existing capability in NSW – including existing and future industrial processes, skills and workforce and key energy and transport infrastructure.

Key points of alignment are considered in detail in Table 4 below.

Box 3.1: Maximising NSW's competitive advantage in energy

Energy is the common critical resource across most CDR implementation options.

NSW is a world leader in renewable energy deployment [64] and has invested a lot in building out a strong renewable resource pipeline. This is a strong drawcard for CDR investment. NSW was almost universally recognised by international interviewees as having a competitive advantage in renewable energy potential on the basis of our land area and solar resources.

CDR will add significant additional electricity demand – between 1,000 and 8,000GWh/yr per Mt of CO_2 - above and beyond what is already required for the energy transition. There is a risk of perverse outcomes where CDR prolongs the life of fossil fuel energy resources if commensurate renewable supply isn't added to meet CDR demand. NSW will need additional large-scale and distributed renewables to facilitate deployment of CDR to prevent adverse outcomes on grid emissions intensity.

Table 4: Alignment between CDR supply chains and NSW industry

	Identified industrial alignment
Use of waste products	**Mining and heavy industry wastes:** For example, ultramafic mine tailings, iron and steel-making slag, cement waste, ash, reject brines and alkaline paper waste as inputs into enhanced weathering and mineralisation storage processes (NSW availability described further in Appendix A and B). **Agricultural, forestry and municipal wastes:** Inputs into BiCRS, with strong potential for BiCRS integration into existing biomass handling supply chains; some BiCRS outputs for example biochar support improved land productivity and decreased reliance on synthetic fertiliser.
Integration with existing industrial processes	**Mining supply chains**: Potential to integrate enhanced weathering into existing NSW mining process circuits at sites producing ultramafic tailings; examples of integrated mine-site weathering projects in other jurisdictions, for example, Mt Keith (WA). **Low grade process heat:** BiCRS thermal combustion options have potential integration with industrial heat uses in for example, the food and beverage industry as a source of low-grade process heat.
Use of existing industrial skills and knowledge	**Mining and quarrying:** Existing skilled workforce to support purpose mining of ultramafic rocks for enhanced weathering and mineralisation. **Chemical manufacturing**: Potential for scaled manufacture of chemical capture agents for DACCS processes in line with existing NSW chemical manufacturing for example, Orica Chemicals, Qenos. **Oil and gas**: Relevant skills and experience in geoscience and reservoir dynamics required for geological sequestration.
Industrial utilisation of captured CO_2	**Concrete and cement industry:** Injection of pure CO_2 (DACCS or BiCRS) or carbon-based cementitious material into concrete for storage and reductions in embodied emissions; use of captured CO_2 in concrete recycling and recarbonation. **Carbon building products**: Production and use of for example, coarse aggregate for road base or finished products like carbon negative plasterboard, for example Mineral Carbon International (MCi); strong demand for these product types, driven by company-level net zero emissions targets.
Energy resources and capability	**Strong solar energy resources:** NSW has excellent solar resources with approximately half the state achieving 20MJ or more during average daily solar exposure [65]; average PV output for NSW of 4.71 kWh/kWp daily, with over 70% of the state achieving average PV output above 4.6 [66]; strong overlap with identified geological storage.

	Additional renewable energy resources: Strong onshore wind resources, for example, along the Great Diving Range and in southwest NSW, offshore wind resources, including areas targeted under the Hunter and Central Coast and Illawarra Renewable Energy Zones (REZs) [67] [68] and potential for pumped hydro, for example, in the New England REZ [69]. **Strong framework for additional deployment:** Robust strategic, planning and regulatory frameworks for additional renewable energy deployment, for example, through the REZs, with planned 3GW capacity in the pilot Central-West Orana REZ [70] [69] and a further 12.5GW in subsequent REZs [71].
Transport infrastructure	**Road and rail infrastructure to support existing mining**: Strong infrastructure and supporting services to enable transportation of geological material, with links to sources of ultramafic tailings at for example, Broken Hill and Nyngan. **Agricultural transport infrastructure**: Existing agricultural transport infrastructure and processes can support the movement of biomass for BiCRS processes. **Extensive road and rail network to other key areas**: Solid infrastructure connections to critical areas, including potential Darling Basin geological storage (rail to Cobar; state roads), and undeveloped serpentinite deposits in the north-west (rail to Tamworth and Armidale; state roads) and south (extensive rail network around Wagga Wagga) of the state.
Alignment with future industries	**Advanced manufacturing**: Manufacturing needs for DACCS and EW align with the goals of the NSW Advanced Manufacturing Industry Development Strategy [72], with potential integration into Clean Manufacturing Precincts [73]. **Mining**: Co-location of enhanced weathering inputs with priority metals identified in the Future of Minerals report [74] for example, cobalt, scandium, nickel; additional priority areas in heavy mineral sands are promising for MOF-based DACCS that may use these elements in capture agent manufacture. **Domestic PV production**: The federal government has targeted domestic solar manufacturing to manage sovereign risk across the energy transition, with an additional AUD45m funding allocated to the NSW-based Australian Centre for Advanced Photovoltaics [75]; based on current demand (4GWp per annum), Australia could support a 1GW local manufacturing market [76]. **Mineralised carbon products**: Potential to become a leader in mineralised carbon products due to strong availability of required resource inputs and world-leading R&D in the state, for example MCi.

Designing for operational success

Achieving the scale of CDR that NSW needs to meet its climate goals will require strategic design to maximise NSW's resource and supply chain potential. Key attributes of operational success include repeatable processes, optimising logistics and siting and an efficient regulatory and planning environment that enables deployment.

Repeatable processes to maximise operational efficiency

Maximising the number and rate of repeatable processes across the supply chain – from manufacturing to deployment, operations, and maintenance – will support faster rates of supply chain learning and efficiency improvements. Where processes are repeated often (for example, ongoing construction and installation of small units in a modular DACCS systems), improvements based on lessons learned can be implemented iteratively, rather than being delayed until the next large-scale project.

The economic benefits of modularity and repeatable processes are discussed in Section 4.

Optimised logistics and siting

CDR methods require specific geographic settings, resources and equipment. While the NSW landmass is an asset for CDR, transporting components over long distances adds supply chain complexity and cost with road, rail or piping. Careful site selection and co-location of materials, manufacturing and infrastructure to optimise supply chain logistics supports the feasibility of industrial solutions.

Location-specific resource or supply chain components depend on implementation options, but may include:

- **DACCS**: Geological storage formations, critical minerals for mineralisation, end users of carbon products, and land requirements for large scale deployment
- **EW**: Critical mineral inputs, suitable storage or application sites, and land requirements for large scale deployment, noting agricultural applications can be co-located with other land uses
- **BiCRS**: Biomass wastes (agricultural, forestry, municipal), end-users of products and energy, geological storage formations, and critical minerals for mineralisation (implementation option specific)

MRV as a component of the system by design

CDR supply chains require MRV services that monitor carbon capture, and storage and durability, including system emissions that can measure net CDR achieved in a way that is comparable across methods. Trusted standards and monitoring regimes are needed to give buyers confidence and reduce demand-side barriers.

"[MRV] is a major driver for our investment partners … it's the first question everyone has."

Current challenges in MRV include:

- Establishing a carbon baseline where carbon removal interacts with biological systems: what was the counterfactual rate of carbon sequestration in the system? Where is the system boundary when carbon is dispersed?
- Adequately measuring carbon removal in open systems, for example, weathering minerals wash from agricultural soils to oceans and mineralisation location and volume is uncertain
- Assessment of broader system emissions, for example, embodied emissions in facility manufacture
- Frameworks to assign responsibility for ongoing MRV and durability for permanent storage options, for example, geological storage, in ways that are not cost-prohibitive.

These are areas of active research and MRV framework development. Innovations in monitoring, including remote monitoring technologies, may decrease costs over time. Please see Appendix A for more detail on the MRV challenges of EW specifically.

An efficient regulatory and planning environment

Building successful supply chains will require an enabling regulatory and planning environment that allows actors across the supply chain – from energy to capture to storage – to progress without unnecessary delay, expense and without major system bottlenecks.

"Planning alone takes five years right now …"

Interviews identified potential regulatory and planning challenges including:

- **Lack of regulation**: NSW lacks the regulatory framework to enable geological sequestration, dampening activity in the state. NSW-based DACCS developers are piloting processes in South Australia and Queensland where they have some existing regulation.
- **Potential conflict with existing regulation**: CDR supply chains touch on multiple domains of regulation. In Queensland, where the regulation that enables geological sequestration is being trialled for the first time, conflicts are being identified with other waste and water regulations. These are likely to exist in NSW legislation too; liaison with other states may help identify points of potential conflict. Waste restrictions may also restrict input availability for BiCRS, for example by restricting use of waste biomass feedstock [77].
- **Regulatory disincentives to innovate**: There are barriers to the adoption of carbon building products in particular due to the time it takes for these products to enter the building code. Their absence from the code is a structural disincentive to voluntary use, as corporates are reluctant to bear the risk of approving a non-code product. Interviews also identified an underutilised **opportunity for government to drive innovation via public**

procurement; instead, government tenders specify products rather than specifying performance standards, reducing opportunities to use new products.

"At the moment a structural engineer has to stick their neck out and sign off [the use of novel building products] … there is huge hesitancy."

Work to identify challenges, streamline regulatory frameworks and remove regulatory barriers is needed to support the rapid development of CDR supply chains.

Box 3.2: The government can help projects navigate the planning and regulatory environment

There is a precedent for the government to support businesses to navigate through regulatory environment where we want to maximise rapid deployment. NSW's EnergyCo plays a parallel role in the renewable energy sector driving deployment in the state's REZs. EnergyCo's role covers building locationally specific social licence and community benefits, and working with regulators and industry to remove planning, infrastructure, resource and grid connection delays and bottlenecks.

CDR would benefit from a similar entity. Key to this role is supporting 'learning by doing' – piloting initial projects through new and existing regulatory frameworks to identify ways it could be improved or streamlined for second generation projects.

Key needs to grow scalable supply chains in NSW

Key needs to support the growth of CDR supply chains include:

- Supply chain infrastructure to support large-scale capture and storage, including renewable energy deployment and transmission capability and development of CO_2 compression, transport and storage sites. Open access to storage supports competition in the industry; if we have a single storage site that has an exclusive agreement with one DAC company, the success of that DAC company carries a lot of risk
- Encouraging increased collaboration between actors across capture and storage
- Precompetitive work to identify and communicate NSW's storage potential, actions to prepare it for CDR, and the relevant timescales
- New regulatory frameworks where they are absent and work to identify and remove regulatory barriers to deployment
- Robust MRV standards to give early buyers confidence and ensure no barriers on the demand side. NSW's approach needs to be in line with the rest of the world to ensure CDR fungibility, but can play a role advocating for quality principles in international standards, for example, ensuring standards account for energy source

- Developing the skills and workforce needed to build supply chain capability via for example, pilot delivery.

Social licence is multi-dimensional and must be earned in multiple NSW arenas

The scale of the industrial transformation to deliver CDR will require a robust approach to building and maintaining social licence.

CDR has the benefit of learning from other industries such as renewables deployment. We know from renewables that social licence is not black and white – it requires ongoing work to build and maintain social licence as deployment expands for example, through NSWs renewable energy zones.

Our research identified four interrelated levels of social licence for CDR, depicted in

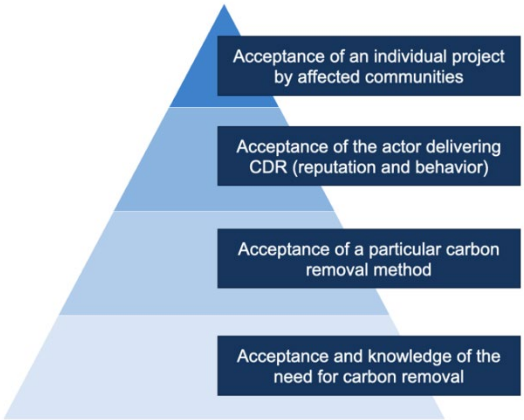


Figure 13, that are needed to facilitate scaled deployment.

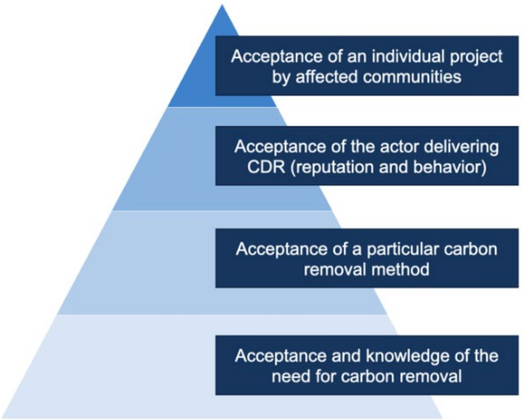


Figure 13: Levels of social licence

Public acceptance will require an understanding of the need for atmospheric carbon removal

The base level public understanding of the need for carbon removal as a critical component of climate change mitigation is very low [78] [79]. Public awareness of the need for CDR to avoid dangerous warming needs to be fostered as a key foundation of social licence.

Interviewees noted emerging opposition to CDR, particularly in the “environmental movement”. Key thematic concerns are that CDR is a licence to continue emitting and that it draws funding away from emissions reductions. However, interviews suggested a major driver of this is conflation of CDR with CCS, and thus the social licence of CDR becomes burdened by the social licence challenges of CCS.

Public support may also be dampened by the high up-front cost of emerging CDR technologies, which are often not considered cost-effective relative to other climate mitigation activities. There is an opportunity for government to communicate the need for CDR at scale – above and beyond the need for emissions reduction – to support social licence. Interviews suggested that trusted, science-based communications, developing a coalition of understanding and support, for example, via roundtables or briefings with industry, the NGO sector and other actors, and communicating the benefits of CDR (both from a climate and industrial growth perspective) can support building community-wide social licence. The US is an emerging example of social licence success, where despite the polarisation of climate change policy in general, DACCS is benefiting from broad bipartisan support [79].

"We have a long way to go to build literacy, understanding and support."

Box 3.3: CDR and moral hazard concerns

CDR is sometimes discussed as ‘moral hazard’ – a situation where actions taken perceived to mitigate future harm engender riskier action in the present [80]. The moral hazard argument against CDR suggests that the prospect of cost-effective, scalable CDR technologies to repair climate damage could be used as an excuse to continue to burn fossil fuels and delay decarbonisation.

The way CDR is funded is directly linked to moral hazard concerns. If CDR is being funded as an offset for current emissions that could otherwise be reduced, or through public funding that could otherwise support decarbonisation, the moral hazard is actualised.

Government can act to minimise moral hazard concerns by:

Clearly communicating the need for CDR *in addition* to emissions reduction, for example, by creating separate targets reductions and removals targets, as being considered by the EU [7], rather than a net reductions target that includes removals. Communicating the need for CDR may in fact increase support for emissions reduction by reinforcing the urgency of climate change [81].
Any funding support for CDR should be additional to funding allocated to decarbonisation – CDR risks moral hazard social licence challenges if it is seen to draw from the funding pool for emissions reduction.
Use of CDR as a form of offsetting needs to be carefully managed. CDR should only be used to balance out the hardest to abate emissions, not as an offset for emissions that could otherwise be reduced. The Science Based Targets Initiative aims to achieve by requiring actual value chain emissions reductions of 90%, allowing only the remaining 10% to be neutralised by permanent carbon removal [8].

Different methods will have different social licence challenges

Beyond acceptance of CDR as a whole, specific methods and implementation options will have different pathways to social licence based on their impact.

Table 5 below steps out method-specific social licence considerations tied to method benefits and disbenefits. While social economic and environmental co-benefits of methods are opportunities to build social licence, disbenefits represent threats to social licence that need to be controlled for in project design and delivery.

Table 5: Benefits and disadvantages of CDR methods and implementation options

Method	Benefits	Disbenefits
Enhanced weathering – cross cutting	In existing mines, social licence issues are largely contained within host mine site; Mining social licence is complex but broadly well accepted in Australia, particularly among local communities [82]. In new mines, regional economic growth and job creation.	Inhalation health risks of particulate matter must be prevented with careful particle size management in line with EPA requirements. Mining social licence issues surrounding ecosystem degradation and the native title rights of First Nations peoples. Asbestos risk of mining of mafic and ultramafic material to be handled as per existing mines under existing or enhanced regulatory/health and safety frameworks; risks of further processing of hazardous material in for example mine site weathering may require enhanced safety controls. Visual amenity impacts from new mines. High energy requirements, requiring large-scale land use change (see Section 4).
Agricultural EW	Nutrient application may increase plant growth and crop yield and improve crop resilience to disease and drought. Improved soil health by reducing soil acidification, benefitting soil structure and potentially increasing the stability of soil organic carbon. Run-off into the ocean reduces ocean acidification. Reduction of CO_2 emissions from liming by supplementing lime as a soil amendment.	Toxicity risks from heavy metals to plants and ecosystems that may impact yield and agricultural productivity (generally mitigated by using mafic as opposed to ultramafic rocks). Potential unpredictable changes soil and water dynamics of agricultural land, which may have unexpected effects on crop yield, soil health etc.
Coastal EW	Reduced ocean acidification. Improved growth of oceanic life and marine ecosystems health. Resilience benefits to coastal communities by restoring eroded beaches through beach nourishment programs of olivine sand.	Aesthetic impacts of for example, green olivine sand application on beaches (though interviews suggest these aesthetic changes are largely imperceptible). Concerns about toxicity risk to marine life, interviewees noted there have been no impacts identified to date.

Mine-site mineral carbonation	Additional mining jobs at purpose-built mines or to deploy augmented requirements in an existing mine (see Section 4). Potential mine site remediation benefits if applied to abandoned un-remediated mine sites with suitable waste rock and tailings.	Tailings pits have a history of leakage and associated environmental toxicity from heavy metal poisoning (note this is independent of EW applications). Often requires large areas of land adjacent to the mine-site where the rocks will weather and sequester carbon, for example, large tailings pits.
DACCS	Few location requirements beyond access to storage, allowing siting in remote environments to minimise impacts on local communities. Industrial and infrastructure development in typically underserved regions. Potential water production pollutant filtration services may have benefits in for example, water-constrained areas of NSW – however, these applications may reduce carbon capture efficiency [83] [83]. Mineral carbonation storage pathways offer a path to value and remediation of alkaline industrial wastes, for example, NSW's 216Mt coal ash reservoir [84] (see Appendix B).	There may be community concern about the injection of CO_2 into groundwater, even when it does not meet potability or agricultural use thresholds; historical concerns in NSW to potential groundwater contamination risks, for example, of coal seam gas [85]. Potential groundwater degradation or toxicity impacts from leakage from geological storage; [86] However, leakage rates are generally low [87], and can be managed by site selection and appropriate monitoring [37]. Some DACCS options are large users of water and so are less suitable for deployment in for example, water-constrained areas in NSW. High energy requirements, requiring large-scale land use change (see Section 4).
BiCRS	Regional development opportunities for agricultural areas in the high rainfall intensive use zone and the broader wheat-sheep zone [88]. Circular economy benefits of creating value from waste. Emissions reductions synergies from for example, the production of biofuels as fossil fuel replacements. Potential energy security co-benefits from bioenergy pathways.	Risk driving indirect land use change and competition with food and fibre for land and water resources; can be managed by restricting use of purpose-grown crops for BiCRS and strategic siting of appropriate biomass. Pollutant and particulate risks from bioenergy facilities. Noise and pollution impacts from the transport of disparate biomass, CO_2 products or modular BiCRS machinery.
Cross-cutting	All CDR methods are likely to contribute to job creation in local communities in either construction or ongoing operation and maintenance phases. However, these jobs benefits are highly dependent on implementation option (see Section 4).	Most CDR methods are likely to have noise, pollution or amenity impacts associated with the transport of material inputs or CO_2 products (trucking, piping).

The benefits and disadvantages mapped above are highly dependent on implementation options and the design of individual projects. For example, bioenergy facilities may have negative impacts (disbenefits) on communities associated with noise and pollution of biomass transport (trucking) or particulate matter pollution – however, these can be managed by siting strategies like co-location with waste sources and pollution control at a facility level.

Implementation options can also be structured to maximise co-benefits, for example, the production of bioenergy. However, any trade-offs with removal potential must be carefully considered.

"People are obsessed with the concept of other benefits … the highest quality of CO_2 removal should be the north star, not how many birds you can kill with one stone."

CDR actors must garner individual social licence

Actors involved in the delivery of CDR will impact social licence at the project, method and broader public acceptance level. There is a risk that 'bad actors' in CDR cause damage not only to the social licence of their own projects but to reputation of the broader industry.

Interviews attested to a role for government in mandating performance for actors in the industry – both in regulations (to minimise for example, community or environmental impacts from waste) and in additional specifications, for example, requiring a particular standard of community engagement to access government funding. Example policy approaches are discussed in Section 5.

"Having clear frameworks that all CDR players must adhere to helps frame the industry as trying to turn a new page… it's an important way for us to introduce ourselves to communities."

The involvement of oil and gas companies in CDR poses a potential social licence hurdle for DACCS. The skills foundation in oil and gas companies is a key enabler for geological injection of CO_2, and companies include Santos and Glencore are pioneering domestic storage pilots [15] [16]. However, some oil and gas actors have already suffered loss of social licence and trust with local communities in NSW, for example, companies involved in NSW coal seam gas projects, which faced sustained community opposition [89]. If these companies fail to demonstrate genuine transition pathways away from fossil fuel industries, they are unlikely to be seen as making a genuine commitment to CDR with potential reputational risks to the broader industry.

The needs of affected communities are paramount

The final level of the CDR social licence pyramid is critically important – the experiences of impacted communities, i.e., the people and places where CDR projects are deployed or who are affected by CDR supply chains. Key principles to support community engagement include:

- **Genuine, transparent community engagement:** Engagement that is ongoing over the life of the project, supported by explicit plans for community decision-making and incorporating feedback [90]. Interviewees noted the importance of understanding particular needs in local community, rather than assuming social licence concerns are standard. For example, communities in areas with a mining history may be less concerned with amenity impacts of new mining and more concerned with potential job creation benefits, or they may be focussed on air quality risks based on historical dynamics.

"You can't assume there's an average behaviour anywhere … each community has unique dynamics, histories, identity."

- **Consent-based siting:** Consent-based siting gives communities a genuine say in the siting and location of CDR projects [91]. Transparency and accuracy around estimation of risks and benefits to a community are key to informed consent, for example, making sure not to overstate job creation benefits of CDR.
- **Distributional equity**: Social acceptance in local communities can be bolstered by the equitable allocation of project risks and opportunities – ensuring that communities bearing the delivery impacts of the project share in the benefits, particularly the economic benefit it delivers [90] (see box 3.4 below for an emerging approach to benefit sharing). Local communities may also want to claim locally-delivered CDR as part of their regional net zero strategy.
- **Minimise number of impacted communities through co-location**: Understanding local needs and minimising impacts takes time and effort to do effectively. Co-location of as many supply chain elements as possible, for example, both capture and storage for DACCS, reduces the number of communities that require collaborative engagement – allowing groups with limited resources to focus their engagement efforts. Disparate supply chains increase community engagement requirements.

Box 3.4: CDR can learn lessons from current large-scale renewable energy deployment in NSW

Renewable energy companies are navigating the hurdles of large-scale deployment in real time as we scale up generation and transmission in the NSW REZs. We can learn lessons from what works in this analogue industry to inform social licence building for CDR.

For example, renewable energy companies are negotiating new arrangements to ensure local communities see genuine benefits from the projects they host. Oxley Solar Development has agreed to pay a AUD5.9 million community benefit contribution and scale back the size of their development to minimise impacts in the local area in response to concerns that these projects have previously had limited ongoing local benefits. These initiatives are being framed as a new expectation, with Armidale Council commenting: “developers can expect little support if they are not engaging meaningfully with locals, minimising the impact of their project and making appropriate financial contributions.” [92]

Other projects are navigating the need to balance social and environmental impacts of energy generation infrastructure to maintain local social licence – for example, the Winterbourne wind farm, which is facing local opposition based on environmental impacts and proximity to national park land [93].

These dynamics will also be important to the deployment of large-scale CDR. EnergyCo is working iteratively to implement lessons from these projects to manage social licence – synthesising emerging social licence concerns with technical and economic considerations in their Network Infrastructure Strategy [94].

Principles for First Nations engagement

Consideration of First Nations peoples is critical to large scale deployment in the NSW context. Approximately half of NSW is under native title claim [95]. These claims are largely non-exclusive, giving native title holders rights to access, hunt and camp on traditional country but not the right to control access to or use of an area [96] – meaning most Aboriginal groups in NSW have limited ability to say no to activities on their land.

We heard that many carbon and renewable energy projects have been implemented without due regard for First Nations land rights and native title. We also heard in interviews that in the effort to avoid harm, some actors choose site projects on non-First Nation land, inadvertently excluding First Nations from benefit sharing.

Different kinds of projects (for example, carbon projects, mining or resources projects, renewable energy developments) fall under different safeguards. Mining projects (comparable to EW), for example, are obliged to negotiate with native title holders, but in the absence of an agreement may still be granted access to the land. Renewable energy developments (comparable to DACCS) have weaker safeguards still and are not automatically required to negotiate with native title holders [97] [98].

In the absence of robust legislative safeguards, government support for best-practice engagement with First Nations groups will be critical to ensure CDR builds social licence and does not re-enact historical harms [90]. Key principles for engagement – drawing on lessons from the carbon market and renewable energy [99] [100] [101]– include:

- **Free, prior and informed consent is critical**: Allowing Indigenous communities the ability to consider a project in the absence of coercion or manipulation, over appropriate timeframes, and with appropriate information and context. This includes for example, information and context to appropriately assess proposed benefit sharing arrangements, which can differ by orders of magnitude from project to project in the resources sector [98].
- **Addressing power imbalances between project proponents and Indigenous communities**: Engagement strategies and initiatives that build the capacity of Aboriginal land holders and organisations to engage with consultation (including organisational, financial, workforce and data management capability), recognising these groups often have limited resources.
- **Transparency with native title holders:** There are only limited requirements to share information with native title holders – for example, in the carbon market, information is held in confidence between the regulator and the project proponent. Transparency with native title holders about activity on their land helps build trust between projects and communities.
- **Access to trusted impartial advice:** Interviews noted the absence of trusted advisors for Indigenous actors was a major factor limiting social licence, trust and Indigenous participation in the carbon economy.

"Almost all advisors out there have a vested interest in getting you to sign up to a project..."

Key requirements to make CDR work for the NSW public

There is a role for government to support the social licence of CDR in NSW by:

- Communicating the requirement for CDR as part of climate mitigation and its potential benefits to the broader community
- Developing governance structures to support best practice environmental performance and community engagement, and minimising the impacts of projects on local communities with particular attention to First Nations engagement
- Ensuring funding and incentive models for CDR doesn't compete with emissions reduction to avoid moral hazard issues.

common capital

Section 4: Economic considerations for NSW

This Section provides an overview of the economic dynamics of deployment. We review major cost drivers and analyse potential for costs of implementation options to come down with scale in NSW.

Key takeaways for NSW policy makers

- Enhanced weathering: Mine-site enhanced weathering (mineral carbonation) has a unique ability to achieve scale quickly because the process can integrate into operating mines producing and storing tailings at a major scale. Optimising the weathering reaction is key to cost effectiveness and expenditure that increase the CO_2 captured can be highly productive. Major cost drivers include energy use, capital expenditure for higher intervention processes such as building mine-site enclosed facilities to optimally store weathering rocks.
- DACCS: scale is critical to unlock cost reduction. Cost drivers and learning rates vary based on the specific technology – major cost drivers include the cost of sorbents/solvents, the manufacturing cost of the DAC unit/facility, energy and operations and maintenance costs.

Understanding cost reduction dynamics

Much of the discussion about CDR solutions focusses on their current high costs. Understanding the cost of implementation options is very important. However, lab and early commercial pilot-scale technologies are not a good indicator of future costs. The crucial questions for policy makers are how far and how fast can costs come down, and what can they do to make this happen within the timeframes required. To answer these questions, we need to understand both the general factors that influence the speed and scale of technology cost reductions, and the potential levers for cost reductions of different CDR methods.

CDR today is similar to where solar was decades ago

The current status of some CDR methods is analogous to the status of solar decades ago – when it was considered too expensive to scale. Indeed, many technologies typically undergo a cycle during emergence where they're popularly dismissed as too expensive to scale. However, instead we can critically assess the ingredients that enable scaled cost reduction.

Box 4.1: Perception of costs

The viability of CDR implementation options should not be assessed against their current costs, but rather against the potential and propensity of their key cost drives to come down.

Analysing technology viability only on current costs risk creating 'self-fulling prophecies'. If policy and industry perceive that costs cannot come down, adequate investment in the technology and ecosystem that are needed to drive deployment will not be provided. In turn, technologies will not be able to scale without that investment and therefore, will not be able to yield the cost benefit of the scaling journey. Then, costs will not come down.

We know from the history of technology adoption, that marginal costs come down significantly with scale. The marginal cost of electricity generated by solar panels has reduced by 15,000 times since the first niche deployments of the technology in the 1950s [102]. Costs have reduced 99% in decades since deployment began in the 1990s. It is well known that much of that cost reduction is due to the economies of scale achieved by Chinese panel manufactures. Less well understood, is that around 49% of that cost reduction was in local "soft costs" across the supply chains in each region that has adopted solar at scale – with Australia an early leader in these soft cost reductions [102].

Just because costs can come down, doesn't mean they will. High initial costs are one important barrier to the mass adoption that is required to achieve scale. If the deployment of CDR was to follow the trajectory of solar, would be at scale pricing by the late 2090's – over fifty years after it is required. Policy – including Australian – has played pivotal roles in both driving and delaying the global adoption of solar that provide lessons to better scale CDR, which we discuss in Section 5.

Costs are not the same in every jurisdiction

The literature on technology diffusion distinguishes between local and global drivers of cost reductions. Cost reductions in one location can be shared globally for technologies or commodities like silicon chips, solar PV panels or iron ore that can be mass produced in a single location and readily transported through global supply chains. However, for most products and services, these represent only one part of the total final cost – with local factors driving the remainder.

For example, with solar, the hardware (panels and inverters) represents only 20% and 50% of residential and utility scale solar respectively. The remainder – known as “soft costs” – cover the human related aspects of deployment including installers, specifiers, sales, marketing, finance and permitting. These human related soft costs are unavoidably local and cost reductions must be achieved one jurisdiction at a time. People in roles across the supply chain can learn from innovations in other jurisdictions but ultimately, the bulk of cost reductions are obtained through what is known as ‘learning by doing’, by local companies and people in each role in local supply chains [102]. Other local factors also have significant impacts on local costs including land and energy costs, costs and protections from regulations, policy incentives, access to skilled labour, as well as supporting infrastructure, services and markets.

We heard from interviews that local factors were key considerations for new CDR companies deciding where to site their first major projects and direct investment. Key challenges they faced included planning, licences, local labour, scouting locations, finding local partners, setting up business and local compliance. The more support there was in a jurisdiction with these tasks, the more likely they were to deploy and begin to scale there.

We conducted economic and removal potential assessments for NSW deployment

We modelled the economics of deployment for a number of diverse options for DACCS and EW at different scales to understand the breadth of cost pathways. All results are in 2023 AUD unless otherwise specified.

We have conducted technoeconomic modelling on archetypal DACCS and EW implementation options to understand the major underlying factors behind costs and cost reduction pathways at scale. We modelled these combining published and interview data based on the current costs and cost components of implementation options with NSW specific cost forecasts for key inputs including land, energy and minerals. All modelled scenarios assume deployment of additional renewable energy capacity to meet the energy demand for CDR without compromising removals. We then applied different learning curves form analogous industries to early stage and scalable cost drivers to understand the degree and ranges with which they can change at different scales.

Box 4.2: Learning curves

Learning curves predict cost reduction from increasing the scale of deployment of technologies. Learning curve forecasting has been found to be reasonably accurate at forecasting cost reductions [103].

Different technologies, including different supply chain components, have different learning rates. Learning rates are the percentage of cost reduction for every doubling of the market.

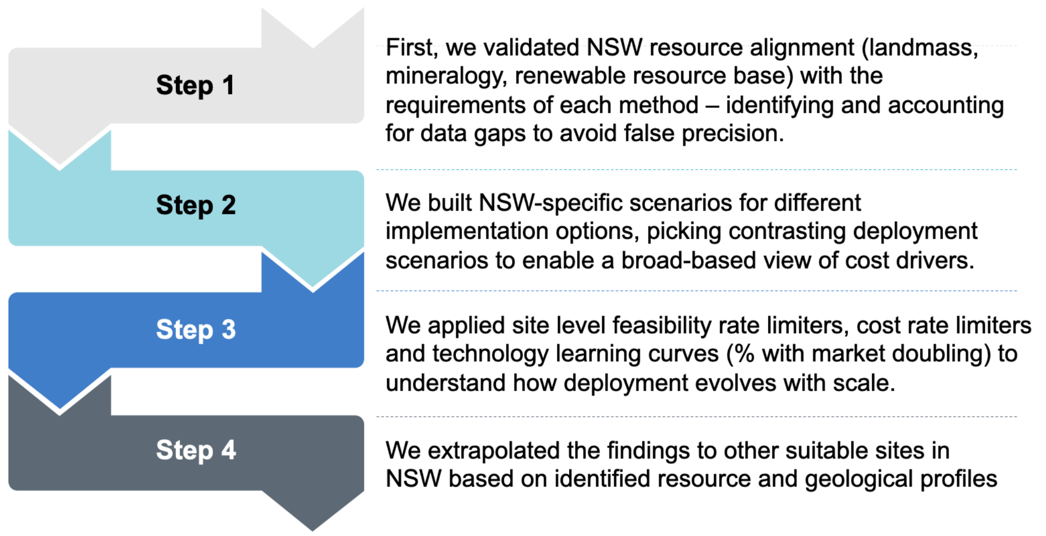
We note for any individual company, scale is also a function of many factors beyond the adoption levels of a technology class – such as leadership, operational capability, strategy, execution, investors, timing and local markets. Therefore, it is not meaningful or feasible to attempt to predict the cost pathway of any individual CDR technology or company. However, understanding the major cost drivers and their potential to be reduced is useful to identify areas to target policy support.

Box 4.3: Our approach to modelling potentials

We have taken a site and implementation option-specific approach to modelling deployment potentials and cost ranges for DACCS and EW in NSW. Our modelling is designed both to provide indicative abatement potentials and costs, and to identify the key drivers influencing cost and abatement potential across methods and implementation options.

Studies to date focus on quantifying high-level theoretical potentials of methods. This has been useful for sizing potential at method level, but is limited in the information actionable it provides policy makers. Rather than modelling broad method-level theoretical potentials, we have taken a mix of specific implementation options, inspired real-world start-ups, for EW and DAC to draw closer to real world implementation dynamics.

Our approach is described below:



Mineral carbonation

In Section 2, we outlined key material inputs and rate limiters on NSW potential for mine site enhanced weathering. In this Section, we investigate the carbon removal potential and costs associated with delivering that potential through specific mine-site deployment scenarios. As outlined in Section 2, engineered-based EW systems are typically called 'mineral carbonation'. We have therefore used mineral carbonation (MC) terminology in this Section. Mine site MC was chosen because it can be operated as a closed system, and therefore has higher measurability certainty. In contrast, it is difficult to measure CDR in open agricultural and coastal EW (see Appendix A). Further, mine-site MC also has significant synergies with existing mining capability in NSW.

Overall, the key lesson from this analysis is that optimisation is required in MC to **balance cost and carbon removal potential**. The primary drivers of cost (in terms of $/t$CO_2$) is ultimately how many tonnes of CO_2 are removed.

Carbon removal and cost variability in MC systems

The carbon removal and cost of MC is determined by the choices made throughout the system:

- **Rock type.** The amount of ultramafic (or mafic) rock that is present is a key determinant of how fast the rock will weather. The specific mineral make-up of the rock type significantly impacts the weathering rate. This variability is modelled in the difference between an existing mine (with suitable, but not ideal rock) and a new purpose-mine (with ideal rock).
- **Purpose/integrated mining.** Many MC implementation options use waste mine tailings from an existing mine, which reduces the cost associated with setting up a new mine for the primary purpose of CDR. However, purpose-mining allows a selection of the most ideal rock type, which can significantly impact carbon removal and therefore cost per tonne of CO_2 removed. Our model compares the removal and cost of purpose versus integrated mining in EW.
- **Mineral preparation.** Before the weathering stage, the rocks can undergo pre-treatment to increase their reactivity with CO_2. This may involve mechanical treatment (for example grinding), acidification or chemical treatment. One such treatment process is thermal activation, in which the ultramafic rocks are heated to 700°C to increase their reactivity. This is particularly suitable for serpentinite rocks, which are highly abundant in three belts across NSW. Due to this, thermal activation has been considered across all scenarios with NSW rock inputs. These activation or pre-treatment processes are significant sources of expenditure but can also greatly increase carbon removal.
- **Weathering process.** The ways in which the weathering is enhanced varies the carbon sequestration rate and cost significantly. Modelling explored the difference between using a low-cost tailings pit where rocks are deposited in thick layers, compared to a high-cost purpose-built enclosed, where the rocks can be finely spread on arrays of stacked sheets in controlled humidity conditions, allowing maximum surface area contact between the rocks and CO_2.

Another factor that impacts cost (and net carbon removal), is transport of the rocks. In agricultural and coastal EW methods, transport has been seen to be a key driver of cost in a number of techno-economic analyses [104] [105]. Transport is not required in mine-site MC, so is not considered in this modelling.

Implementation option modelling results

The archetypal MC implementation options we modelled include variations between:

- Purpose-mined versus integration into a productive mine
- Weathering in sealed tailings pits with mechanical acceleration versus weathering in a purpose-build enclosed facility
- Mineral preparation.

We modelled the cost per tonne of CO_2 captured and stored with combinations of these variations.

Box 4.4: Data collection and assumptions

We predominately considered NSW-specific rock inputs. The purpose-mine scenarios were modelled with rock inputs from the NSW Great Serpentinite Belt and other optimal rock sources. Due to limited data availability on the precise mineralogy of the belt, existing mine scenarios were modelled with rock inputs consistent with nickel mines around the world, rather than NSW specific.

The carbon removal rates were based on data collected from interviews and research into various MC research and commercial groups. Energy requirements were selected based on literature reviews and requirements provided by interviewee. Costs for energy and materials were also based on both NSW and Australia-specific cost data from government source such as CSIRO and AEMO forecasts, as well as data supplied by interviewees. Note that these values do not consider the emissions embedded in the process, and therefore show total carbon removal, rather than net removal. However, due to the significant energy requirements of these processes, there is a high risk if non-renewable energy is used that these processes could be a net source of emissions. Fossil energy use would likely be the greatest determinant of poor lifecycle emissions outcomes.

Learning curves were not used in MC modelling as deployment achieves scale quickly and standard learning curves at a percentage cost decrease for market doubling may not be suitable. However, we note this is a conservative assumption and novel technologies such as mechanical carbonation acceleration technologies may indeed have material learning curves.

Due to uncertainties surrounding NSW rock mineralogy and weathering rates, a range was modelled:

- **Conservative case:** This represents scenarios where the rock inputs for both integrated and purpose mines are somewhat from less optimal deposits. It also assumes that actual weathering rates are slower than the data provided through interviews and literature review. This case also assumes electricity price equivalent to the retail price for a large industrial user.
- **Optimised case:** This represents an ideal rock source, with a high abundance of the rarer brucite mineral. The limitations on public data of NSW mineralogy means there are gaps in data for brucite availability. Due to this limitation, the mineralogy was selected based on sites in California.

Figure 14 below illustrates the potential range of CO_2 removed at a site for each option and the marginal cost range to deliver that potential per tonne of CO_2.

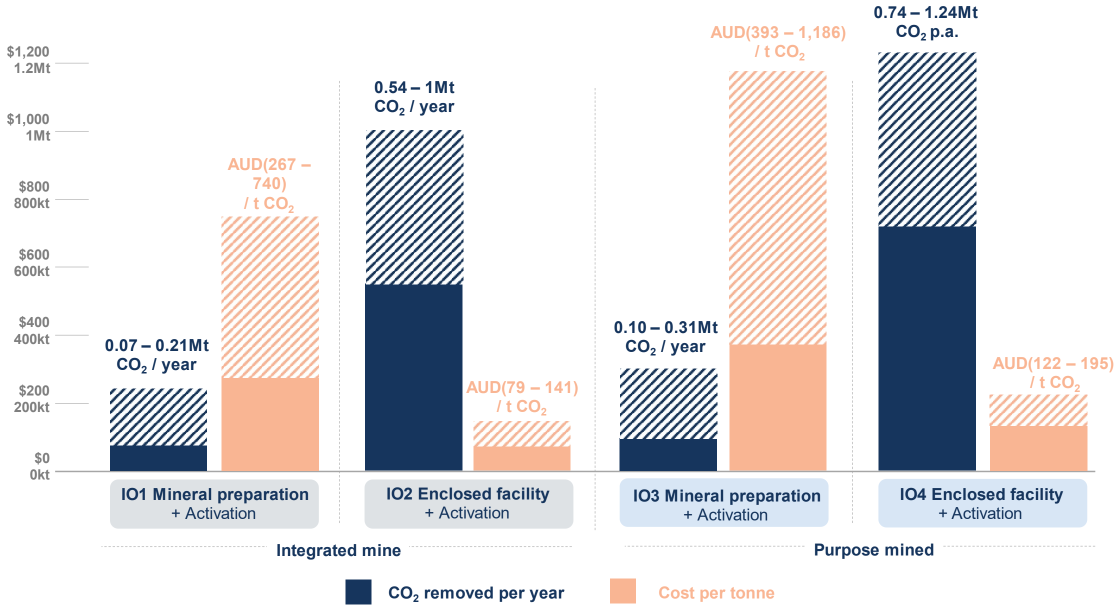


Figure 14: Abatement potential and cost per tonne of modelled enhanced weathering implementation options

The results suggest that:

- **The enclosed facility weathering option removes significantly more CO_2 than the mechanical acceleration option.** The enclosed facility includes stacked thin layers of ground rock to ensure atmospheric CO_2 has access to all rock, allowing for much greater rates of weathering. Conversely, tailings pits are limited by the thick layers of rock that prevent continued weathering of the deeper rocks.
- **The enclosed facility weathering options is cheaper per tonne of CO_2 removed.** Despite lower overall capital and operational expenditure on the mechanical acceleration option, the lower carbon removal benefit extracted significantly increases its cost per tonne of CO_2.
- **Integrating EW processes into existing mines is cheaper that building purpose-mines.** Despite the improved rock mineralogy in purpose-mines that increase carbon removal, the cost of the new mine outweighs the removal benefit. Note that this still relies on suitable existing mines, with high amounts of serpentinite in tailings. Nickel, cobalt and platinum-group element mines are likely to be suitable, amongst others [22].
- **Rock input and weathering rate have a large impact on total cost and carbon removal.** The difference between upper and lower ranges are due primarily to current uncertainties in rock input and weathering rate, and the size of this range is evidence of the large impact of these two factors. Further experimentation and pilot sites as well as investigation and characterisation of NSW's rock resources would strengthen the certainty of these findings.
- **There are realistic pathways to large-scale MC in NSW.** Multiple options include cost viable pathways, particularly when integrated into mine sites. Integration into mine sites

also means the scale of these sites can be leveraged and the potentials listed here can be achieved relatively quickly as they mirror they scale of the site and integrate into the existing supply chain.

Figure 15 represents the cost breakdown for the mechanical acceleration and enclosed facility weathering methods, in both an integrated mine and a new, purpose-mine. The ranges represent the difference in cost for energy. The lowest cost options assume that the energy required for the enhanced weathering processes is met by a purpose-built solar farm. The higher prices use electricity purchased at retail prices from a zero emissions source. The rock input and weathering rate does not vary by option – only the conservative estimates using less favourable rock mineralogy are used.

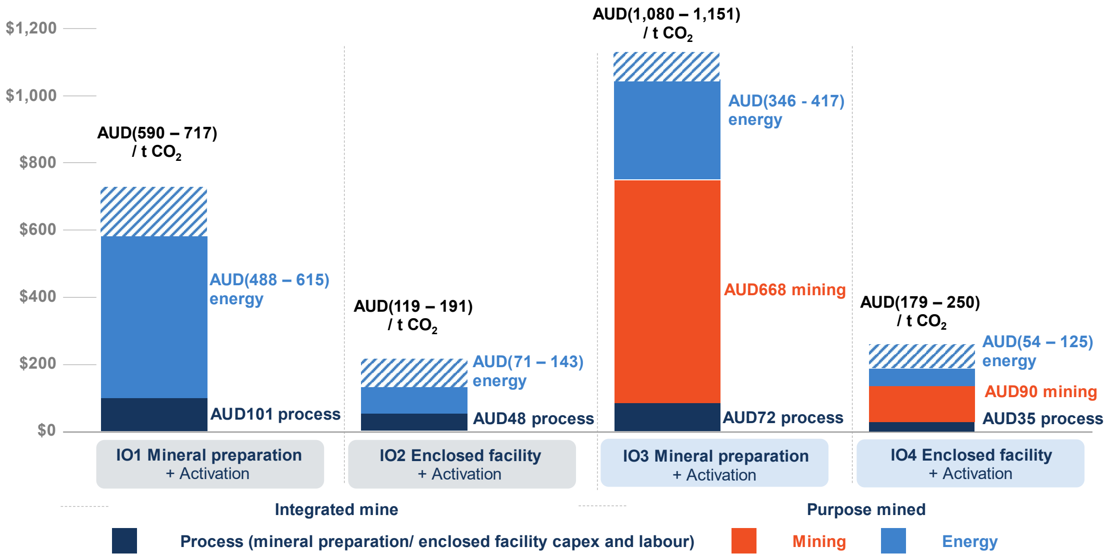


Figure 15: Cost breakdown for modelled enhanced weathering options

Despite having equivalent mineral preparation energy requirements and lower capex requirements, the cost per tonne of CO_2 removed is much larger for the mechanical acceleration process. The results suggest that:

- **The cost of a new mine outweighs the carbon removal benefits for the** mechanical acceleration **process.** The capital and operational expenditure of a purpose mine blow out the cost of the mechanical acceleration process to over $1000/tCO_2$. This expenditure also increases the price of the enclosed facility method when compared to an integrated mine, but remain within a very reasonable range, around $200/tCO_2$, which is due to the increased carbon removal benefits.

- **Energy is a major cost driver across all scenarios.** This energy for mineral preparation in both processes assumes a purpose-built solar farm with battery firming.

- **Purpose-built solar and battery storage reduces costs.** The capital expenditure on a solar farm is justified when compared to the high costs of retail electricity price.

Trade-offs between carbon removal volume and cost

There are many methods to increase weathering and therefore the amount of CO_2 removed. However, each of these methods adds cost to the process. Therefore, research and pilot efforts are currently focused on optimisation. Overall, we have identified a set of key trade-offs:

- **Higher upfront capex versus lower weathering rates:** Some technologies like automated mechanical acceleration of tailings have low expenditure but yield modest acceleration and reduced CO_2 removal. On the other hand, higher upfront expenditure approaches like purpose-built enclosed facility weathering appear to greatly enhance the weathering rate and therefore total tonnes captured i.e. the expenditure has high productivity.
- **Locating a mine site with optimal minerals versus mineral preparation:** the preparation (e.g. thermal activation) step is required due to sub-optimal mineralogy of the tailings. Where integrating into a mining process, the location will not be fully optimised for weathering material and therefore activation will likely be required if. However, if a site with ideal mineralogy is identified and purpose-mined in NSW, thermal activation may no longer be as important to increasing weathering rate. Specifically, brucite minerals are fast weathering, even without activation, and sites with > 5% brucite may be ideal for MC without activation.
- **Maximising rock turnover versus weathering:** The rate at which the rocks weather decreases over time. Therefore, optimisation of the time that the rocks are left to weather is important to maximise CDR and minimise cost.
- **Ambient air only versus added direct air capture CO_2:** There is scope to pair the mechanical acceleration process with direct air capture to increase the total weathering (or mineralisation) achieved.
- **Lower land use versus higher weathering rates:** A significant limitation on mechanical acceleration MC is that the rocks are deposited in thick layers in the tailings pit, which limits the reaction between CO_2 and the deeper rocks. However, for the low-tech mechanical acceleration solution, the depth of the rock layer can be reduced by increasing the size and surface area of the tailings pits. This will increase weathering rate and carbon removal but will require increased land use.

Land and energy use

- **Land requirements:** Between 600 and 4,000 hectares of land is required for mine-site EW methods modelled in this section. Around 3,000 hectares are required for a large-scale dedicated mine site. A large enclosed facility is required for options B and D, and solar farms are required across all options to generate the energy required for activation. These results are outlined in Table 8 below.
- **Energy for activation:** The activation process involves heating a large volume of mined rocks to high temperatures. Between 1 and 8 MWh of electricity is required for activation per tonne of captured CO_2. Our model assumes this energy is generated from additionally deployed solar generation capacity to prevent energy emissions negating the CDR benefit.

Table 6 Land and energy use for enhanced weathering

	MC IO1 – integrated process with mechanical acceleration	MC IO2 – integrated process with enclosed facility weathering	MC IO3 – Purpose mine with mechanical acceleration	MC IO4 – Purpose mine with enclosed facility weathering
Land required (hectares)	598	870	3,598	3,902
Energy required (MWh per year)	550,399	607,038	550,399	637,177
Energy required (MWh per tCO_2)	8	1	5	1

NSW economic benefits

- **Induced value to the economy:** EW at mine site scale will cost between $1.6 and 4.4 billion over the mine lifetime. This expenditure will stimulate a total of between $4.6 and $13 billion of activity across the broader economy (please see modelling appendix).
- **Employment benefits:** Between 1,900 and 7,900 jobs will be required to construct mine-site scale EW, and 200-660 ongoing jobs generated to manage the process over the life of the mine.

Table 7 Direct expenditure, economic value and number of potential and current jobs generated by different enhanced weathering implementation options

	MC IO1 – integrated process with mineral preparation	MC IO2 – integrated process with enclosed facility weathering	MC IO3 – Purpose mine with mineral preparation	MC IO4 – Purpose mine with enclosed facility weathering
Direct expenditure ($bn)	$1.6	$2.3	$3.6	$4.4
Total economic value over project life ($bn)	$4.6	$6.8	$10.4	$12.9
Construction jobs	1,900	6,300	3,400	7,900
Ongoing jobs	202	253	597	660

Direct air capture and storage

In this Section, we investigate the costs associated with delivering at different scales through different archetypal deployment scenarios.

As outlined in Section 2, DACCS represents a diverse category of technologies. We identified well over 200 CDR companies – most at venture stage. There was high variation in these companies. We identified around 15 different technology approaches just within the 60 DAC companies we benchmarked. This means there is no single answer to what scaled and deployed looks like and how costs will come down with scale. There is high variability across many system components that drive costs. Key areas driving cost variability include:

- **capture agents**, including dozens of different types of solid sorbents and liquid solvents. Some agents are low-tech and readily available such common minerals for example limestone or silicates while others require chemical manufacturing for example MOFs, zeolites and polymers. Capture agents are regenerated and the same material is used for many cycles of the process until performance erodes. This reusability greatly reduces the volumes of capture agent required. Many capture agents will not need to be produced locally as very large volumes will not be required.
- **modularity versus large industrial scale plants.** Many new DACCS start-ups have adopted a modular approach to capture units, rather than large traditional industrial plants. Many modular-based start-ups intend to manufacture their capture units locally near deployment locations. This is to add local economic benefits to support social licence and to avoid transport costs of bulky units. However, local deployment needs must be able to support sufficient manufacturing scale to achieve the required economies of scale to bring costs down.
- **energy requirements.** DAC processes typically require industrial quantities of input energy for air handling and/or capture agent regeneration through separating the CO_2 from the capture agent into a concentrated form. Energy consumption varies between options across each stage, but the high energy demand is common to all DAC start-ups we reviewed.
- **CO_2 storage pathways.** Injection into geological formations and carbon mineralisation are the two overarching pathways to store captured atmospheric CO_2. Start-ups typically focus on capture, with intention to partner with storage providers.

We modelled two archetypal options for the capture process

We modelled two archetypal DAC implementation options:

- A low-tech sorbent that is already low cost and requires high heat zero emissions technology for regeneration, deployed at a location requiring offsite energy.
- A high-tech sorbent which is currently at very high lab-scale costs, requiring low heat for regeneration, deployed a location allowing 24/5 behind the meter solar and battery storage.

These capture costs for both of these options below do not include CO_2 transport and storage costs which vary by storage option and are discussed separately.

All three options are based on NSW specific input costs where both relevant and scaled scenarios are at 2050 energy costs and reflect learning curves for cost drivers which are currently at an early stage. We have used historical learning rates from analogue processes to forecast cost reductions for sorbent and manufacturing costs in both scenarios (see modelling appendix).

Figure 16 illustrates the range of marginal costs per tonne of CO_2 removed for each option at three different scales: initial small scale, a 1 Mt scale deployment, and a 22 Mt scale deployment. Notably, the initial small-scale pilot for the low-tech option is considerably larger than for the distributed high-tech sorbent option. This is due to the minimum scale required to efficiently utilise high heat zero emissions technology for regeneration for high-temperature sorbent regeneration, compared with the low temperature regeneration for the high-tech sorbent.

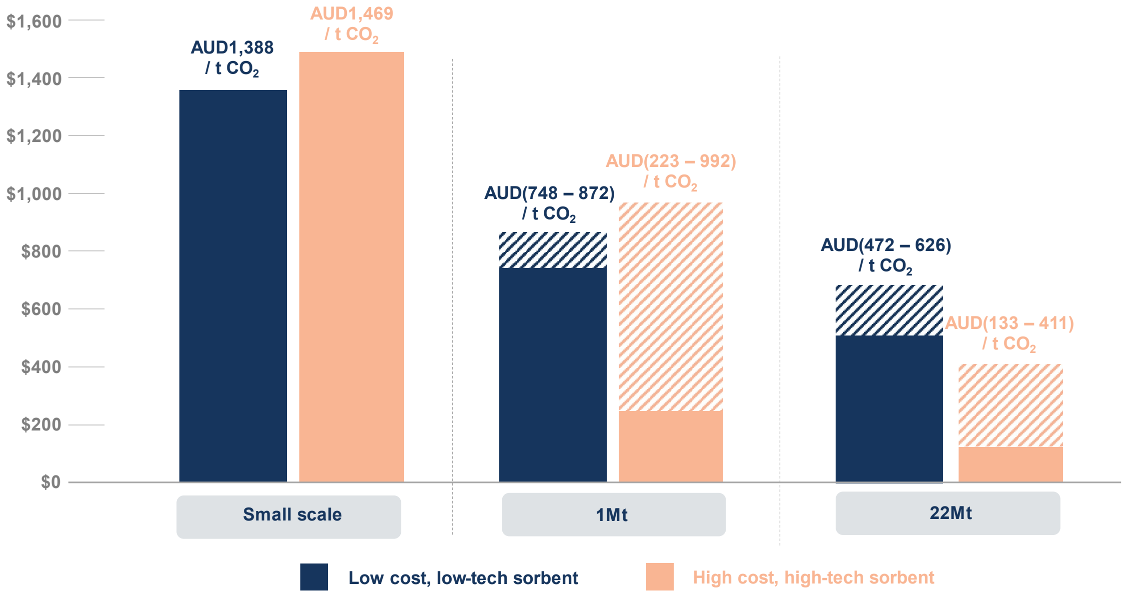


Figure 16: Cost per tonne of two modelled implementation options across different scales

As Figure 16 illustrates:

- Scale has a major impact on cost. There are significant cost reductions from moving from small scale deployment to 1Mt across both implementation options, with reductions continuing as scale further increases.
- DAC costs are not uniform. In these archetypes, this is demonstrated by significant variations in the scale of cost reduction between the high-tech and low-tech sorbent scenarios we modelled. The modelled high-tech sorbent scenario shows a greater potential for more rapid cost reduction with scale if the technology development is able to follow typical learning rates for industrial chemicals[5]. The drivers of these reductions are discussed further below.
- We see higher costs at scale for the low-tech sorbent. This is largely due to the energy procurement dynamics for this specific implementation option in NSW rather than

[5] Note: we cannot (and should not) conclude from this modelling that this is universally true for high tech and low tech sorbents. This results are based on specific NSW dynamics. Further modelling testing more sorbent/solvents types is also required.

generalisable technical factors. Specifically, the NSW geography limits where this technology can be optimally placed due to climatic drivers of sorbent optimisation which in turn limits cheaper energy procurement options.

- The ranges of uncertainty in costs are significant. The drivers of this uncertainty are explored in further detail below.

High tech sorbent cost drivers

The figure below illustrates the cost breakdown, including high and low ranges for sorbent costs based on different learning rates, for a **high cost, high tech sorbent** across the three different deployment scales.

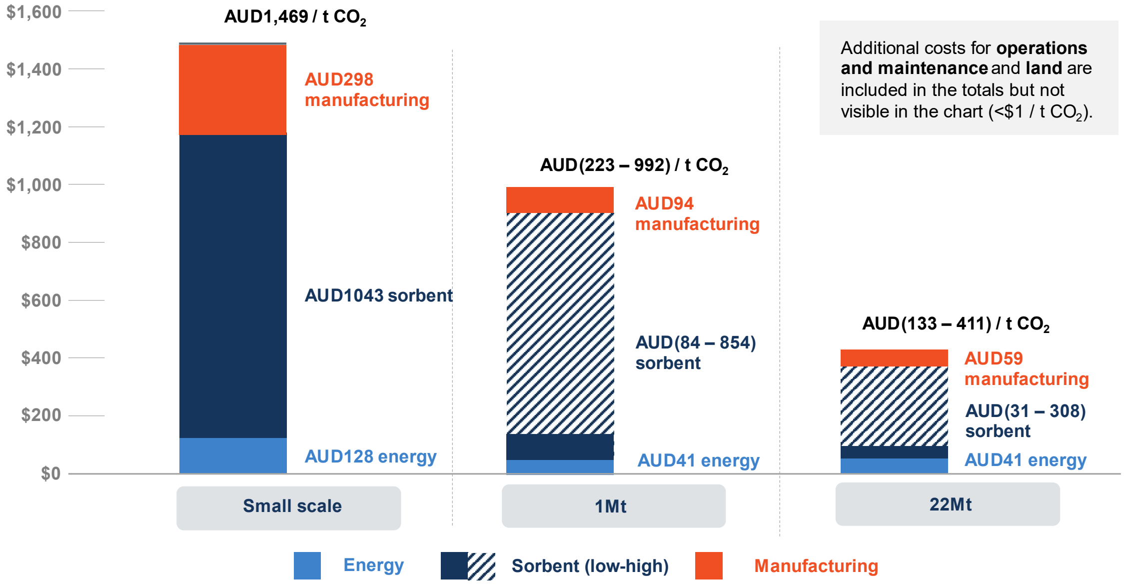


Figure 17: Cost breakdown for a high-cost sorbent at different deployment scales

As Figure 17 illustrates:

- The biggest cost driver of this option is sorbent costs followed by manufacturing of the units and energy, with land cost in remote areas of NSW and operations and maintenance (O&M) negligible when amortised over 25-year lifetime removals for a unit.

- The high-tech sorbent is also the largest potential lever for cost reductions due to the learning rates reduction costs of moving from small lab scale to industrial chemical facility production volumes and improving sorbent efficiency through continued R&D.

- The sensitivity of potential cost reductions to the ability for R&D to also improve sorbent lifetimes – for example, the $31/t CO_2 sorbent cost modelled at 22 Mt deployment scale is the marginal cost of sorbent if R&D can deliver long lifetimes, versus $308 for a low-cost sorbent with short lifetimes.

- The next biggest cost reduction drivers are from learning curves on manufacturing cost at large scale and from energy cost reductions that reflect piggy backing of forecast falling battery and solar prices to 2050.

These findings are consistent with lessons from innovation diffusion literature and with what we heard in interviews.

For example, MOF sorbents are currently very expensive as they are made in bespoke batches to custom specifications for small experimental lab trials. They are approximately $100 a gram currently – and they need to get to a couple of hundred dollars a kilogram to scale. High-tech and currently high-cost sorbents are analogous to pharmaceutical or industrial chemical manufacturing.

“Making one pill is expensive – producing those pills in the millions gets cheap.”

We saw from the initial German experience with solar, that manufacturing cost learning curves kick in when design standardisation and scale afford purpose designed and built production equipment instead of equipment repurposed form other technologies. Chinese manufactures then drove further deep cost reductions from process automation and cost savings focused on performance optimisation. Interviewees described manufacturing process like the mass production of HVAC as a good analogue for the air handling, regeneration (heating) and CO_2 compression for the non-sorbent elements of DAC units. For example, at the 22 Mt scale, the $59 / t CO_2 in manufacturing costs represents around $3,900 in up-front cost over the life of the equipment (excluding sorbent, solar and battery costs).

We also found scaling this option has significant overall land and energy requirements:

Table 8: Energy and land use for a high cost, high-tech sorbent

	Small scale	1Mt	22Mt
Total land use (km^2)[6]	0.02	20	440
Energy use (GWh/year)[1]	0.98	1,965	43,241

Both this option and the subsequent DACCS option modelled below have significant land requirements (as do most CDR methods at scale when accounting for energy generation). By comparison, Human induced regeneration projects currently registered under the Emissions Reduction Fund currently cover 12,979km^2 of NSW [106], with an average total productivity (total ACCUS yielded by all HIR projects to date) of 9,680t CO_2 / km^2 [107]. This modelled process is much more productive in CO_2 removal terms per km^2, yielding 50,000t / km^2 / year, or 1.25Mt per km^2 over a 25-year facility lifetime.

[6] Land use includes both capture and energy generation as each module in this scenario includes integrated solar generation and storage.

Low tech sorbent cost drivers

The figure below illustrates the cost breakdown, including high and low ranges for sorbent costs based on different learning rates, for the **low cost, low tech sorbent** across the three different deployment scales.

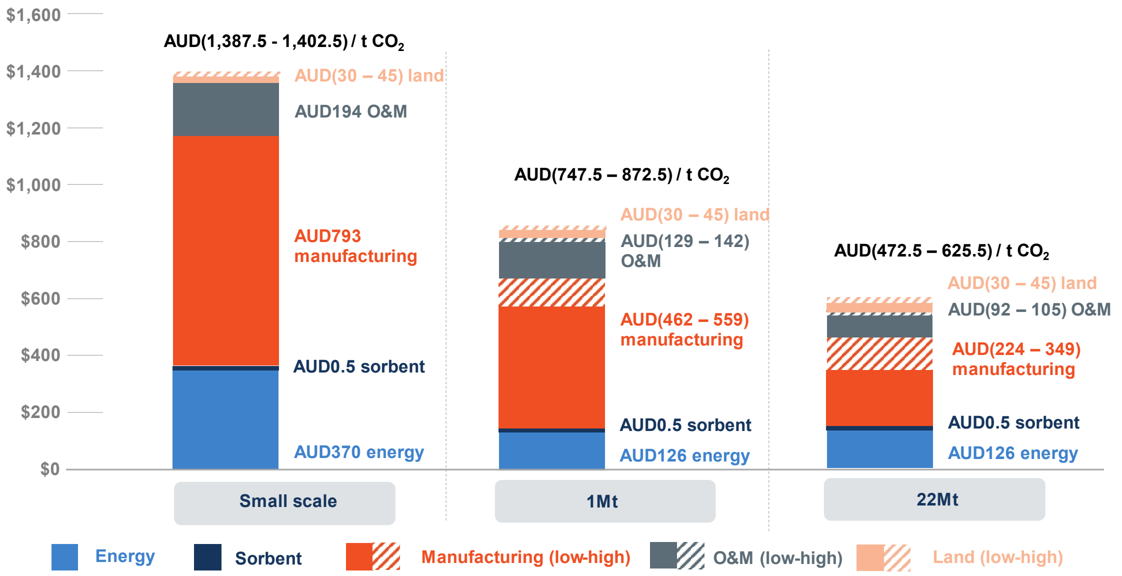


Figure 18: Cost breakdown for a low cost, low-tech sorbent across different deployment scales

As Figure 18 illustrates:

- The biggest cost drivers are capex on building the DAC plants amortised over lifetime removals and annualised operating expenditure on energy.
    - Plant capex comes down with scale to $224-349/t CO_2 at 22 Mt scale. However, these reductions are not as significant as those achieved by the small modular hi-tech units.
- Sorbent costs are much lower than costs for the high-tech sorbent at $0.5 without scope for learning curves due to existing commodity scale pricing.
- Land costs are more material for this option as significantly higher land values have been used relative to the high-tech sorbent scenario. This is because this option has more specific climatic requirements due to the nature of the sorbent, and therefore has specific siting requirements - necessitating deployment on more expensive (closer coastal proximity). The ranges in land cost shown here also reflects the sensitivity of these costs to the density of capture equipment that can be achieved through R&D.
- Energy costs are higher than costs for the high-tech sorbent in NSW. **This is not due to a greater energy demand**, it is due to the climatic requirements of optimising the low-tech sorbent which limits geographic positioning to areas which happen to be high land value regions **in NSW**. This means that cheaper on-site renewables are not viable due to large land footprints. This is not a generalisable lesson beyond NSW.
- O&M costs were reported to be also more material for facilities of this nature, with ranges reflecting sensitivity to which R&D can drive steeper learning curves for automation and process efficiency.

We heard in interviews that companies with larger industrial scale capture facilities were targeting significant economies of scale and cost reductions through standardisation of plant design, modular production of key components and process automation. We also heard that forecasting capital costs and learning rates was challenging until the first few large-scale plants had been built. This is because there are fewer iterations to learn by doing from building a facility that would remove 22 Mt compared than those afforded by production of the many more smaller units required to remove the same amount of CO_2.

This is not to say that large, centralised facilities cannot achieve economies of scale. Simply that the scale required to drive significant cost reductions is greater than the illustrative 22 Mt NSW only scenario. Indeed, most DAC and other CDR companies we benchmarked are targeting ultimate scales in the gigatonnes and eventual sub-US$100 / t CO_2 costs at scale.

Rather, a key takeaway from these findings is that a NSW only scenario could drive significant enough scale to drive material cost reductions for the high-tech, small modular option.

We also found scaling this option has significant overall land and energy requirements:

Table 9: Energy and land use for a low cost, low-tech sorbent

	Small scale	1Mt	22Mt
Facility land use (km^2)	0.03 – 0.07	0.3 – 0.7	7.2 – 14.5
Additional energy generation land use (km^2)	32.9	32.8	723.5
Total land use (km^2)	**32.9**	**33.1 – 33.5**	**730.7 – 738.0**
Energy use (GWh/year)[1]	**200.16**	**2,000**	**44,000**

While the previous option includes on-site energy in its facility land use, this option requires the additional deployment of large-scale renewables.

NSW will benefit from global scale-up

In the above examples we have looked at scenarios where NSW is moving independently. In reality, NSW will not move independently, it will benefit from global scale. We also modelled extended learning curves out for both options to understand what NSW scenarios would look like if these technologies had achieved gigatonne scale globally.

Figure 19 illustrates the further cost reductions that would occur if the 22 Mt in NSW was deployed in the context of global gigatonne scale deployment – as is likely.

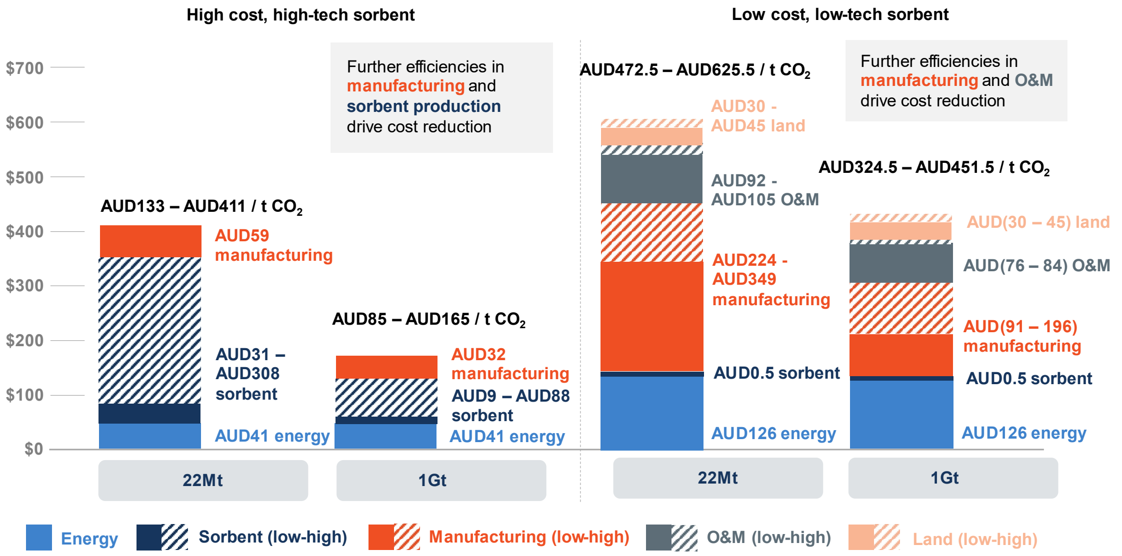


Figure 19: Ongoing cost reductions at gigaton scale global deployment

As it illustrates:

- For the high-tech sorbent - further economies of scale help take the total marginal cost of CDR from $133-$411 down to $85-$165 / t CO_2, largely due to steep further sorbent cost reductions down to $9-$88 / t CO_2 (depending again on the levels of R&D success in extending sorbent lifetimes).
- For the high-tech sorbent, cost of energy is higher at $126 / t CO_2 as compared to $41 / t CO_2 for low-tech sorbent due to climatic constraints which indirectly limit renewable energy options. This is because there is overlap of these climatic considerations with high land value NSW regions and because otherwise cheap renewable energy options are land intensive. The low-tech sorbent is modelled using one of such renewable energy options as it is location agnostic and can be placed in NSW regions with low land value.
- For the low-tech sorbent - further economies of scale reduce total marginal cost of CDR from $472.5-$625.5 down to $324.5-$451.5 / t CO, largely due to economies of scale driving plant capex and O&M costs down.

This again is analogous with the lessons from solar – which found the 15,000-fold cost reductions from the 1950s were an international effort attributed to contributions of five countries – United States, Japan, Germany, China and Australia [102].

Australia's contribution to the cost reductions of solar was twofold. First, Australian scientists lead by Martin Green, out of the University of NSW, achieved step-breakthroughs in the efficiency of solar panels in the early 1990s. Efforts to commercialise the technology in Australia failed, in part, due to investor reluctance to compete with international incumbents with scale, but with less efficient technology. Instead, a core team of Australian and Chinese born students from the UNSW lab moved to China and commercialised the technology there. Their company, Suntech, transformed the cost of mass-produced solar panels – largely through advanced manufacturing automation (not low cost labour), enabled by provincial and municipal government support in the form of loan guarantees, free land, subsided energy and fast tracked permitting [102].

Australia's second contribution was in the 2010s leading learning by doing cost reductions across the installation supply chain which drove down the non-hardware related soft costs. In the 2010s national renewable energy target combined with state government rebates and feed-in tariffs drove the Australian solar industry to achieve economies of installation scale.

NSW can import or export inputs to supply a global scale up

NSW's experience with the loss of world leading technology and scientists to China offer insights into potential pathways for the scaleup of DAC in Australia. The Australian Government has identified the importing of billions of dollars in solar panels from China – made using the UNSW technology as a squandered economic opportunity and risk to sovereign capability, and has committed to building a local manufacturing industry [108]\.

The deployment of DAC offers similar choices to NSW and Australia. For example, the above scenario for a 22 Mt p.a. NSW deployment of a high-tech sorbent involves $193 million to $1.9 billion per year in sorbent costs at global gigatonne scale pricing. If these sorbents are manufactured internationally this represents a direct drain of that amount to the NSW economy. Alternatively, a domestic manufacturing capacity of that scale would translate to $560m-5.6bn in value added gross state product and 1,300-13,000 direct and indirect jobs, using ABS multipliers. If NSW were able to supply just 10% of a global market at giga tonne scale, for example, this would translate to $900 million to $9 billion in import revenue, $20-90 billion valued added and 6,000 to 60,000 jobs.

Similarly, at the 22 Mt scale the scenario represents $2.3 billion in non-sorbent unit costs which could be imported or made locally. With local manufacturing yielding $3 billion in value added gross state product and 5,600 direct and indirect jobs, using ABS multipliers or a further $138 billion in value added gross state product and 250,000 direct and indirect jobs, using ABS multipliers if NSW captured 10% of a global Gt scale market.

Interviews with Australian and American DAC companies cited NSW production facilities as highly plausible subject to sufficient policy support for both first of a kind scaled deployment and the establishment of local component manufacturing. As discussed in Section 3 -interviewees saw Australia's low cost renewable energy, abundant land and highly skilled workforce as highly attractive for CDR deployment. However, as discussed in Section 5 – a number of policy factors are and will shape the locations companies chose to begin to scale from.

NSW is already home to leading scientists in advanced sorbent research, and mineral carbonation technologies for storage.

CO_2 transport and storage

We investigated the cost drivers of CO_2 transport and storage to understand the feasibility of CO_2 piping across distances and different storage options. We conducted interviews with major CO_2 storage projects and experts in Australia, gas piping experts and CO_2 mineralisation experts and project developers.

CO_2 storage

As outlined in Section 2, there are multiple ways to store CO_2 and further investigation is needed to define the total potential of NSW storage. We investigated two types of NSW storage to determine the major storage cost drivers: saline aquifer injection and CO_2 mineralisation.

We found that saline aquifer injection is significantly more cost effective than CO_2 mineralisation:

- The cost of saline aquifer injection, including compression is estimated at **approximately \$8/tonne CO_2 at Mt scale** based on cost data provided by interviewees, including compression at well head and monitoring. We note that if injection is used for pilot scale the costs per tonne at pilot scale will be much greater as the storage costs will be distributed over few tonnes initially (i.e., it is like building a power station and turning on one lightbulb).
- The cost of mineralisation storage is estimated at **approximately \$93/tonne CO_2 at Mt scale.** Mineralisation is a significantly higher cost pathway as it relies on the sourcing of suitable minerals (for example, serpentinite) and thermal energy to prepare the minerals for the mineralisation process.
- Interviewees noted **risks related to injection storage prices due to monopolies** if a single storage operator is able to restrict access to geological storage, limiting the number of capture companies who are able to operate in NSW and reducing competition. A key driver of achieving price reduction is competition [102] and the nature of injection storage means a monopoly is likely. Government intervention in storage to ensure open access (for example a hub concept) may be required to manage this risk.

Noting that the geological injection storage potential in NSW has high uncertainty, it is also worth noting that northern NSW is also in proximity to the CTSCo storage site in Queensland at the Surat Basin, and Southern NSW is in proximity to the Victoria Gippsland storage site. It may be feasible to pipe to these locations as CO_2 piping was not found to be a major cost driver, as discussed below. This means NSW-based geologic storage is not a hard rate limiter. As most of the economic benefits are derived from the capture rather than storage process interstate storage partnerships would not materially impact on the NSW economic benefits of DACCS – however, they introduce jurisdictional risks of access to interstate storage.

Box 4.5: Carbon capture, utilisation and storage (CCUS) pathways as a bridge to cost reduction

Deployment of solar from 1950s to the early 1990’s was largely driven by demand from iterative waves of small-scale niches applications that could support higher prices (for example, satellites) backed by policy support for R&D and demand subsidies. The learning curves afforded by this iterative expansion in scale helped drop prices from over USD100,000 MWh to around USD1,000 MWh (compared to USD20 today) [102].

DAC paired with carbon utilisation in long-lived products for durably storage similarly has potential to bridge initial costs of scaling. Many of the first wave of international DAC companies have explored CCUS revenue streams to offset their initial scaling costs.

Many applications proposed for DAC with carbon utilisation are not CDR as they do not include durable storage. Examples include CO_2 from DAC for enhanced oil recovery and synthetic fuels.

However, other there are also many products that do offer durable storage and can therefore be considered CDR (depending on the life cycle emissions associated with their deployment). For example, companies like CarbonCure, who inject CO_2 into concrete as is sets, or the leading NSW based MCi which combines CO_2 with ultramafic rocks, slag and other materials to store in as mineral carbonate in saleable building products.

A challenge with CCUS is that few products in the world are used at the gigatonne scale required to meet climate goals (with concreate the notable exceptions).

To understand this, we modelled the potential of mineral carbonation for building products as a niche storage option for DAC. Revenue from the sale of mineral carbonation products could help take the cost of storage from AUD618 to AUD93.4. However, for context of scale – if mineral carbonation products were used to meet 60% of NSW market demand for supplementary cementitious materials – this would store 0.017 million tonnes p.a. Based on the cost modelling above, CCUS pathways alone are unlikely to drive major DAC cost reduction at this scale.

In contrast this is a material level of storage compared with typical point emissions of 1.15 MT of CO_2 from a cement plant of that size. It therefore remains a potential low-cost pathway for onsite storage of CCS for cement industry decarbonisation.

Piping CO_2 to storage sites

When investigating piping, our primary area of enquiry was to test a common hypothesis that CO_2 piping is prohibitively expensive. We found that piping is unlikely to be prohibitively expensive:

- We modelled piping at a distance of 300km. At this distance, we found piping adds an **estimated $6 to total DACCS costs at Mt scale**.
- High-grade, high-pressure steel piping is only required to transport supercritical CO_2. Distance transportation does not require supercritical CO_2 as it can be transported as much lower pressures.
- The lack of high-pressure requirements for distance transport means that more cost effective and non-corrosive plastic polyethylene (PE) piping can be used. PE piping is significantly cheaper than steel piping as it does not require high skilled labour (welders) to install it and it is a long-proven technology that is easy to manufacture. Further, lower pressure piping has reduced regulatory compliance costs as safety and permitting requirements are lower under the Pipeline Act. For reference, the majority of the gas distribution network in NSW is plastic piping.
- High-grade, high-pressure piping is only required at the injection site as supercritical CO_2 is required for saline aquifer injection. CO_2 can be raised to this pressure with a compressor at well head. Compression at wellhead also has greater electricity efficiency.

Considering lifecycle emissions

We conducted high-level modelling of potential lifecycle emissions from DACCS. The structure of this analysis was based substantively on previous LCA by Madhu et al. (2021) with local embodied emissions and grid intensity factors [109]. Overall, we found that:

- Fuel source was a major driver of lifecycle emissions. Given DACCS is a high energy process, non-renewable fuels have a major emissions impact and can outweigh the emissions benefit. Using the current NSW grid emissions factor, it may require emissions of 1.58t CO_2 to capture 1t CO_2. It is, however, acknowledged than in pilot phase it may be appropriate for start-ups to initially deploy small amounts of non-renewables for technology demonstration purposes.
- Excluding energy, lifecycle emissions were minor relative the CO_2 captured. This included accounting for the cement and steel required to build facilities and units.
- We did not size any potential emissions from land use change. However, we recommend this be considered in future in understanding the baseline of the system. For example, it could create a perverse emissions outcome to change a carbon sequestering land use to DACCS use. This should be considered during DACCS siting.
- Many interviewees noted that lifecycle emissions should be included in MRV frameworks, with tonnes of emissions netted off from the total CDR tonnes to reflect the actual benefit realised.

BiCRS

BiCRS implementations have dramatically different capital equipment, feedstocks and operational requirements. As such, there is significant variation in estimated BiCRS costs in the literature, with ranges of US$15–400 identified for BECCS options alone [110]. Of these, ethanol fermentation, which produces relatively pure CO_2, is estimated to be lower cost ($20-$175), while combustion for heat or electricity with flue gas point source capture is estimated to be higher cost ($88-$288).

Real world examples of demonstrated BiCRS removals tend to show higher costs, including:

- **Drax** report net costs of £150 per tonne of CDR [58] with variation in total cost based on changing energy spot prices.
- **Charm Industrial** has sold early CDR under advanced market commitments at US$600 per tonne [111], with planned cost reduction pathways to US$100 per tonne.

Major cost drivers include transport, feedstock costs and capex requirements

Key cost drivers for BiCRS include:

- **Capital expenditure requirements** of large projects, for example, construction of pyrolysers or fermentation or gasification plants. Advisory workshops and interviews put an approximate capex cost of technically intensive BiCRS at 50% of total cost per tonne. Producing smaller modular units (for example, small pyrolysers) is cheaper per unit and may achieve faster learning rates due to modularity, but each unit processes fewer tonnes biomass, reducing economies of scale.

- **Cost of biomass** varies significantly by source, with much higher costs associated with purpose grown biomass. Bioenergy in Australia is currently reliant on being paid via waste levies to take waste biomass; however, future large-scale BiCRS will likely need to pay to source waste. Approximately 25% of Charm's per tonne expenses are associated with agricultural waste sourcing (i.e., payments to farmers).
- **Transport distances for biomass and CO_2** add significant cost. Extant bioenergy facilities in Australia reduce these costs by co-locating with sources of municipal or commercial waste, for example, processing plants; however, depending on implementation option, BiCRS facilities need to balance location of biomass with potential storage locations.

Box 4.6: Trade-offs between modularity and economies of scale

Interview findings were conflicted on how to manage transport costs.

One company argued it is advantageous to deploy modular conversion, for example, small pyrolysers, to minimise the cost of moving biomass, which is much less dense and therefore, harder and more expensive to collect, bale and transport than compressed CO_2 or products like biochar and bio-oil. However, we also heard the perspective that the economies of scale benefit of processing at large facilities outweigh the cost of biomass transport.

Different companies will need to trial different implementation pathways to identify the most suitable options.

- **MRV on capture and durable storage** varies significantly by implementation options. Options that produce CO_2 will face similar MRV and storage costs to DACCS facilities; MRV of bio-oil in storage will likely be cheaper as it solidifies underground and has very low risk of re-release.
- **The amount of external revenue** attracted by bioenergy or long-lived product pathways is a key driver of net cost. However, maximising for bioenergy revenue may reduce the abatement potential due to differences in relative carbon and energy density of feedstocks. There may be more alignment with revenue and CDR rate in pyrolysis processes that additionally produce syngas, which can be refined into secondary fuels like synthetic aviation fuel (SAF).

Indicative carbon removal potential

As discussed in Section 2, NSW has strong availability of biomass wastes. However, there are likely limits to the availability of this waste for BiCRS purposes. Some agricultural biomass needs to be left on a farm to protect soil health and prevent nutrient loss, and a proportion should be assumed to be inaccessible or uneconomical to reach. BiCRS is also likely to see limits to availability due to competition from other industries or applications, for example, composting of organic waste, circular economy applications for cropping and horticultural waste (for example, production of low-emissions agricultural inputs), use in steel production.

As we reviewed BiCRS at a higher level than DACCS and EW, our site-based approach to understanding the dynamics of cost and potential has not been applied. However, based on our review we estimate indicative removal potential for NSW of **nearly 7MT annually**. This uses a fast pyrolysis conversion rate, which assumes a yield of 0.85t CO_2 removed per tonne biomass input [112], and assuming 50% constraints on availability due to sustainable sourcing of farm biomass and competition with other industries.

Table 10: Indicative annual potential of NSW biomass waste

Group	Assumed availability	CDR potential
Cropping	25%	2.6MT
Organic waste	50%	2.8MT*
Forestry	50%	0.96MT
Livestock	50%	0.54MT*
Horticultural	25%	0.04MT
Total		6.93MT

*Values given for municipal and livestock waste are illustrative only – while these wastes can by pyrolised [113] [114], they are not part of the current process and are likely to have different carbon conversion rates.

Section 5: Implications for policy

This section discusses why getting the policy settings right in NSW matters, what policy can do to address nine key barriers to scaled deployment of CDR, and summarises principles for CDR policymaking in NSW.

Key takeaways for NSW policy makers

The right policy settings can help attract CDR companies to deploy pilot programs in NSW.
There may be challenges importing some CDR technologies developed in other jurisdictions with different climate and resource profiles to NSW.
There are nine key barriers to deployment that policy can help address: R&D investment, revenue streams, project finance, social licence, information barriers, governance structures, infrastructure requirements, direct industry experience and MRV standards and frameworks

Developing the right policy settings is key to catalysing CDR

Today's carbon sequestration tools represent the first tested and piloted CDR technologies. Focused attention is now required from governments to catalyse the deployment of these and newly emerging solutions – because we know that these solutions are needed to meet climate goals.

NSW has a policy opportunity to become a domestic and international leader in CDR, support the growth of an important new industry in the net zero economy, grow CDR to meet NSW net zero targets, and reap economic benefits from exporting CDR as a service (in the form of removal credits, skills and expertise) to other jurisdictions. However, delivering CDR at the scale required will require significant investment and policy action. If NSW is slow to act, it may face a longer, more challenging road to meeting CDR needs (for example, importing CDR credits) and losing out on the macroeconomic benefits of this new industry.

CDR start-ups have finite resources and consider policy to prioritise the jurisdictions they enter

There are a finite number of companies working on engineered CDR solutions, and they have limited resources to scale. While several companies we spoke to are actively considering alternate jurisdictions for early deployment of their technologies, they have limited resources and need to carefully evaluate and prioritise future markets.

While operational requirements (for example, availability of key inputs and required geology for storage) are key determinants of suitable jurisdictions, interviews and advisor workshops revealed that CDR companies are considering the policy settings of potential deployment locations. There was broad agreement that the quantum of funding provided for DACCS in the US, for example, was responsible for driving most global activity there – with one key DACCS player ruling out exploring other jurisdictions as they pursued opportunities in the US market. The relevant policy settings include both financial incentives, where the US has invested significantly – for R&D, project finance, and ongoing revenue streams – but also a broader set of interventions across governance, social licence, precompetitive information and MRV.

“As a government, you want to get companies doing demonstrations quickly … to provide some kind of sandbox where they can do that.”

Developing the right settings in NSW will be critical for attracting or growing high quality companies to pilot CDR here.

Companies optimise their technology to suit their early deployment setting

NSW needs to attract CDR companies early in their development to encourage them to design technologies that are suitable for deployment in our environment. Some technical CDR methods – particularly DACCS and enhanced weathering – can be sensitive to factors like climate and water availability. NSW has a very different profile to deployment settings in parts of North America and Europe, where most technology is being developed.

If NSW cannot encourage CDR developers to consider our climactic requirements as they optimise their technologies, we risk a growing gap between the technology that is being deployed elsewhere in the world and technology that works in NSW.

Policy can help remove barriers to deployment and attract CDR to NSW

Consultation findings identified nine key barriers to scaled deployment of CDR in new jurisdictions:

R&D investment
Project finance
Revenue streams
Social license
Governance structures
Information barriers
Infrastructure requirements
Direct industry experience
MRV standards and frameworks

Figure 20: Barriers to deployment

These barriers do not exist in isolation – they are interrelated and reinforce each other. For example, revenue stream uncertainty makes it harder for CDR projects to access critical project finance. However, this means policy that addresses one gap may help solve or reduce other barriers. For example, policy work to establish robust governance frameworks may help the CDR industry build and maintain social licence.

R&D funding

CDR methods have already seen significant R&D investment to get us to the proven, high-confidence solutions we see today. However, additional R&D effort can help optimise solutions and increase efficiency to drive down capital and operating costs. In particular, there are opportunities to optimise CDR for local climactic conditions and resources (mineral availability, BiCRS feedstocks) in NSW.

This R&D could take the form of large-scale field trials or continued lab testing for optimisation of for example, DACCS capture agent properties and manufacture.

Examples of initiatives in other jurisdictions:

- UK government has committed £100m R&D funding to help develop DACCS technologies for deployment in the UK [115]
- The EU Horizon Fund has released CDR-specific R&D grants, for example, €15m to develop DACCS and BECCS technologies [116]
- Private funding for R&D, including the $100m X-PRIZE for carbon removal, a four-year competition for technologies who can demonstrate 1000t per annum removals with a pathway to gigaton scale [117]

Project finance

Some CDR methods have large up-front capital expenditure requirements for manufacture and construction – up to 75% of near-term costs for an example DACCS interviewee. This is particularly true for first of a kind projects that do not have any efficiency benefits from supply chain learning and the economies of scale that are critical to ongoing cost reduction.

Later stage projects face ongoing project finance challenges accessing capital given the uncertain revenue streams of CDR.

Examples of initiatives in other jurisdictions:

- The US Office of Clean Energy Demonstrations Regional Direct Air Capture Hubs policy, which provides US$3.5b to support the development of four DACCS hubs with capacity of greater than 1Mt per annum [29]
- Canada's Investment Tax Credit for Carbon Capture, Utilization, and Storage, which provides a 60% tax credit for capital invested in eligible capture equipment used in a DACCS project and a 37.5% credit for CO_2 transport and storage equipment [118]

Revenue streams

CDR requires long-term, stable revenue streams to unlock investment and support future financial viability. While in the near term, CDR companies are seeking higher revenue from early actors in the voluntary market, long-term revenue streams of at least US$100 per tonne will be needed to support a mature industry based on cost projections.

Revenue availability is a key factor that attracts companies and projects to a jurisdiction.

"Where revenue streams get created, projects get up and running."

This is closely related to the project finance barrier. Providing long-term, stable revenue streams can help de-risk CDR and encourage private investment.

“If an investor can look at cash flows coming in … there is hundreds of millions of dollars on the sidelines ready to deploy into these projects.”

Policy approaches that can help build revenue streams include market-based mechanisms like tradeable obligation schemes (for example white certificate or cap-and-trade schemes, which place an obligation to procure certificates or credits on large emitters), public procurement or direct fiscal incentives, for example, subsidy or tax credit mechanisms [119]

Examples of initiatives in other jurisdictions:

- Section 45Q of the US Internal Revenue Code, which provides a tax credit of US$180 per tonne of geologically sequestered CO_2 captured through DACCS [120]
- California’s Low Carbon Fuel Standard, a credit trading scheme which has an approved protocol for generating credits from DAC and geological storage [121]
- Luxembourg’s proposed Negative Emissions Tariff, under which the government would grant a premium per tonne of CDR under five-year contracts [122].

Due to the importance of this barrier, revenue streams are discussed in more detail below.

Social licence

Public awareness of the need for CDR is low and some CDR methods are beginning to face challenges gaining or retaining social licence, as described in Section 3. CDR must be deployed in close collaboration with local communities to build social licence.

There is a potential role for government in helping communicate the need for and the benefits of CDR to help build social licence, and to establish best practice social and environmental guardrails for the industry that help maintain it.

“We need to know that there’s some excitement, or the ability to enter the market socially … having there be some groundwork around carbon removal being an essential part of the climate solution is an important component.”

Examples of initiatives in other jurisdictions:

- Funding under the US DACCS Hub initiative is linked to strict community engagement criteria, which aims to mandate best practice for the emerging industry to support social licence. Funding under the policy is covered by the Justice40 initiative, which requires that 40% of government expenditure flow to disadvantaged communities [123].

Governance structures

CDR systems and supply chains touch many different domains with different regulatory, legislative and planning frameworks, as discussed in Section 3. These regulatory frameworks are onerous to navigate and key frameworks to enable storage in geological reservoirs or in long-lived products are absent or disincentivise innovation.

This barrier is linked to the social licence barrier. Strong governance structures that mandate a particular level of social and environmental performance can help projects and the industry build and retain social licence.

Examples of initiatives in other jurisdictions:

- Queensland, South Australia and Victoria have enabling legislation to support geological storage of CO_2 [124].

Information barriers

While NSW is perceived as a strong deployment location based on our renewable energy potential, lack of information on NSW reserves of key mineral requirements and suitable sites for geological injection is a major barrier to attracting international investment in CDR.

Interviews revealed that the provision of granular precompetitive data on resource availability is a 'leg up' that makes some jurisdictions more appealing than others.

NSW has begun to address this gap for geological storage of CO_2, with the NSW CO_2 storage assessment due to release data on second stage drilling in the Darling Basin later this year [125].

Examples of other initiatives:

- During consultation, we heard the Western Australia Government is conducting an initiative to assess the mineralogy of tailings to further assess their potential. One interviewee (start-up) noted this government-led work is an incentive to locate operations in a jurisdiction as it significantly decreases the company's assessment requirements
- The US Geological Survey has a long history of investigating and publicising potential geological storage of CO_2 in the US.

Infrastructure requirements

CDR implementation options are not individual technologies, but entire supply chains with infrastructure needs across energy, transport, capture and storage. For solutions to scale effectively, capacity needs to be built entire supply chain to avoid bottlenecks in deployment.

Interviews revealed that DACCS companies, for example, are largely looking at capture in isolation and will require requisite capacity from storage partners and associated storage infrastructure. Similarly, they will need access to firmed renewable power.

Some interviews expressed the need to avoid monopolies across the supply chain to encourage competition and ensure open access, for example, to storage facilities:

"When there's government funding going into a DACCS hub, the worst thing you can do is allow it to be monopolised … if there's public money going into storage reserve it has to be open access."

Examples of international initiatives:

- The US DAC hubs initiative is structured to build capacity across the supply chain by funding projects that *both* capture and store CO_2 at a megaton scale, encouraging capture and storage companies to form consortia.

Direct industry experience

NSW has the key capabilities in engineering, trades and peripheral industries (including financial services, legal services) to deliver large scale CDR. Core points of supply chain alignment have been discussed in Section 3. However, as no large-scale demonstrations have been conducted in NSW to date, these supply chain partners have no direct experience in CDR with CDR-specific projects. Supply chains will need to learn by doing as they deliver first of a kind CDR projects and iteratively improve delivery.

Examples of initiative in other jurisdictions:

- The US Department of Energy Loans Program Office provides funding to emerging technologies to support early commercial-scale deployments and commercial scale-up in order to fill this gap. This funding supports early project delivery and builds supply chain capability and experience.

MRV standards and frameworks

Individual methods and implementation options require robust MRV standards and frameworks that allow for like-for-like comparisons of abatement potential – ensuring X tonnes of removal from a particular method are fungible with X tonnes from another method.

Interviewees stressed the importance of MRV standards that suitably capture life-cycle emissions in the process of delivering CDR, to ensure certifications accurately reflect net removals, i.e., gross removals minus gross emissions, for example, from DACCS energy source, carbon-intensive transport, or crop production in the case of purpose-grown BiCRS. This is particularly relevant for energy intensive methods like DACCS, where net removals look very different when powered by renewables than when powered by natural gas.

"The corresponding LCA regulations [need to have] wide system boundaries, cradle to grave … you might very quickly be in a situation where you're emitting more than you're removing."

Interviewees identified trustworthy, comprehensive MRV standards and frameworks as a key enabler of market confidence in CDR.

“Standards and frameworks [that are] consistent, that enable CO_2 pulled from the atmosphere in one country to be transferable, fungible with others, [are] really essential to create a global market.”

As standards need to be cross-jurisdictionally comparable to enable a meaningful global market, this is not an area where NSW can or should act alone. However, NSW can play a role advocating for robust standards – ensuring that they draw suitable system boundaries and account for durability and additionality of removals.

Examples of initiatives in other jurisdictions:

- The European Union is developing a voluntary EU-wide carbon removal certification framework for removals generated in Europe, including criteria for definition and processes to monitor, report and verify the authenticity of these removals [126].
- Private certification frameworks, for example, CarbonPlan are developing verification frameworks for a range of methods [127]; Charm Industrial is collaborating with researchers to develop a certification methodology for bio-oil [128]. There are existing CDR methodologies in some voluntary carbon markets, for example puro.earth, Verra.

Spotlight on revenue streams: CDR projects need policy support to build clear pathways to revenue

While each barrier is important, we found that acting on the revenue stream barrier likely has strong potential to unlock other barriers, particularly project finance barriers.

CDR projects need stable revenue streams to unlock financing and fund ongoing operations

Identifying revenue streams and attracting revenue is crucial to the future viability of CDR projects. However, unlike conventional industries, CDR does not provide a conventional product or service with a strong existing customer market.

Revenue streams are critical for both:

- Funding ongoing **operational expenditure** like input procurement, storage as a service, O&M and MRV services
- To support access to finance for **capital expenditure**. Many CDR projects are capital intensive and currently face a high cost of capital. Stable revenue streams over the project lifetime help de-risk projects and build investor confidence.

"If investors can look at cash flows coming in and just get comfortable with the tech risk, there are hundreds of billions of dollars on the sidelines ready to deploy."

Initiatives that provide access to revenue are key to catalysing a CDR industry.

"The most active place in world is [the US] with 45Q. They provided a revenue stream for storing CO_2 and that's why most activity in the world has been there."

Projects may need to access multiple types of revenue streams

Current and emerging revenue streams are detailed in the table below.

Table 11: Potential revenue streams for CDR

Revenue stream	Source	Details
Production tax credits	Public	Tax incentives paid per tonne of removed or sequestered carbon, for example, the US Section 45Q Credit for Carbon Oxide Sequestration, which pays a US$180 tax credit per tonne of CO_2 captured by DACCS and geologically sequestered [129].
Government procurement	Public	Commitment by government to purchase a prescribed volume of carbon removal, for example, the proposed Luxembourg Negative Emissions Tariff, under which the government would grant a premium per tonne under five-year contracts or proposed government procurement auctions in Ireland [122].
First-wave voluntary market	Private	Sale of carbon removal under advanced market commitments to market leaders who are willing to pay elevated prices ($1,000/t) to catalyse carbon removal or address their historical emissions, for example, the US$925 million advanced market commitment Frontier, which is buying carbon removal on behalf of buyers included Stripe, Alphabet, Shopify, Meta and McKinsey [130].
Second-wave voluntary market	Private	Sale of carbon removal under advanced market commitments or offtake agreements to a wider pool of potential buyers at a lower price point, for

		example, $600/t for planned second generation carbon removal projects.
Compliance markets	Private	Sale of credits for carbon removal to obligated parties under compliance-based market schemes, for example, the Californian Low Carbon Fuel Standard contains a credit generation mechanism for carbon captured by DACCS and geologically sequestered [131].

Most commercial carbon removal pilots are reliant on the small first-wave voluntary market paying elevated prices for carbon removal. Interviewees attested to a broader second-wave voluntary market interested in second-round projects where lessons from pilot programs and developing economies of scale have begun to bring costs down, for example, the proposed NextGen CDR Facility purchasing arrangement [132].

However, there was broad agreement among interviewees that the voluntary market alone will be insufficient to bring prices down to the <$200 mark needed to support scaled deployment, and even at lower prices the voluntary market is unlikely to be deep enough to support the scale of CDR required.

“The voluntary market at $1000/t gets you to 1000s of tonnes … it doesn’t get you to scale.”

If a carbon credit funding approach is relied upon, compliance markets will be likely to fund CDR into the future. For this funding to work effectively for CDR, mechanisms that acknowledge differences between removals and reductions and differences in permanence and durability of removal are critical. Engineered CDR technologies deliver robust, durable carbon removal, but cannot compete on price with low cost avoided emissions or lower durability methods (for example reforestation methods) that dominate one size fits all offset markets. Higher cost, high durability CDR mechanisms are likely to be crowded out and see restricted access to funding via these markets if they are considered like-for-like with emissions reduction or lower durability methods, which will make it harder for them to come down the cost curve and delay deployment of the portfolio of CDR solutions that will be required.

Box 5.1: Beyond offsets – future models of funding CDR

Over time, governments may re-conceptualise the funding approach to CDR. As CDR moves from a mechanism to offset emissions to a requirement as an atmospheric ‘clean up’ service to restore safe temperature, it may be suitable to consider funding CDR in the same approach as other public good services such as waste municipal waste management. These services also add value to the economy. According to the Department of Climate Change, Energy and Water, waste management businesses contributed AUD3.3 billion and AUD3.5 billion to Australia’s gross domestic product (GDP) in 2009-10 and 2010-11, respectively [133].

Revenue stacking helps get projects off the ground

CDR companies spoke of the benefits of being able to access multiple incentives and revenue streams in a jurisdiction – for example, the commercial appeal of stacking 45Q and LCFS incentives, potential capex funding, and revenue on the voluntary market in the US.

Government-funded revenue models like government procurement should be carefully considered as to whether they preclude further access to other revenue sources in for example, the voluntary market as these will have impact on commercial viability.

Lessons on global scaling and local policy

Taking CDR from its current state to the global gigatonne scale needed within decades is a massive task. But it is not a task that NSW must undertake alone. Moreover, as illustrated above, it is a task that other state and national jurisdictions are already undertaking regardless of what NSW or Australia does. We've seen in Section 4 that there are degrees to which NSW could benefit from international learning curves on some cost components of some CDR deployment options. But we also saw that many cost drivers are local and will be subject to NSW specific learning by doing and competition to achieve cost reductions. Regardless, the nine policy levers above are not problems that NSW can entirely solve by itself. However, there are lessons from solar and the broader energy transition on how state level governments can both influence and benefit from broader national and international policies and markets.

Box 5.2: How solar became cheap – and why it took so long

Gregory Nemet, a Professor at the University of Wisconsin-Madison, undertook a seminal review of the technology, market, and policy dynamics that drove the 15,000-fold reduction in costs since small scale commercial deployments in the 1950s [102]. He draws from specific insights for policy makers and industry on the lessons than can and can't be learnt for other decarbonisation and CDR technologies. This story of how solar became cheap – and why it took so long – is a story of the successes, failures, and interaction of national, state and municipal policies from five countries – United States, Japan, Germany, China and Australia.

Nemet finds that the cost reductions demonstrated by solar where the result of learning curves achieved by increases in deployment scale over a series of R&D and deployment waves in different countries over 70 years. The four key drivers of these learning curves were economies of scale, economies of scope, learning by doing (including international spill over of lessons), and competition. Specific R&D and production design choices drove further economies of scale (for example, modularity of panel production and installation) and capitalised on broader innovations (for example, piggy backing off technology breakthroughs in silicon wafer production and manufacturing automation). Learning by doing in technology R&D and supply chain deployment was also greatly facilitated by the high-cycles of iterative learning enabled by solar small modular nature (every panel made and installed and every unsuccessful sale offered lessons and improvements for the supply chain).

However, the national, state and municipal policies were the engine of growth behind the sale of demand that enabled these learning curves was driven by successive waves of supply and demand side subsidies in different jurisdictions. These included:

American, Japanese and German Government supply side support for at R&D at succussive stages of maturity and scale
Japanese, German, American and Australian state and national government demand-side subsides for roof top deployment (feed in tariffs, rebates and retailer obligations)
Chinese municipal and provincial government support for do build scaled manufacturing capacity (loan guarantees, tax credits, subsidised land and energy costs, planning support).
Nemet's key takeaway on why solar took so long to scale is the stop-start nature of policy support driving series of booms and busts in different countries, with a loss of knowledge and momentum as companies and people left the industry. He identifies political push back from incumbents (utilities) as key driver of policy driven crashes – and the development of benefit sharing policy and business models as a potential pathway to avoid future pushback.

These lessons from solar resonate with what we heard in interviews about the barriers and pathways to local scaling of CDR from start-ups, investors, multinational supply chain partners and CDR science and technology experts. From this, we can draw out concluding principles to help guide assessment of the opportunities and policy options for NSW to achieve its net zero goals and meet its CDR needs. These are:

- **Build bridges to local scale** – State-based policies alone can't fund all the R&D, supply and demand side support required to reach gigatonne scale pricing. But they can have powerful impacts when designed to harness national and international funding towards building local economies of scale. For example, NSW solar rebates and feed-in tariffs had on driving down local solar soft-costs had a significant effect on soft costs. Similarly, the NSW Peak Demand Reduction Scheme (PDRS) and Renewable Fuel Scheme (RFS) are specifically aimed at helping build local demand management and hydrogen industries to the scale so they can compete and take advantage of much greater levels of national and international funding.

- **Long term thinking is critical** – Avoid boom bust cycles, boost investor confidence and reduce project finance costs through legislated long term – but price flexible – supply and/or demand side incentives mechanisms (for example NSW Safeguard Targets to 2050, RFS targets to 2045, 10 years of cost recovery funding mechanisms for AEMO Services Ltd to issue 20 year insurance contracts to renewable energy investors).
- **Design scalability** – At each stage of solar's stalled progress until the 2000s, international leaders hit technology lock ins and price plateau's as they locked in technology and business models designed to serve the niches and policies that initially helped them grow. Executives from a German firm that at one time dominated the global market lamented "The Chinese thought in GWs while we thought 100 MWs". The world needs CDR in the tens of gigatonnes and only technologies and firms pursue that pursue gigatonne scale solutions will attain the economies of scale required. It's not feasible for NSW to fund gigatonne scale removals but a NSW industry that serves greater global demand is more likely to deliver steep cost reductions and enduring economic benefits to NSW. This is a factor for example in considering pathways to ensure policies can continue to scale as they succeed and the scalability of critical infrastructure (for example geological storage sites and sorbent manufacturing).
- **Scale iteratively** – While long term gigatonne scale is the ultimate goal – a crucial factor in solar's cost reductions was many iterative rounds of scaling, learning by doing and improvements at core technology, manufacturing and supply chain levels. Building a full-scale industry in one go – either now or in 15 years will lock in high local supply chain costs and miss the benefits of learning curves. Policies that pursue steady but iterative increases in scale and reductions over time will better drive local learning by doing, build industry capacity and piggyback of international technology spill overs.
- **Foster competition** – Price-based competition was a key factor that maintained pressure on the international solar industry to pursue the cost reductions afforded by learning curves as demand grew. Not all industries achieve such reductions with scale. Market based policies which are technology neutral and outcomes-base incentive mechanisms can help drive competition – though careful design is required to ensure early winners/inconsistent rules don't crowd out subsequent innovations. The business models of key infrastructure are also crucial to the scalability of a NSW industry – for example one interviewee pointed to the risk of price gouging from monopoly control of CO_2 injection reservoirs.

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common capital

Appendix A – Enhanced weathering

This Appendix provides an expanded technical description of enhanced weathering as discussed in this report.

What is enhanced weathering and how does it work?

Enhanced weathering (EW) is the sequestration of atmospheric carbon dioxide (CO_2) through the weathering of mafic or ultramafic rocks at an accelerated rate [13] [14]. Weathering of mafic or ultramafic rocks (usually in the form of silicates) is a natural reaction that regulates the concentration of CO_2 in the Earth's atmosphere over million-year timescales [15]. In this process, atmospheric CO_2 and water react with calcium or magnesium-rich silicates to produce inorganic carbon in the form of bicarbonate (HCO_3^-) or carbonate (CO_3^{2-}). This weathering process naturally removes around 1 $GtCO_2$ from the atmosphere every year [16]. However, this reaction can be enhanced to accelerate the sequestration of CO_2. Grinding and crushing the silicate rocks (for example to sizes below 1 mm) is the most common method of enhancement, as the increased surface area increases the reaction rate to remove atmospheric CO_2 on the timescale of months to decades [14] [17]. These crushed silicates can be left to react naturally with atmospheric CO_2, or can be distributed over land or oceans, as discussed further below.

- The process of EW **captures and stores** atmospheric CO_2 in one reaction pathway.
- EW uses globally **abundant resources** (silicate minerals and water).

- EW is relatively **cheap** at current state, when compared to other CDR options. This is because of the abundance of inputs and because capture and storage occur in one process.
- EW has important **co-benefits** depending on the implementation option. These may include increased soil and ocean health.
- Measurement of carbon sequestration in EW systems is **complex** and still a work in progress.
- EW is almost always **limited by the reaction rate** of CO_2 with the mafic/ultramafic minerals.
- If the ultramafic and mafic rocks require additional mining and crushing, as well as transport to their final location, the total **energy requirements** of EW can be high.

Mafic and ultramafic rock

Mafic and ultramafic rocks are two types of igneous rock characterized by their mineral composition and chemical properties. They are technically defined by their percentage of silica (SiO_2). Ultramafic rocks are <45% (by weight) silica, while mafic rocks are between 45 and 55% silica by weight [134, 135]. This reflects their chemical composition, with a higher percentage of reactive ions, such as magnesium and iron, than other rocks. Mafic and ultramafic rocks are made up of reactive minerals, at the top of Bowen's Reaction Series (Figure 21). These are minerals that crystallise out of magma at the highest temperatures, which means they are least stable at ambient temperatures [135]. Mafic rocks, are rich in minerals such as pyroxene and olivine. Basalt is a common, and globally abundant, example of a mafic rock. Ultramafic rocks, have an even higher composition of olivine and pyroxene minerals, with minor amounts of other minerals such as serpentine. Examples of ultramafic rocks include dunite (which is dominated by the olivine mineral) and serpentinite [135].

The high reactivity of mafic and ultramafic rocks can be attributed to a number of related factors [135]:

1. Their constituent minerals are the least stable at ambient temperatures, having crystallised out of magma at very high temperatures.
2. They contain more chemically reactive minerals, such as magnesium.
3. They have less compact crystal structures, as the crystallisation process occurs more quickly at the higher temperatures than the lower temperatures.

It should also be noted that although iron-rich minerals are reactive, they are not as suitable for agricultural and coastal EW as magnesium and calcium-rich minerals. This is due to the formation of unfavourable secondary products from the released iron cations, that can cause CO_2 release.

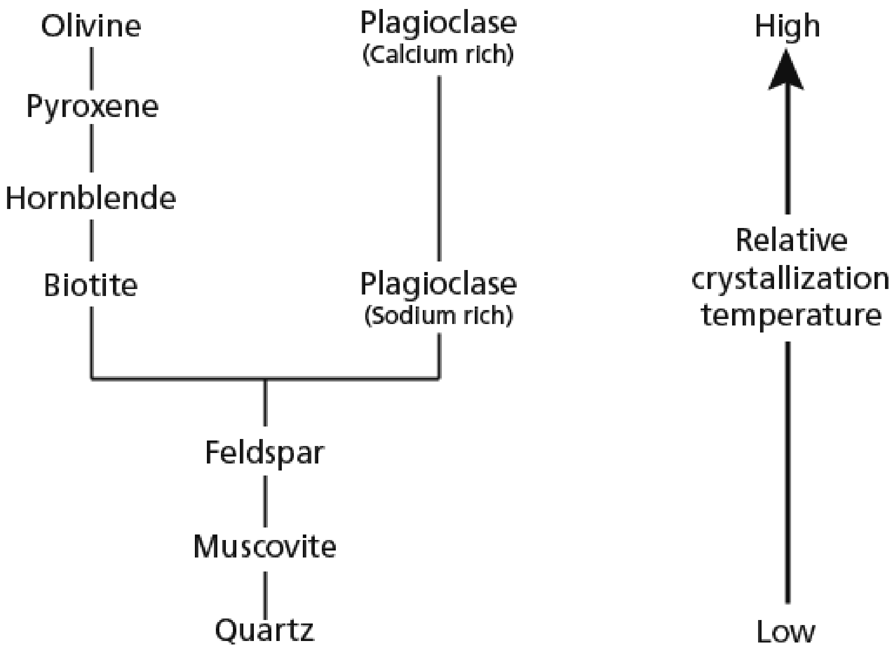

Figure 21. Bowen's Reaction Series defines the order in which rocks crystallise from magma. This also defines which minerals are most reactive. Olivine and calcium-rich plagioclase are the most reactive mineral types.

Implementation options include weathering at mine sites, in agricultural soils and on coastal beaches

The key points of variation between EW systems include:

- **Application**. The minerals may be allowed to weather at mine sites (for example in mine tailing pits), may be distributed over agricultural land, or may be distributed over coastal waters and beaches. This point of differential is the most important, and often determines the mineral type and mineral source, as well as the co-benefits and reaction rate. There are also proposals for the distribution of silicate rocks over unproductive, acidic soils, and the surface of the open ocean. These application options have been less studied, and do not have many of the advantages in weathering rate and co-benefits that exist for mine-site, agricultural and coastal options. Therefore, they have not been considered further [136].
- **Mineral type**. Most commonly, mafic rocks (for example basalt) or ultramafic rocks (for example dunite) are used. Ultramafic rocks weather faster, but are less abundant, and contain heavy metals that may cause toxicity to ecosystems. In some implementation options, industrial waste materials can also be used. This is discussed below.
- **Mineral source**. The mafic and ultramafic rocks may be mined purposefully for use in EW (purpose-mined) or may already be available as mine tailings. Using existing mine tailings eliminates or reduces the requirement for grinding, as mine tailings are already well-ground.

Figure 22 demonstrates the different choices that can be made in the implementation of EW at different stages of the process. This also highlights the variety of potential implementation options.

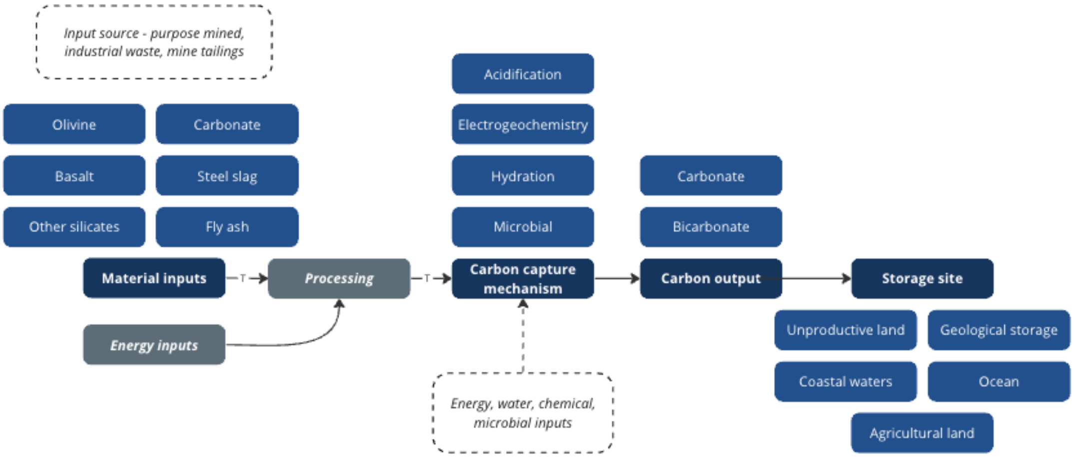

Figure 22: Enhanced weathering system map

Mine-site enhanced weathering

Mafic or ultramafic minerals may be left to react at the mine-site at which they are produced. Generally, this will occur in large pits, where minerals are piled up. Mafic or ultramafic rocks may be used for this process, although ultramafic rocks should be prioritised, as they weather more rapidly and should not cause ecological complications from heavy metal release, as tailing pits are designed as closed systems to prevent leaching of water. Therefore, **ultramafic rocks** are predominantly used in this implementation option. **Mine tailings** are largely used for this implementation option, as they are already stored in large pits, although there are no technical restrictions on using purpose-mined minerals – this is the difference between purpose and integrated mine use, modelled in Section 4.

The advantage of weathering ultramafic (or mafic) tailings at the mine-site include:

- The potential for other activation and acceleration processes to further enhance the weathering rate. Specifically, acidification, thermal treatment, stirring and alkaline salt additions may greatly accelerate the carbon sequestration rate [137]. These processes are not viable in agricultural or coastal settings due to potential ecosystem impacts of chemical addition and due to the distributed nature of the solution, in that it may require treatment facilities at each farm and coastal site, compared to a limited number of mine sites that produce significant quantities of ultramafic tailings. Interviews suggested that these accelerants are likely to be essential in achieving significant CDR in mine-site EW, but are still in early stages of development or protected by proprietary interests. More detail is provided on these activation and acceleration processes below.
- Reduced cost and energy requirements for transport, grinding and distribution. Mine tailings have already been ground to a size suitable for rapid weathering, and no transport or distribution is required.
- More simple and accurate measurement of carbon sequestration. As the mine-site pits are enclosed, inorganic carbon cannot leach out of the system, like it can in agricultural and

coastal settings. Further, the systems are much simpler than other settings, as they are composed primarily of silicates and water, reducing the enormous variability present in soils that complicates agricultural EW measurements.

The disadvantage of weathering ultramafic tailings at the mine-site include:

- No co-benefits to soil, plants or oceans from the release of nutrients or alkalinity by the weathering process. This process is therefore solely centred on carbon capture and storage.
- Potential limitations in the CO_2 removed per tonne of rock. In mine-site EW, large volumes of tailings are produced and dumped into pits. This means that tailings only have a short time to react with atmospheric CO_2 before they are buried too deeply to react. Estimates suggest that at depths greater than 25 cm, CO_2 is unable to penetrate mine tailing pits. Each mineral will therefore only react to a small extent of its capacity. In comparison, agricultural or coastal EW allows the rocks to react to a greater extent of their total capacity. This disadvantage can be alleviated through technological innovations, such as spreading the rocks in thin layers (for example 3 mm) in large, humidified enclosed facilities or by injecting ~20% CO_2 gas into the buried rocks in the tailing pits to increase the carbonation.

Agricultural enhanced weathering

Mafic minerals may be distributed over agricultural land to act both as a **carbon sink** and **soil amendment**. When applied on agricultural fields, the mineral type will be **mafic,** and the mineral source will *usually* be **purpose-mined**. This is because ultramafic rocks and mine tailings often contain high contents of heavy metals that can damage plant growth and soil biota.

The advantages of applying mafic silicates to agricultural land include:

- The potential for increased weathering and carbon sequestration from biological activity of the plants and soil microbiome [138]. The respiration of organic matter by soil microbes greatly increases the concentration of CO_2 in the soil pore space – up to 100× atmospheric concentration. This accelerates CO_2 sequestration. Studies have also suggested that the release of acids by the plant and microbes can accelerate weathering, although clear conclusions quantifying the relationship between agricultural biota and the weathering rate have not yet been established [138] [136].
- Benefits to the soil through the neutralisation of soil acidity and improvement of soil structure. Silicates have already been used as a soil amendment for decades due to this effect [139].
- Benefits to the plant through the release of important nutrients, including calcium, magnesium and silicon [139]. However, studies also show that excess heavy metal concentration in the applied minerals can harm plant growth [139] – these are much more commonly found in ultramafic rock, rather than mafic rock.
- Mitigation of ocean acidification as the alkaline bicarbonate ions produce run-off into rivers and the ocean [140].

The disadvantages of applying mafic silicates to agricultural land include:

- Difficulties in measuring the amount of CO_2 removed and stored. Soil systems are highly complex, and the accurate measurement of carbon sequestration in agricultural systems is currently a focus area in EW research. This is discussed further, below.
- Energy and cost requirements of mining mafic minerals, grinding the minerals to an appropriate particle size, transporting the minerals to the agricultural setting, and distributing over the fields [104].
- Limitations on the weathering rate. Mafic rocks applied in agricultural settings may have the slowest weathering rate of the EW implementation options due to the reduced reactivity of mafic rocks compared to ultramafic rocks, and limitations on water availability.
- Difficulties in optimising the reaction rate. Due to the complexity of soil systems, it is likely to be very difficult to optimise the various factors that influence reaction rate, which include soil pH, concentration of CO_2 in the pore spaces, hydrology patterns, soil microbiome composition etc.

Coastal enhanced weathering

Mafic or ultramafic rocks may be distributed over coastal waters and beaches to sequester atmospheric CO_2. Despite the levels of heavy metals, studies have so far suggested that **olivine** can safely be used without damaging the coastal ecosystems. So far, no projects have assessed the ecotoxicity of using mine tailings as opposed to purpose-mined minerals.

The advantages of applying mafic and ultramafic silicates to coasts include:

- Increased weathering and carbon sequestration rate. Coastal enhanced weathering interviewees report that the abundance of water eliminates a potential limiting factor, and the action of the waves improves the kinetics of the reaction. However, the magnitude by which the wave action increases reaction rate is still uncertain. The use of ultramafic minerals, such as olivine, increases reaction rate over the use of mafic rocks.
- Mitigation of ocean acidification as the alkaline bicarbonate ions produced neutralise acidity in the ocean [140].
- Potential ecosystem health benefits from the dissolved nutrients, including silica [14].

The disadvantages of applying mafic silicates to coasts include:

- Difficulties in measuring the amount of CO_2 removed and stored. This is largely because the inorganic carbon produced by the EW reaction becomes quickly dilute in the coastal waters, making accurate measurements difficult.
- Energy and cost requirements of mining mafic minerals, grinding the minerals to an appropriate particle size, transporting the minerals to the coastal setting, and distributing over the beaches and waters [141].
- Overall increased levels of uncertainty surrounding the process. Research and business development in coastal enhanced weathering is very limited, leaving many limitations in the understanding of reaction rate, ecosystem effects etc.

Box A.1: EW deployment case studies

Arca (Canada) accelerates the natural weathering of ultramafic mine tailings at the mine-site. The company is currently focusing on nickel mine tailings, due to the high content of ultramafic minerals. Through proprietary treatment processes, including stirring of the mine tailings, Arca can increase the reactivity and the carbon capture potential of the ultramafic minerals with no additional energy or cost requirements for grinding, transport or distribution of the minerals. Arca is in the late field trial stage, with multiple millions in funding and advanced market commitments from Frontier and Shopify.

Lithos (US) distributes mafic mine tailings over agricultural land. With over US$6m in funding and advanced market commitments from Frontier, this group has recently entered the field trial stage by testing the carbon sequestration and ecological impacts on farms in the US Midwest. Lithos have a clear focus on improving the measurement of EW carbon sequestration, with a proprietary machine learning algorithm in development.

Project Vesta (US) is testing the application of finely ground ultramafic minerals (specifically olivine) to coastal beaches and waters to capture and store atmospheric CO_2 as bicarbonate or carbonate in the ocean. Although currently using purpose-mined olivine, the organisation has stated its intention to test the feasibility of using ultramafic mine tailings as well. Project Vesta has recently completed extensive testing of the ecological impacts of olivine in coastal ecosystems, and have found no major effects. The group is now looking to implement field trials to determine the CDR potential of this EW implementation option. Project Vesta have advanced market commitments from Microsoft and Stripe to fund their scale-up.

Figure 23: Variation across enhanced weathering case studies

	Application	Rock Type	Rock Source
Arca	Mine-site	Ultramafic	Mine tailings
Lithos	Agricultural	Mafic	Mine tailings
Project Vesta	Coastal	Ultramafic	Purpose mined

NSW has a significant supply of industrial waste that can be used for EW and mineral carbonation

The primary rock inputs for EW are discussed in the main report. Beyond ultramafic and mafic rocks, two alternative inputs are **calcium carbonate** and **alkaline industrial waste**.

Calcium carbonate is a globally abundant mineral, that reacts with CO_2 and water to convert the CO_2 into bicarbonate [142]. This reaction is outlined below:

$$CaCO_3 + H_2O + CO_2 \rightarrow Ca^{2+} + 2HCO_3^-$$

In fact, this reaction has naturally governed the Earth's response to high atmospheric CO_2 in the past [142], as the reaction naturally occurs in the ocean to buffer ocean, and by extension atmospheric CO_2 levels. However, calcium carbonate has been less studied and is not considered further in this paper – partly because of the following reactions. The first reaction is the reaction of calcium carbonate with nitric acid, which can form in agricultural fields from the use of fertiliser, and leads to net emission of CO_2. [14].

$$\mathrm{CaCO_3 + 2HNO_3 \rightarrow Ca(NO_3)_2 + CO_2 + H_2O}$$

The second reaction is a natural reaction – the precipitation of carbonate from bicarbonate – which is effectively the reverse of the first reaction above. This occurs to a small extent in the ocean, and to a more variable extent in soil, leading to no net change in atmospheric CO_2, and rendering the application of calcium carbonate pointless from a CDR perspective.

$$\mathrm{Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + H_2O + CO_2}$$

Alkaline industrial waste is highly abundant in NSW and has high potential for use in both EW and mineral carbonation. The advantages of using alkaline industrial waste are as follows:

- They are often very reactive, more so than ultramafic rocks [143] [137] [144].
- Using them in EW and mineral carbonation reactions provides a waste disposal method.

However, their use also has downsides:

- They often contain high levels of toxic contaminants, preventing their use in agriculture or coastal beaches. They can therefore be used for **mine-site[7] EW** or **mineral carbonation**, both of which are closed systems [143] [137] [144].
- They are often by-products of carbon-intensive processes, such as combustion [143] [137] [144]. They are therefore a good source of existing minerals, but should not be produced for the purpose of CDR – as this will be a net-emitting process.

Appropriate industrial waste for reaction with CO_2 includes [143] [137] [144]:

- Iron and steel-making slag – usually waste products from reactions in the furnaces.
- Cement waste – including by-products from cement manufacture, such as cement kiln dust from the furnace and actual cement that is no longer in use.
- Ash and other furnace residues – from municipal solid waste ash to coal and oil shale ash.
- Alkaline paper mill waste – such as lime kiln residues.

Our findings suggest NSW has an abundance of coal ash, cement waste and iron and steel slag. The current production rates of these waste by-products could support Mt scale CO_2 capture. It should be noted that the current production numbers are estimates based on available data, but a proper analysis of NSW capacity would provide a more accurate measure of potential. This report has not investigated how these production rates are likely to change as these heavy industrial processes undergo decarbonisation.

[7] The term 'mine-site' is misleading here, as these alkaline waste products are produced at heavy industry sites, such as combustion furnaces. There would be no reason to transport these minerals to a mine site, so in this instance 'mine-site EW' refers to their weathering at the site of their production – potentially in a pit, enclosed facility or in another method.

Table 12: Industrial alkaline waste sources for EW and mineral carbonation in NSW.

	Current Reservoir	Current Production	CO_2 storage capacity[8]
Coal ash	216 Mt [145]	4.8 Mt/yr [145]	10 Mt + 0.1 Mt/yr
Cement waste	Unknown	0.3 Mt/yr [146] [147]	0.15 Mt/yr
Iron and steel slag	Unknown	1.75 Mt/yr[9] [148]	0.8[10] Mt/yr

Our findings suggest NSW has negligible amounts of oil shale ash, alkaline paper mill waste and suitable municipal solid waste.

Land and coast availability

EW is unlikely to be limited by land or coast availability in NSW. Table 13 summarises the availability of land/coast for each implementation option in NSW as well as very loose estimates of capture and rock input requirements for each scenario.

Table 13: Land limitations by implementation option

Implementation Option	Area available	Rock requirement (every 5 years)
Mine-site	Not land limited	Not land limited
Agricultural	52,000,000 ha	2.6 Gt basalt
Coastal	900 beaches	120 Mt olivine

Mine-site EW is unlikely to be land limited as facilities can be created within the boundaries of the mine-site. Despite significant land use, **agricultural EW will be limited by rock inputs before land requirements**. The Australian Bureau of Statistics estimate that there is about 52 million ha of agricultural land in NSW and the ACT, including both cropping and grazing land [149]. Assuming an application rate of 50 t(basalt)/ha, which is commonly used in experimental studies and modelling scenarios, this would require 2.6 Gt of basalt upon every application [150]. This is certainly a more limiting factor than land use.

Similarly, **coastal EW is likely to be limited by rock inputs before land requirements**. NSW contains around 900 beaches. Based on estimates for beach nourishment requirements in

[8] These are very rough estimates designed to give 'order-of-magnitude' numbers, rather than precise figures. They are based on general estimates for total mineralisation capacity [105].
[9] This is an Australia-wide figure, due to limitations in data for NSW. However, NSW is the largest producer of cement out of the Australian states and territories.
[10] This is an Australia-wide figure.

Sydney, standard beach nourishment practices across all NSW beaches could support *at least* 120 Mt of olivine (or other ultramafic rock), ground to sand size or smaller [151].

Implementation option specific considerations

Each implementation option has a number of key input and climatic considerations that will affect weathering rate. EW systems are deeply complex, and the limiting factor is often different in different systems. Some potential limiting factors or constraints for the three implementation options are outlined in Table 14 below.

Table 14: Potential limiting factors by implementation option

Implementation Option	Potential constraints
Mine-site	Water supply, activation/acceleration process
Agricultural	Water (precipitation), soil type, soil pH, soil biology
Coastal	Water temperature, water pH, wave activity

Water is a key input into the weathering process that is essential for the CO_2 sequestration process. Water requirements will be important in mine-site EW, depending on the implementation option. Tailing pits must hold the tailings in slurries to accelerate the weathering process. This report does not consider the water requirements of this process in detail – but it is worth considering that they will not be additional to existing mine-site practices when integrated at existing mine sites.

The water requirements for agricultural EW are likely to be critical to the weathering potential, particularly in NSW and Australia. Experiments have repeatedly shown the importance of sufficient moisture for EW (for example [152]), and our interviewees have suggested that many areas in NSW are less suitable to agricultural EW due to low precipitation. Limitations in studies that quantify the impact of water, globally and more importantly in NSW, make precise determination of questions such as ‘how much precipitation is suitable’ very difficult to answer. Ultimately, more water and precipitation seem to always enhance weathering, with subject matter experts suggesting that it may have its highest potential on highly irrigated crops, such as almond trees in NSW. This was not investigated further.

Interviews with subject matter experts have also suggested that water not only accelerates the weathering process, but that many current measurement processes rely on analysing products of the weathering reaction in the leachate that has run-off to rivers. Without sufficient rainfall (or irrigation), weathering measurements may be more difficult, as the weathering products will remain in the soil – requiring frequent soil sampling. Soil sampling is time consuming and very difficult to retrieve representative samples for an entire field.

Characterisation of mineral CDR potential

A key finding of this report centres on the current lack of data surrounding the size and CDR potential of NSW’s mineral resources. As a potential source of Mt scale CO_2 capture, this is important to remedy. This section briefly provides further detail on technical considerations in the characterisation of the CDR potential of a rock deposit. Importantly, both elemental composition and mineralogy are important:

Mineral composition is the % by weight of the individual elements within the rock or mineral samples. The % weight of calcium, magnesium and iron are particularly important., as they determine both the carbon capture capacity of the rock (i.e. how much CO_2 is can theoretically capture) and the reactivity of the rock (i.e. how quickly it will actually capture CO_2). High magnesium and calcium indicate high capacity for CDR, as they are reactive elements that will react with the CO_2 (in carbonic acid form) to form bicarbonate or carbonate. Iron is not as suitable for reaction, as it forms problematic secondary compounds, such as iron hydroxide. This is why, for example, determination of mineralogy alone is not appropriate for determining CDR potential – olivine is a mineral form, but can be rich in either magnesium or iron, which makes a significant difference to its carbon capture capacity. However, high percentages of iron, as well as calcium and magnesium are indicative of a highly reactive mineral – which means that it is likely to reach its CO_2 capture capacity at a relatively faster rate than less reactive minerals. A process known as **X-Ray Fluorescence** (XRF) can determine the elemental composition of rock samples. This can be quite straightforward and quick to use, with certain XRF machines designed for use in the field for quick measurements with decent accuracy.

Mineralogy is the structure and type of minerals within a rock sample. Minerals with the same elemental make-up can have very different structures, which alters the weathering rate (i.e. how quickly it captures CO_2. Even different types of serpentine have different weathering rates which can alter the overall economic viability of the process. A process known as **X-Ray Diffraction** (XRD) can determine the mineral type and structure of rock samples.

Accelerating the weathering reaction

The goal of all EW implementation options is to accelerate the CO_2 sequestration weathering reaction. There are different ways to accelerate the reaction, which can generally be divided into two separate methods [153] [154]:

- Pre-treatment – processes that occur before the weathering reaction.
- Acceleration – processes that occur during the weathering reaction.

Pre-treatment methods commonly include thermal activation and acid leaching [153] [154]. Grinding of the rocks to a smaller particle size can also be considered pre-treatment, but this is applied across all EW implementation options. Both thermal activation and acid leaching increase the CO_2 removal, but are primarily applied in closed systems – mine-site EW and mineral carbonation.

Thermal activation is modelled in Section 4. It involves the heating of the rock types to increase their reactivity. This is particularly useful for serpentinite minerals, which have hydroxyl (-OH) functional groups physically shielding the reactive magnesium atoms from reacting with CO_2. Heating serpentinites to around 650 to 700^{o}C effectively removes these functional groups, increasing the availability of the magnesium, and therefore increasing the rate of the CO_2 sequestration reaction [153] [154]. However, this process requires large amounts of thermal energy – raising questions around cost and net CO_2 negativity depending on the energy source.

Acid leaching is the reaction of the rocks with an acid prior to CO_2 weathering. The acid reacts with the rock more rapidly than CO_2, releasing reactive cations such as magnesium, and making them available for carbonation. The optimal acid has not yet been settled on, and the use of acid leaching also raises environmental and health concerns [153] [154].

Acceleration methods can also be employed during the weathering process. In agricultural and coastal EW, these acceleration processes cannot be controlled, but biological activity (including the release of acids), pH, temperature, salinity and other environmental factors may all have an accelerating (or decelerating) effect on the weathering. In mine-site EW and mineral carbonation, these accelerants can be controlled. Studies are currently focused on optimising these methods, which include [153] [154]:

- Addition of specific salts (such as ammonium sulfate and sodium chloride), which can accelerate the precipitation of carbonates from solution and the dissolution of CO_2 into solution before reaction.
- Heating the reaction system.
- Churning or mechanically agitating the reaction, which increases the surface area contact between rock and CO_2, increases the kinetic energy of the system, and helps prevent the formation of a passivating layer on the rock surface,
- Addition of grinding media (such as inert, abrasive particles), which disrupt the formation of a passivating layer on the outer surface of the rock, and therefore accelerate the weathering reaction.
- Addition of carbonic anhydrase, a specific enzyme which catalyses the conversion of CO_2 into bicarbonate. This is an example of the potential biological accelerants that can occur in agricultural EW systems.

Measurement of EW

The measurement of EW is considerably more difficult in open systems, such as agricultural fields and coastal beaches.

Mine-site EW measurement requires a measurement of carbonate. As the system remains closed, this carbonate can be measured with high certainty. Mine-site EW approaches do not consider bicarbonate to be CDR, because the bicarbonate can precipitate into carbonate, which releases a CO_2 molecule. Therefore, measuring carbonate is a slightly conservative, but more valid measurement of CDR.

Agricultural EW measurements are much more difficult because they operate in an open system. The products of the weathering reaction can leave the soil and enter the plants or rivers and oceans. This leads to a number of issues, with one primary concern being that it can be difficult to measure small amounts of weathering products when they quickly become dilute in the larger ecosystem. Fundamentally, MRV of agricultural EW either requires measurement of the cations released from the weathering, or the bicarbonate and carbonate formed. Unlike mine-site EW, the open nature of the agricultural (and coastal) systems also allows bicarbonate to be measured as a stable form of CDR. Unlike in mine-site pits, where the bicarbonate will remain in solution where it could re-precipitate into carbonate, the bicarbonate from agricultural EW will run off into the ocean, where it will be stabilised by the complex existing carbonate equilibrium within the ocean [142]. A small amount of this bicarbonate will precipitate into carbonate, releasing a CO_2 molecule, but this will be more consistent in the ocean than in individual mine-site pits, allowing a discounting factor to be more easily established and applied. Measuring bicarbonate and carbonate is more direct, but can be difficult due to the limitations of (bi)carbonate analysis techniques at low concentrations. Cations are easy to measure, but do not always provide an accurate measurement of CDR, particularly in acidic conditions, or in fields with fertilisers [136]. Finally, scaling these measurement techniques is timely and costly. They require sampling of the run-off from fields into nearby rivers and catchments, and often sampling of the soil. It is very difficult to take representative soil samples, creating a trade-off between number of soil samples (and time and cost of analysis) and accuracy. Overall, there is significant debate in the EW field about how to most accurately and feasibly measure CDR, and it is a current area of focus [136] [155].

Coastal EW measurements are also difficult. The complex existing cation and carbonate chemistry of the ocean make small changes very difficult to detect. As with agricultural EW, both bicarbonate and carbonate are measured as stable forms of CDR.

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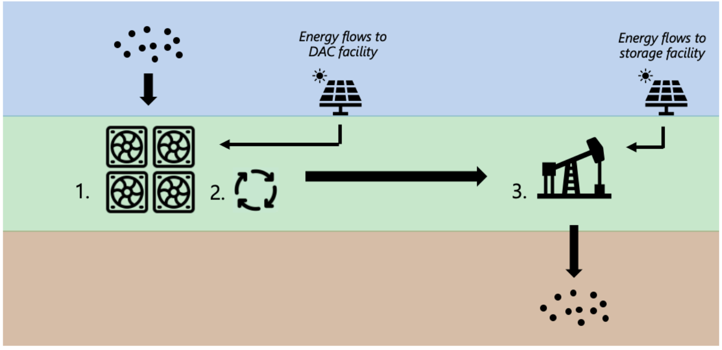
Appendix B – Direct air capture and carbon storage

This Appendix provides an expanded technical description of direct air capture and carbon storage as discussed in this report.

Overview of DAC

Direct air capture and carbon storage (DACCS) is a cyclic process that removes carbon dioxide directly from ambient air for long-term storage [26] [27] [28]. CO_2 in the ambient air is brought into contact with a specific compound with high affinity for CO_2, the capture agent, which chemically or physically captures the CO_2 molecule. Once saturated with carbon or carbon dioxide, the rest of the air is removed and the capture agent is regenerated for re-use, usually resulting in the output of a stream of concentrated CO_2 that can be durably stored underground or in long-lived carbon product.

As of 2022, the International Energy Agency (IEA) identified 18 direct air capture plants in operation capturing just under 0.01Mt CO_2 per year [28], around half of which is permanently sequestered [156]. This is projected to scale up, with a 1MT per annum plant under development in the US [157]; the US Regional Direct Air Capture Hubs policy (discussed in more detail in Section 5) provides US$3.5bn to incentives four further 1MT capacity DACCS hubs [29].



1. **Capture**: Ambient air passes through the unit and the CO_2 is captured.

2. **Regeneration**: A regeneration process separates a pure stream of CO_2 from the sorbent.

3. **Storage**: The CO_2 is stored – in this example, compressed and piped underground, where it is stored in a geological reservoir.

Figure 24: An example DACCS process

Key considerations for DACCS include:

- DACCS has **low resource requirements** compared to other CDR methods as the capture agent is cyclically regenerated [27].
- As most DACCS generate a stream of isolated CO_2 [34], **MRV of capture is simple and low cost**; mass of captured CO_2 can be assessed with a flow meter.
- DACCS facilities are **isolated from natural systems,** in contrast to methods like BECCS and blue carbon. This, coupled with their low resource requirements, give them high potential scalability.
- DACCS tend to have **high energy requirements**. Energy is often used to bring air into contact with the capture agent, in addition to energy used in the regeneration process
- DACCS facilities are often technically complex and may have **complex facility or sorbent manufacturing requirements**.

Implementation options vary widely across sorbent/solvent type, modularity, energy use and storage

There is wide variation across DACCS implementation options. Key points of variation include:

- **Nature of capture agent**: There are a range of different agents that can capture CO_2 from the air. Early DACCS capture agents fell into two main classes, solid **amine-functionalised sorbents** and liquid **hydroxide solvents**. Emerging technologies include **zeolites** [30], **lime-based capture agents** [31], **electrocapture agents** [32] and **metal-organic frameworks** (MOFs) [33].
- **Nature of air contactor**: Most DACCS processes are **active**, using fans to bring ambient air into contact with the capture agents [26]; more recent innovations include **passive** processes that don't require additional movement of air and efforts to integrate DAC with existing airflow infrastructure, for example cooling towers, wind turbines and HVAC units to reduce energy requirements [27] [158].
- **Nature of regeneration process**: A range of processes can be used to regenerate or separate the CO_2 from different kinds of capture agent. These include **temperature-swing** (an increase in temperature to around 100 degrees for amine sorbents and up to 900

degrees for hydroxide solvents [34]), **electro-swing** (an electric current [35]), **moisture-swing** (change in humidity [36]) or **reaction-swing** (where the saturated capture agent is reacted with another input to release carbon). The applicability of these regeneration processes to different implementation options depends on the physical and chemical properties of the capture agent. Different regeneration processes can dramatically change the energy use profile DACCS technologies.

- **Storage pathway:** Once separated from the capture agent, there are a range of potential storage pathways for captured CO_2. These include:
    - **Injection into sedimentary formations** to store carbon in depleted oil and gas reservoirs, deep saline aquifers and coal beds [37]. Captured CO_2 is compressed and pumped into subsurface formations at depths below 800m, where pressure keeps CO_2 in a supercritical, liquid-like state. Multiple mechanisms serve to keep the CO_2. In storage [37]:
        - Physical trapping below an impermeable caprock layer
        - Retention in the pore spaces of sedimentary rock
        - Dissolution in subsurface water
        - Adsorption onto organic matter in coal and shale
        - Reaction with subsurface elements to form carbonate minerals

      Global availability of storage is high, with suitable geological storage capacity estimated at three times total historical emissions since the Industrial Revolution [159]. Deep saline formations are believed to have the largest capacity globally [37]. Ideal formations are both highly porous and highly permeable, i.e. there is interconnectivity between the pores in the rock, which increases injection rates by allowing CO_2 to spread beyond the injection point [160].

      This option is referred to as 'geological storage' across the paper.
    - **In-situ mineralisation**, where injected CO_2 and water reacts with subsurface mafic and ultramafic rock [38] – the same chemical mechanism by which enhanced weathering captures ambient CO_2. We present this as a storage mechanism as distinct from injection into sedimentary formations as the mineral profiles of suitable storage sites are very different.

      While two pilot projects aiming to maximise mineralisation in basalt formations have been launched in Iceland and the USA, relatively little is known about this storage pathway compared to injection into sedimentary formations [161], where the reservoir dynamics are well understood by the gas industry. Potential advantages of this method may include the global abundance of basalt for injection and low risk of leakage post-mineralisation; potential disadvantages include MRV challenges and the volume of water required for injection [161].

      Both injection into sedimentary formations and in-situ mineralisation have associated infrastructure requirements, including the development of compression facilities and well-heads at suitable sites and transport of CO_2 to the injection site.

- **Mineralisation and use** in long-lived products including cement, building materials and fertilisers. This process involves the reaction of CO_2 with reactive forms of calcium and magnesium within industrial waste or mafic and ultramafic silicates. This forms magnesium and calcium carbonates embedded within the product that are stored for > 100 years. Mineralisation and use has potential applications in any products that contain carbonates, but development has largely been focused on cement and construction aggregates. These products provide additional revenue streams that partially offset the cost of storage and capture.

  The key points of differentiation within mineralisation and use storage pathways include the **inputs, acceleration process and end-product.** Magnesium- and calcium-rich minerals can be used as inputs. These may be sourced from industrial waste **inputs**, including:

  - Iron and steel-making slag
  - Cement waste
  - Ash from combustion processes
  - Reject brine from desalination
  - Alkaline paper mill waste

  Reactive mafic and ultramafic silicates may also be used as a source of calcium and magnesium in this process. Mineralisation and use is effectively the same process as enhanced weathering, except with concentrated forms of CO_2 from DAC. The types of mafic and ultramafic silicate inputs are discussed in Appendix A, but are often less reactive that industrial waste, and may require additional mining and grinding to extract.

  The acceleration processes are methods to enhance the carbonation reaction rate. This involves changing reaction conditions or adding chemicals. Many mineralisation and use pathways that involve multiple of the following **accelerants**:

  - Acid extraction – releases the reactive magnesium and calcium from the mineral input before reaction with CO_2.
  - Salt extraction – releases the reactive magnesium and calcium from the mineral input before reaction with CO_2.
  - Increased concentration of CO_2 – increases carbonation reaction rate.
  - Increased temperature – increases carbonation reaction rate.
  - Increased pressure – increases carbonation reaction rate.

  Finally, the end-product of the mineralisation and use pathway may differ. The most common end-products are:

  - Cement – the storage of CO_2 in cement can enhance the strength and durability of the product. As a huge global market, the value of cement partially offsets the expense of capture and storage.
  - Construction aggregates – this capitalises on a large global market.

- **Modularity:** Approaches to DACCS are increasingly modular, i.e. partitioned into smaller independent or semi-independent components, like an array of air contactors which can be individually regenerated [34]. Modular units may allow for more flexible siting and deployment [162] and may demonstrate faster learning rates as their mass manufacture allows for iterative improvement [163].
- **Production of saleable byproducts**: Some emerging DACCS produce saleable byproducts in addition to captured carbon, e.g sulfuric acid [164]. While these products may support additional revenue streams, the system emissions from utilisation need to be taken into account when considering net removal potential.

The diversity of these implementation options is represented below:

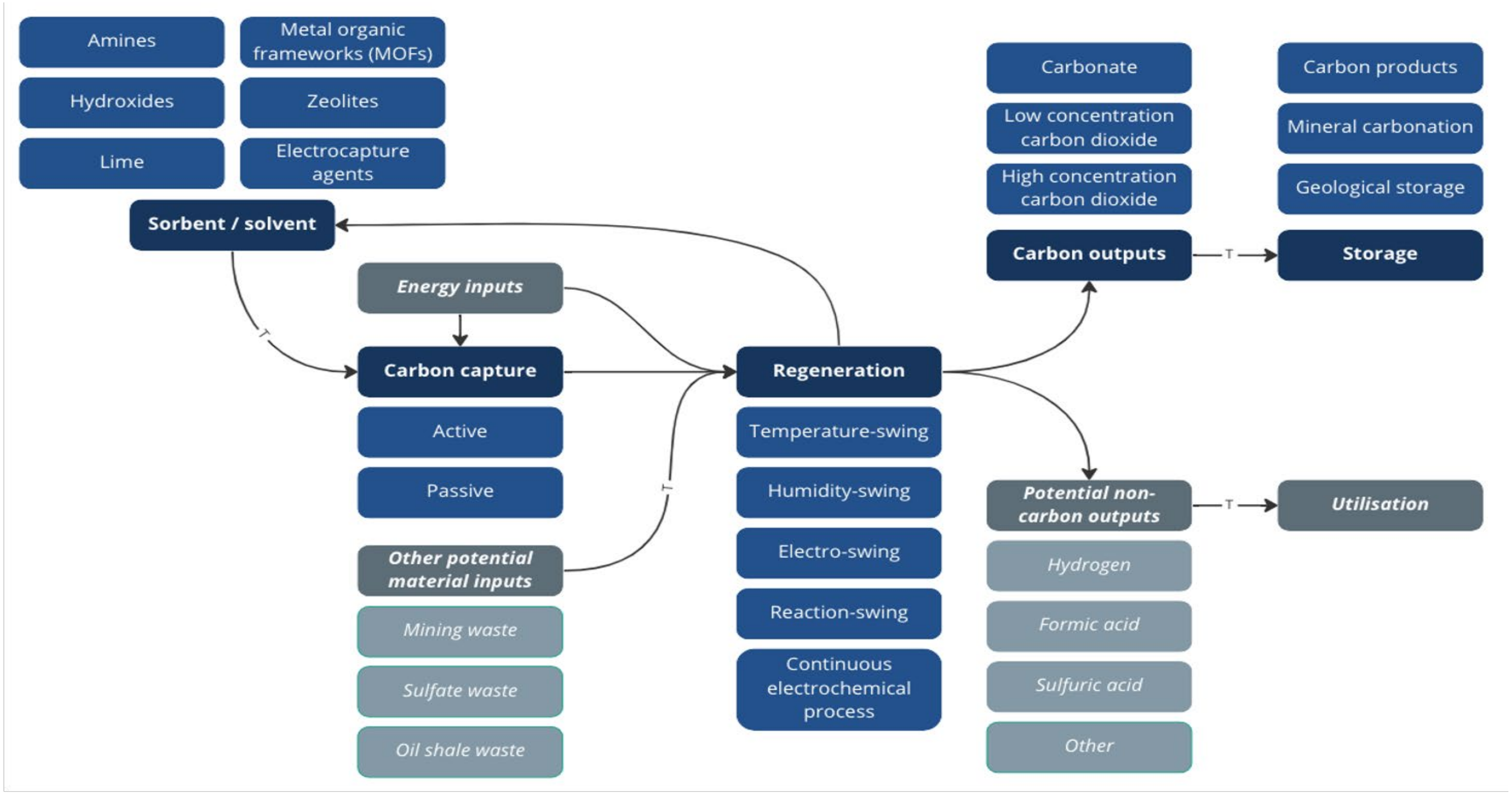


Figure 25: DACCS system map

These diverse implementation options have bespoke deployment setting requirements. Different capture agents are impacted by climactic factors like temperature and humidity in different ways, have different resource requirements, and require different regeneration approaches with different energy needs (as discussed further in the following section). Different options may be suitable for deployment in different jurisdictions based on the combination of these factors.

A future of scaled deployment is unlikely to be dominated a single ‘silver bullet’ DACCS technology, but rather a range of technologies tailored to different deployment settings. The development of a number of different implementation options in a range of geographies will be critical to reaching net zero climate goals [34].

Box B.1: DACCS deployment case studies

Swiss company **Climeworks** is probably the best-known DACCS company and operates the world’s first large-scale pilot plant, the 4,000t Orca facility, in Iceland [39]. Climeworks used a functionalised amine sorbent regenerated in a vacuum at 80-100 degrees C, with electricity for the air contactor and heat for regeneration provided by geothermal energy [40]. CO_2 captured at the plant is injected into basalt formations for mineralisation by their storage partner Carbfix [39].

The NSW partnership between **AspiraDAC and Southern Green Gas** is developing highly modular units with built-in solar energy and battery storage capacity [41] [42]. Their units use a zirconium MOF optimised for Australian climactic conditions that can be flushed at low heat. They are deploying a pilot site at a geological storage reservoir in Moomba with an advanced market commitment from Stripe [43].

Heirloom (US) use limestone to produce their calcium oxide sorbent to reduce sorbent costs. The sorbent is hydrated, treated by proprietary technology and passively exposed to ambient air where it reacts with CO_2 to form a carbonate, which is calcined in an electric kiln to release the CO_2 and regenerate the sorbent [44]. They have partnered with CarbonCure to inject CO_2 into concrete for their pilot application [45], but are pursuing geological storage at larger scales [46].

Travertine (US) have pioneered a unique reaction-swing process with potential for industrial application. They react sodium hydroxide with CO_2 in an air contactor to form sodium carbonate. When exposed to industrial sulfate wastes, the sodium carbonate forms sodium sulfate and long-lived carbonate minerals which safely store the captured CO_2. The sodium sulfate is electrolysed to form sodium hydroxide (regenerating the solvent), with additional generation of hydrogen and sulfuric acid as potential saleable outputs [164].

	Capture agent	*Air contact*	*Regeneration*	*Pilot storage medium*
Climeworks	*Amine*	*Active*	*Low heat*	*Basalt formations*
AspiraDAC	*Zirconium MOF*	*Active*	*Low heat*	*Geological storage*
Heirloom	*Calcium oxide*	*Passive*	*High heat*	*Carbon products*
Travertine	*Hydroxide*	*Active*	*Reaction*	*Mineral carbonate*

Figure 26: Variation across DACCS deployment case studies

Alignment with NSW physical parameters

An assessment of the key physical parameters for DACCS systems suggest NSW is well-placed to deploy this technology.

DACCS have been mapped on the basis of their alignment with NSW-specific resources and physical characteristics below. Areas of strong alignment are unlikely to be limiting factors to scaled deployment; areas of medium alignment may be limiting factors, and areas of weak alignment are likely to be limiting factors.

Physical resources

NSW has strong availability of relevant resources to produce the capture agents described above, for example limestone (more than 4Mt annual production in NSW; over 400 deposits, with undeveloped resources of >250,000t [47]), zircon (>560kt annual national production; production capacity in Murray Basin and western NSW [48]). Resource requirements are significantly lower per tonne of CO_2 captured by DACCS compared to for example enhanced weathering as the capture agent is cyclically regenerated after use.

Many sorbents and solvents are commonly produced chemicals, for example hydroxides, which can be produced by Australia's strong chemical manufacturing capability [165]. Scale up of this capability are not expected to be resource constrained – however, limits to manufacturing capacity may add cost or constrain deployment at scale (discussed in Section 4).

Energy

NSW has strong capacity for renewable generation to meet DACCS energy requirements. NSW has world-leading renewable energy resources: approximately half the state achieving >20MJ of solar exposure per square meter per day [65]. Areas of highest solar potential overlap with potential Darling Basin storage.

However, DACCS technologies are generally energy intensive and scaled deployment will add significant energy demand to the state. They will face competition for energy and storage with deployment of renewables for grid decarbonisation and other green technologies that will add demand, for example electrification of transport, green hydrogen.

Water availability

Many DACCS require water as part of their regeneration process. Assessments of some proposed DACCS technologies have estimated water use of up to 2Mt [83] and evaporative water loss (during heating for regeneration) of up to 8.2Mt water per Mt CO_2 captured [160].

NSW is a drought-prone geography and many parts of inland NSW, including where storage minerals or reservoirs may be located, are significantly water constrained. Climate change is expected to increase variability in water availability in NSW. Water intensive processes are unlikely to be suitable in these environments.

However, other technologies like some MOF-based unit do not require significant water inputs, and some technologies may be net water generators, as DACCS filters capture water in the process of capturing CO_2. For example, the Climeworks processes requires water in an input, but captures a larger quantity of water, yielding a net 0.8-2 tonnes of water per tonne of CO_2 produced [83]. This is sometimes regarded as a technical problem for DACCS, as water capture reduces CO_2 capture effectiveness [83]; however, in water-constrained environments like western NSW water capture (for DACCS process inputs or for other uses) may increase feasibility of deployment.

While DACCS processes that require high volumes of water are unlikely to be suitable for deployment in water constrained areas, there is sufficient innovation in low-water DACCS for this not to be a major limiting factor.

Climactic considerations

DACCS processes are sensitive to local climactic conditions, with variables like humidity and temperature affecting the carbon capture efficiency and regeneration rate of the capture agent.

Many capture agents, for example hydroxide solvents and amine sorbents, are most efficient with relatively high ambient humidity. These variations can be significant, with cost of capture varying by a factor of two between cold, dry conditions and (preferred) warm, humid conditions for an example liquid solvent [49]. By contrast, physisorbents like MOFs can be less effective in humid air, due to the relatively low concentration of CO_2 in the air relative atmospheric moisture. Some MOFs can become oversaturated by moisture, inhibiting their capture potential [166]. However, rapid advances in R&D are developing MOFs that are stable under a range of conditions, including MOFs that are less moisture sensitive [167]. This variation means that DACCS implementation options can be paired with climactic regions they are most suitable for.

NSW's climate is characterised by temperate, humid conditions along the coast and hotter, more arid conditions inland, for example near potential geological storage in the Darling Basin. Climate change expected to make these regions hotter and dryer but increase humidity on the coast [168].

Due to this diversity, some DACCS will be more or less suitable for deployment in NSW based on climactic variability. R&D effort may be required to optimise existing technology for NSW conditions.

Land availability

DACCS generally have a relatively low land footprint on a facility basis. For example, each 500 tonne per annum carbon dioxide collector in a Climeworks facility is approximately the size of a shipping container, which can be stacked with other units [169]. This allows the development of relatively large capture facilities on par with large-scale industrial sites.

Alternate approaches, for example modular deployment of many smaller units, may have a larger facility land footprint. However, this footprint is inclusive of energy needs, can be sensitive to land availability, and may be collocated with other land uses.

As DACCS processes require significant energy, facilities will to require a large land area for the deployment of renewable energy resources – these have been modelled in Section 4.

NSW generally has high land availability, particularly in regional areas. NSW is well placed to deliver DACCS land needs on this basis, noting that land use planning will be important to ensure deployment is sensitive to local community needs and concerns.

Storage capacity

NSW has suitable storage capacity to deliver DACCS. Potential storage capacity includes:

- **Geological storage in deep saline aquifers**: Preliminary exploration (Stage 1b) under the Coal Innovation NSW's CO_2 storage assessment program has found theoretical storage potential of up to 555 million tonnes in the Darling Basin.

  This capacity is currently being explored in more detail in a second stage drilling program. Additional unexplored potential, although likely at lower capacity, may be available in other sub-basins of the Darling, in Gunnedah Basin or in Oaklands Basin.
- **Ex-situ mineralisation with mafic and ultramafic rocks**: NSW has strong availability of the required rock materials for carbon mineralisation, as described in Appendix A.
- **Mineralisation and use**: NSW has strong availability of industrial waste for mineralisation and use, as described in Appendix A.

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Appendix C – BiCRS

This Appendix provides an expanded technical description of biomass carbon removal and storage as discussed in this report.

Overview of BiCRS

Biomass carbon removal and storage refers to CDR processes that:

- Use biomass to remove CO_2 from the atmosphere,
- Store that CO2 underground or in-long-lived products, and
- Do no damage to food security, rural livelihoods, biodiversity conservation and other social and environmental values [52].

BiCRS is a broadening of the better-known term BECCS – bioenergy carbon capture and storage, which was first proposed 25 years ago and has been included in the IPCC's integrated assessment modelling since 2007 [170]. BiCRS includes BECCS alongside include a broader set of processes for biomass-based removal and storage.

BiCRS was coined in the Cool Earth Forum's BiCRS Roadmap, which articulates two reasons for this change [52]:

- **It refocusses the method on CDR**: Where BECCS emphasises bioenergy, BiCRS refocusses the method on the removal of carbon. The Roadmap notes that at many carbon prices, the value of carbon removal is more valuable than the production of energy, as most biomass has high carbon but poor energy values. BECCS plants designed to optimise energy production and BECCS plants designed for CDR will look different and have different carbon capture rates [60].

- **It captures emerging implementation options**: BiCRS captures a broader range of carbon removal options that do not include bioenergy that do not fit in conventional but share biomass as a removal agent. These include but are not limited to:
  - Use of long-lived wood products like oriented strand board
  - Conversion into bio-oil via fast pyrolysis for geological storage
  - Conversion into biochar via slow pyrolysis for storage or agricultural applications, which is typically represented as an alternate method to BECCS

While biochar is included under BiCRS, we note that this is out of scope for this report

BiCRS is distinct from afforestation and reforestation methods, which use biomass but do not include durable storage. Under these methods the carbon is not removed from the fast carbon cycle and once the trees die stored carbon is re-released. BiCRS achieves much longer permanence, with implementation options using geological sequestration returning captured carbon to the slow carbon cycle.

Key considerations for BiCRS include:

- It is at **high levels of technological readiness**. It utilises a natural capture mechanism (photosynthesis and production of biomass) and many conversion technologies (for example fermentation for bioenergy, pyrolysis, production of wood products) are at high levels of technological readiness. There are extant large-scale demonstrations of many bioenergy BiCRS processes, for example production of bioethanol and geological storage of captured CO_2 [51].
- It is **low cost** today relative to methods like DACCS [110].
- Some BiCRS may attract **additional revenue streams** from the production of energy and long-lived products.
- BiCRS products can **utilise existing biomass wastes**, including agricultural, forestry and municipal wastes.
- Attaching carbon value to biomass has a risk of perverse outcomes like **competition for land** against food production and **indirect land use change**, which may inadvertently lead to net positive systems emissions [60]. This can be managed by limiting BiCRS to waste products (biomass residues) or strategic siting of on degraded or low-value agricultural land.
- BiCRS processes producing fuels like for example bioethanol may **slow other pathways** to emissions reductions in relevant sectors like transport electrification.

BiCRS implementation options

There is wide variation across BiCRS implementation options. Key points of variation include:

- **Feedstock:** Different biomass feedstocks have different moisture, carbon and chemical compositions, require different pre-treatment, and are suitable for different conversion processes. Common and emerging feedstocks include:
    - Wastes, including agricultural, forestry, municipal wastes
    - Purpose grown energy crops
    - Forestry inputs
    - Emerging inputs like micro- and macroalgae; note these vary by moisture, carbon and other chemical composition so have different needs
- **Conversion process**:
    - Biochemical conversion, for example the use of microorganisms like yeast and bacteria for fermentation
    - Thermochemical conversion, i.e. controlled heating and decomposition into liquid, gaseous and solid byproducts in processes like gasification, pyrolysis, liquefaction
    - Manufacturing processes to produce long-lived wood products.
    - Selection of a suitable conversion process depends on the composition of the feedstock input. Figure 26 below shows interrelation between common feedstocks and conversion technologies [171].

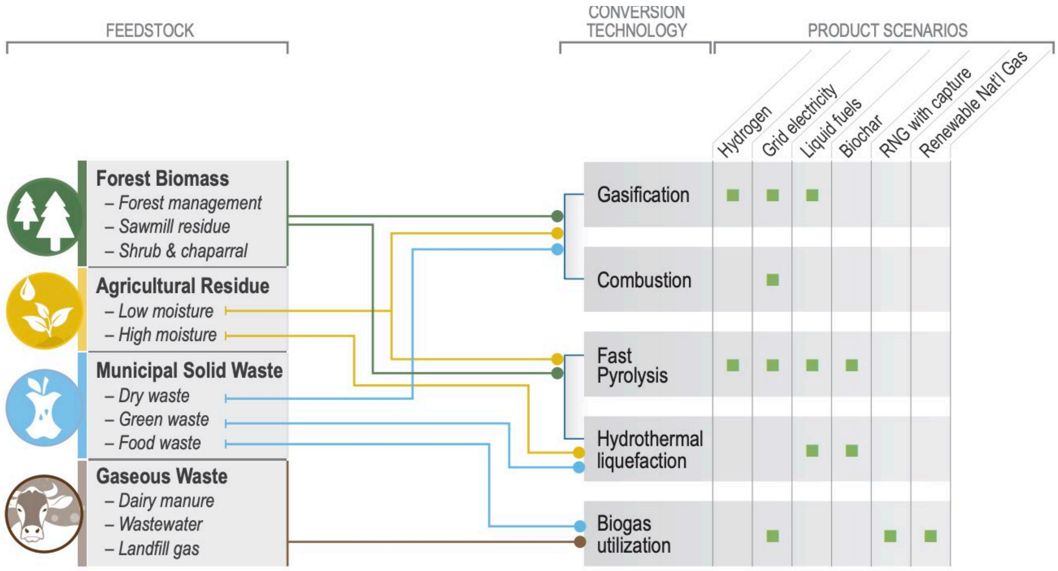

Figure 26: Relationship between BiCRS feedstocks and conversion processes [52]

- **Carbon separation**: Again, the requirements for carbon separation are highly dependent on the conversion process used. Processes include:
    - Conventional solvent for flue gas capture, i.e. point source capture for combustion of biomass. Note that there are ash handling challenges for CCS technology for some biomass feedstocks.
    - Pyrolysis to produce and store biochar or biooils

- Separation of pure CO_2 as a byproduct from fermentation
- Compression and separation of landfill and digester biogas

- **Storage pathway**:
    - Geological storage (compressed CO_2 or bio oil)
    - Concrete and other long-lived product storage (CO_2 or biofibers)
    - Wood product storage
    - Application to farmland (biochar)
    - Biomass sinking (mariculture, i.e. cultivation of aquatic biomass)

NSW biomass availability

NSW has strong biomass availability, as identified under the ARENA's Australian Biomass for Bioenergy Assessment (ABBA) study.

The majority of biomass waste in the state is agricultural cropping waste (12.2M dry tonnes) – a popular feedstock for BiCRS processes – with considerable secondary volumes of organic waste (municipal solid waste, commercial and industrial waste and construction and demolition wastes, for example wood, 6.59 DT). NSW has smaller volumes of forestry (2.2DT), livestock (manure, 1.26M) and horticulture waste (0.16MT).

Table 15: NSW biomass waste production volumes

Group	Category	Volume (dry tonnes)
Cropping (2013-2018 FY average)	Cereal Straw	8.41M
	Non-cereal straw	1.97
	Hay and silage	1.2M
	Sugarcane residues	511K
	Rice hulls	108K
	Cotton gin trash	41.K
	Total	12.2M
Organic waste (2015-2018 FY average)	Municipal solid waste	3.16M

	Commercial and industrial	2.6M
	Construction and demolition	837K
	Total	*6.59M*
Forestry (2011-2015 CY average)	Harvest residues	1.55M
	Sawmill residues	701K
	Total	*2.25*
Livestock (2013-2018 FY average)	Manure residues – *total*	1.26M
Horticulture (2013-2018 FY average)	Winery residues	0.12M (wet tonnes)
	Nut residues	0.04M
	Total	0.16M

Interviews with domestic bioenergy experts suggested there may be structural underestimation in self-reported agricultural ABBA data, so these numbers may give a conservative picture of NSW's biomass availability.

While lot of BiCRS projections assume total availability of waste for these processes at low cost, there are likely limits to total useable waste for BiCRS purposes, including:

- **Limits to sustainable sourcing of agricultural waste:** Some agricultural waste needs to be retained on farm for soil health and to prevent nutrient loss. While there is no agreed definition of sustainable sourcing of farm biomass waste, one major BiCRS company in the US using agricultural waste leaves 50% of waste on farm to ensure sustainability.
- **Changing waste volumes:** These waste volumes are not static year-to-year, and will vary in response to climactic variation (especially cropping, forestry waste – likely cyclical variation) and policies and programs to reduce waste volumes through supply chain efficiencies (especially organic waste, i.e. municipal, commercial and industrial, and construction and demolition – likely reduction in volume over time).
- **Location of biomass:** Not all biomass will be suitably located for BiCRS. While innovations like modular pyrolysis reduce transport requirements for biomass, some proportion of waste will not be economical to transport or reach with modular units.
- **Competition for biomass:** BiCRS is likely to see competition for waste from other industries or applications, increased composting of organic waste, circular economy applications for cropping and horticultural waste (for example production of low-emissions

agricultural inputs), use in other applications that require carbon-based input (steel production, synthetic aviation fuel). Competition is likely to limit waste availability and may add cost to sourcing.

NSW CDR potential

We have estimated indicative removal potential for NSW of **up to 7MT annually**. This uses Charm Industrial's average fast pyrolysis conversion rate, which yields 0.85t CO_2 removed per tonne biomass input [112], and assuming constraints on availability due to sustainable sourcing of farm biomass and competition with other industries.

Table 16: Indicative CDR potential from NSW biomass waste

Group	Assumed availability	CDR potential
Cropping	25%	2.6MT
Organic waste	50%	2.8MT*
Forestry	50%	0.96MT
Livestock	50%	0.54MT*
Horticultural	50%	0.07MT
Total		*6.97MT*

*Values given for municipal and livestock waste are illustrative only – while these wastes can by pyrolised [113] [114], they are not part of the current Charm process are likely to have different carbon conversion rates.

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Appendix D – modelling approach

This Appendix outlines the modelling approach used to assess costs of various direct air capture and mine-site enhanced weathering implementation options in New South Wales.

Modelling approach

Modelling can identify the major drivers of costs that policy can target: real world costs of nascent technologies will not be known without deployment

Government support will be needed to achieve the speed and scale requirements of CDR deployment. Policymakers will need to design catalytic policies and programs that unlock major barriers to both speed and scale. However, like with all nascent technologies and industries, policymakers will need to design mechanisms with imperfect information. As discussed throughout the report, there are many unknowns related to several CDR methods, and many of these unknowns translate into unknown costs.

The costs of some novel CDR methods and implementation options are unknown due to the nascent nature of the technologies, which can combine both mature and novel components and materials. The challenge for policymakers is to keep moving forward with sufficiently targeted policy in this context. To this end, the purpose of this modelling is not to try and speculate exact costs – we know from extensive consultation that costs can be understood at an order of magnitude level currently, but for highly novel approaches, they are not known with greater precision with meaningful confidence levels. Rather, this modelling aims to understand likely major cost drivers and how widely they might vary across implementation options so that policy can target interventions across different major cost drivers that will provide the greatest long-term benefits.

We note this modelling focused largely on the physical deployment of implementation options, without including many considerations that ultimately translate into business cost that we have discussed qualitatively throughout the report, for example the costs related to social licence, regulatory and planning processes, and costs of capital.

Technoeconomic assessments were carried out to analyse the economic drivers of selected mine-site enhanced weathering and DAC implementation options. The assessments estimated the economic drivers of two overarching implementation options for both methods, with different scenarios assessed within these options to understand sensitivities and drivers, as well as the application of learning rates.

A combination of reduced energy prices through the energy transition, economies of scale and further technological/efficiency progress is expected to reduce costs. The aim of this model is to understand the most significant cost dynamics, and the potential magnitude of cost reductions. Once these dynamics have been understood, suitable policy levers can be identified which best unlock progress.

Approach to data and assumptions

A broad range of sources were used for this analysis, including:

- Consultation with domain experts
- Academic literature
- Market reports and literature (NSW where available)

We have used real cost data where possible:

- Energy pricing is based on long term energy costs for the modelled scenarios at scale (2030 for enhanced weathering and 2050 for DAC), as we heard from interviews the timeline for large scale deployment is long term, particularly for DAC (interviewees noted mine site enhanced weathering may be scaled faster).
- Land costs are based on present land value of selected NSW regions which have likely have suitable characteristics for the implementation option.
- Mining costs, cost of sorbent / solvents are all based on current available prices (see further discussion below regarding uncertainties).

Approach to technological uncertainties

As discussed, due to the nascent nature of these technologies and the industry, there are costs that can be known with higher confidences and costs that are inherently difficult to precisely estimate due to novelty, which many interviewees stressed during consultation. Hence, the purpose of these models was not to deliver specificity (or false precision) on exact costs, but rather to understand what the major cost drivers are and how they interact with scale and changes through energy transition- such as a shift in energy and storage prices. These inputs have been taken from estimates provided by interviewees and triangulated with other academic papers, or sources such as Frontier and Stripe publicly available procurement documents, who are market leaders in carbon removal purchases.

Further, in a small number of cases, model inputs were on attributes of scale deployment scenarios for which references pilot scale case studies were not available (particularly collector height and density limits for DAC and EW enclosed facility implementation options). In these instances, we derived hypotheses on parameter values to test based on plausible scenarios derived from interview insights. These are identified as "tested parameter derived from interviews".

A sensitivity was run on cost buckets which carried the highest level of uncertainty; hence the output of the model is to deliver a range of costs at each scale.

Major uncertainties are distributed across technological parameters, which then translate to costs. Uncertainties will decrease with deployment, including spill over lessons from international projects for technology costs, along with lessons learnt from the real-world projects already underway in Australia.

Direct air capture and storage

Model overview

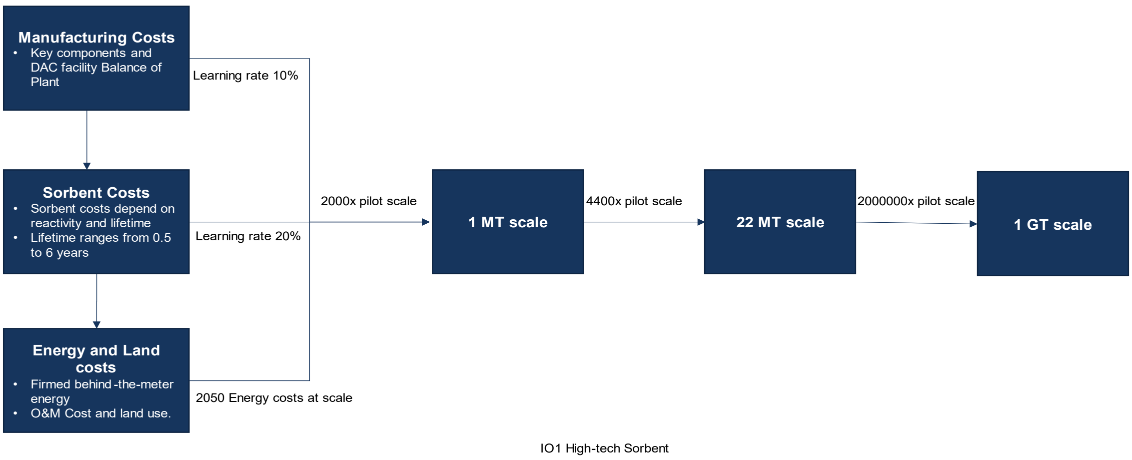


Figure 27: IO1 High tech sorbent model outline

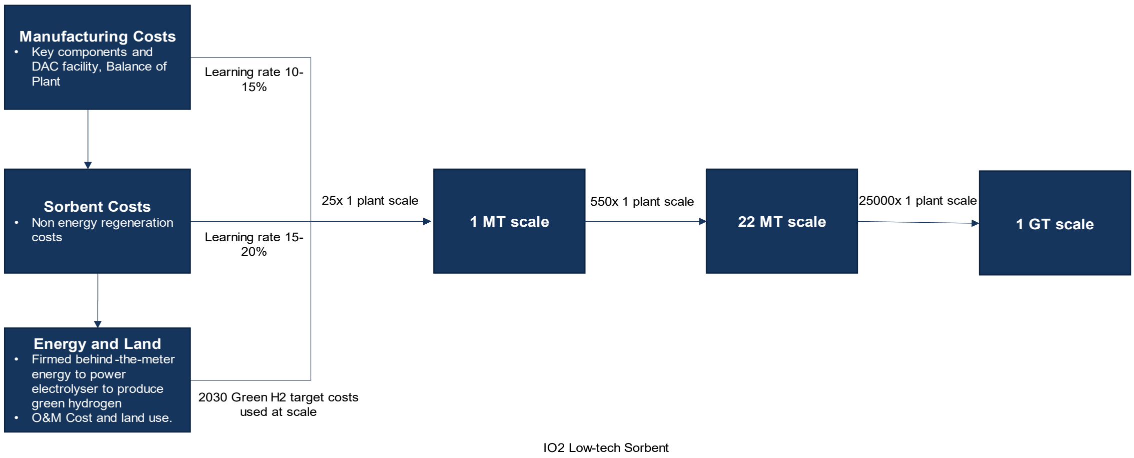


Figure 28: IO2 Low tech sorbent model outline

We performed two technoeconomic assessments for DAC, for two diverse implementation option. These implementation options are based on a number of real-world start-ups that were interviewed. These two implementation options have limited crossover in resources and inputs, so could both be applied at scale in NSW. In these models, both have been applied to New South Wales specific scenarios. The cost input for the pilot scale DAC plants was assumed to be US$1000 per tonne of CO_2, as this is the price estimated by a number of start-ups on proposals for Stripe and Frontier Advanced Market Commitments for full pilot scale deployment (not lab scale). We used pilot scale as the starting point for this analysis. We note precise pilot costs are commercially sensitive, so this was used as a best endeavours proxy. We have also applied sensitivities around key uncertainties, due to the variability across pilot plants. This was used instead of bottom-up price calculations due to a lack of available and consistent data on pilot costs.

Geological storage

Our modelling uses a storage estimate of 550Mt.

Energy requirements associated with injection and compression of CO_2 were sourced from independent studies on carbon capture and storage using enhanced oil recovery. Geo sequestration cost at well head was estimated using cost data provided in interviews by an Australian carbon storage company. Capital cost of compressors was based on sizing compressors according to energy required for compression. And finally, opex for land rental cost was a function of the area of each well head, the capacity of each well and land value in marginal land.

With regards to piping, piping costs only include the capital cost of polyethylene pipes and does not account for other cost buckets such as social licensing and encasement costs etc. The optimal pipe diameter at flow rate of filling 1 MT of CO_2 at storage site per year was calculated using an optimized hydraulic diameter equation, which is a cost optimization equation. The inputs for this equation are viscosity, density of CO_2 at inlet and outlet pressure and volumetric flow rate of CO_2. Using the optimized diameter, the cost per km of polyethylene piping was used across the transport distances considered.

Mine site mineral carbonation

Model overview

Mineral carbonation aims to significantly accelerate the reaction of silicates in mined ultramafic rock with CO_2 to form stable carbonates. This model estimates the potential and cost of carbon removal using various mineral carbonation options at an archetypal mine site in NSW.

The primary scenario settings for each implementation option are outlined in Table 41.

Table 41 Major scenario settings for mine site mineral carbonation model

Assumption	MC IO1 – integrated process with mechanical acceleration	MC IO2 – integrated process with enclosed facility weathering	MC IO3 – Purpose mine with mechanical acceleration	MC IO4 – Purpose mine with enclosed facility weathering
Mine construction and operation	×	×	✓	✓
Mineral preparation	✓	✓	✓	✓
Mechanical acceleration	✓	×	✓	×
Enclosed facility process	×	✓	×	✓

For all implementation options, mined rock is diverted from the business as usual tailings storage through a two stage mineral carbonation process. The first stage involves thermal activation to increase the reactivity of the rock. The second stage varies between implementations, with the activated rock weathered either in sealed tailings pits with mechanical acceleration or in a purpose-built enclosed facility. For all options the carbonated rock is stored on the mine site per business as usual.

This section details the modelling approach and assumptions for all implementation options for the four major calculation steps in the model:

- **Mining activities** – estimating the amount and type of rock available for enhanced weathering, and (for purpose-built implementation options) the costs associated with developing and operating this mine.
- **Thermal activation** – estimating the increased reactivity of the activated rock, the energy required for activation, and associated capital and recurrent costs.

- **Enhanced weathering process** – estimating the amount of carbon capture from the enhanced weathering process used for each option, and the associated land, capital and recurrent costs.
- **Electricity use costs** – assumes that the energy used for the process is met with purpose-built renewable energy with battery storage.

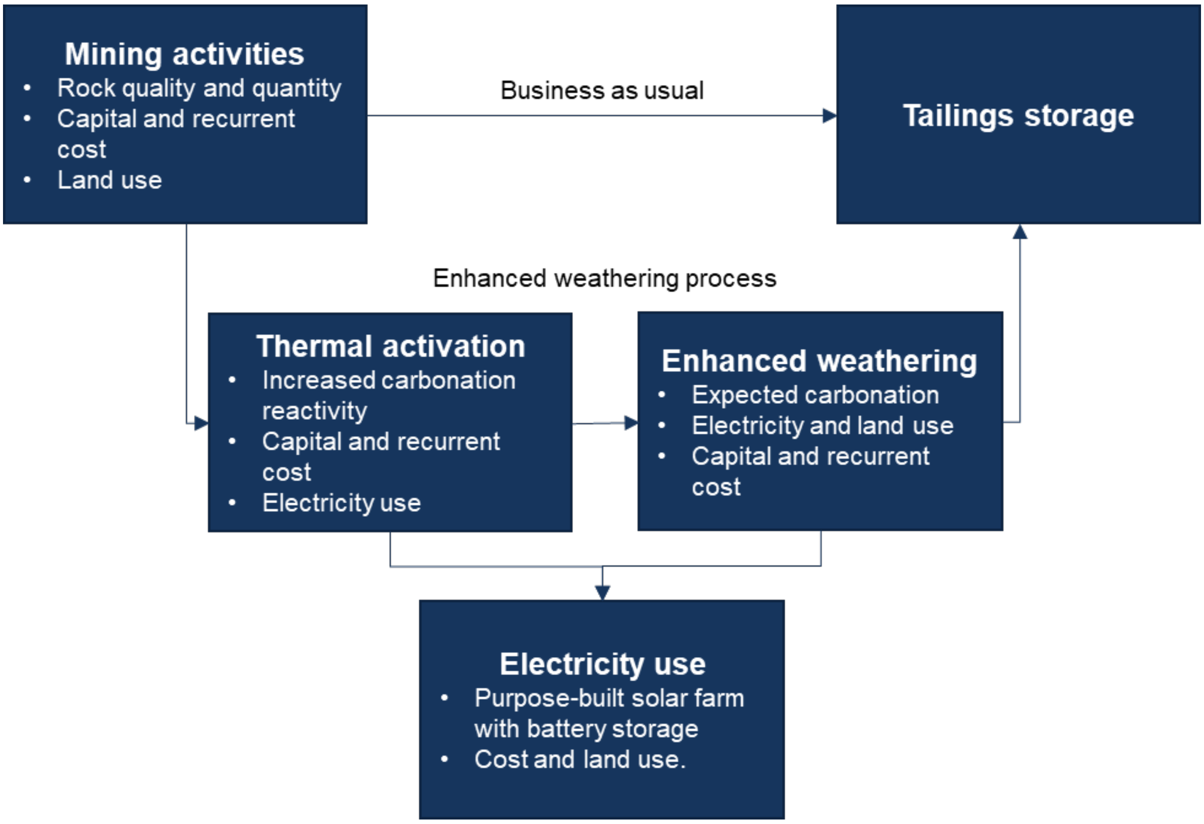
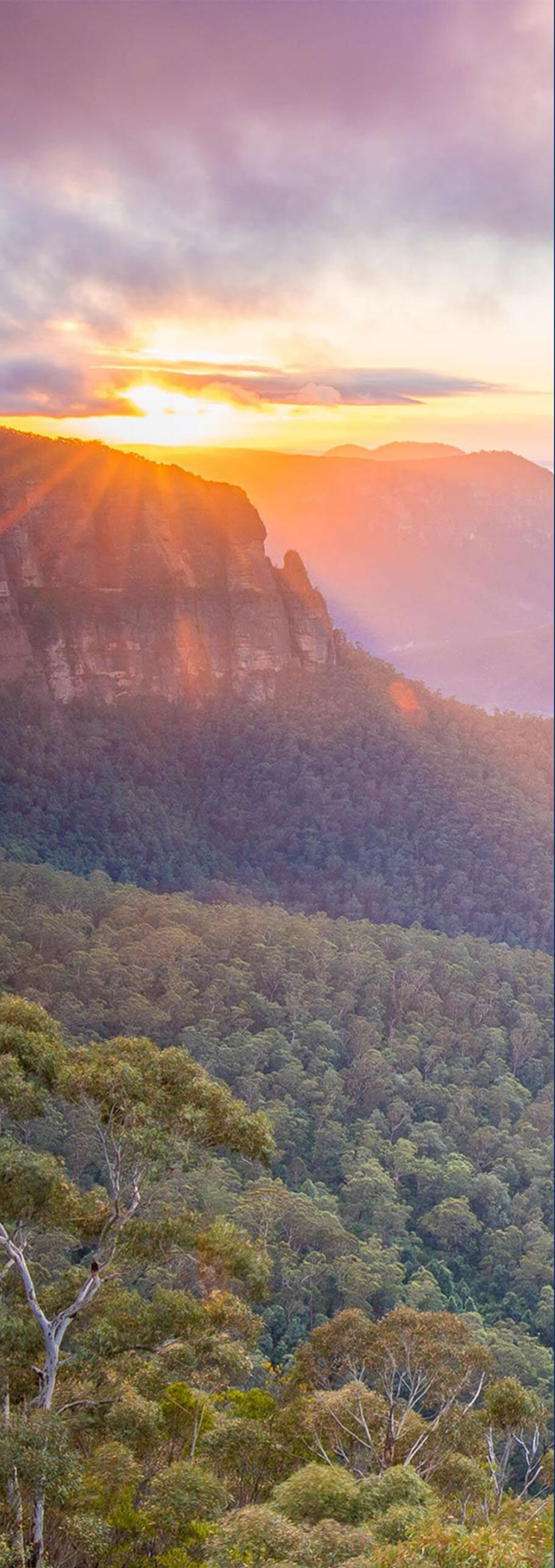


Figure 29 Enhanced weathering model outline



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