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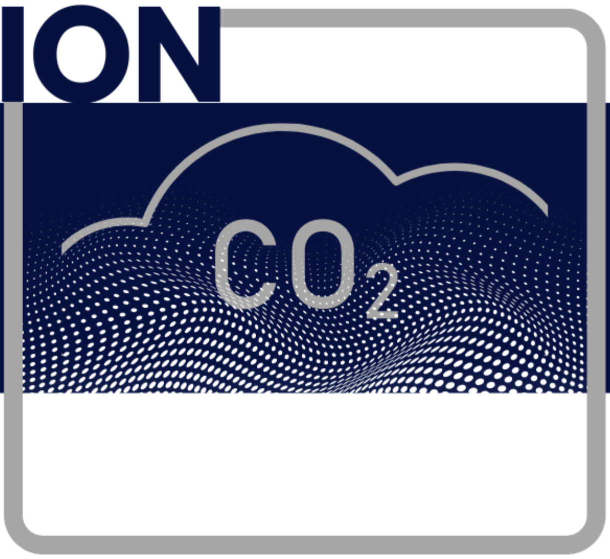
Minerals Research Institute
of Western Australia

MINERAL CARBONATION



A Roadmap to Decarbonise Western Australia Through Integrated Mineral Carbonation

Report collaborators

This report addresses the MRIWA Mineral Carbonation focus area and our commitment to the use of minerals research to benefit Western Australia. We thank Curtin University and Australian Venture Consultants for their detailed insights and analysis.

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Ministerial Foreword

For well over a century, Western Australia has been a world-leading supplier of various mineral products, underpinning the major economies across the globe. Just as the State has facilitated global economic expansion in this regard, the legacy waste products from this mining and processing activity now presents Western Australia with an opportunity to perform an even more significant role in the sequestration of carbon dioxide produced not only from domestic emitting industries, but also those industries globally.

Accelerated mineral carbonation technology, whilst still at relatively early stage of development, is an opportunity for State and industry to pursue to convert very large legacy stockpiles of mining and processing waste into sequestration assets. By using either carbon dioxide captured directly from emissions sources, or extracted from the atmosphere, to carbonate the minerals in those stockpiles, it is possible to sequester that carbon on a relatively permanent basis. In Western Australia, this can be achieved at a gigatonne scale.

To further explore and develop this opportunity, the Western Australian Government has, through the Minerals Research Institute of Western Australia (MRIWA), commissioned the development of this Mineral Carbonation Roadmap for Western Australia.

The Roadmap provides a science and technology, economic assessment, social and environmental and regulatory development pathway to de-risk the prospective development of a future mineral carbonation industry in Western Australia.

Through MRIWA, the Western Australian Government will facilitate and support collaboration between government, industry, academia and communities, including First Nations communities, to realise the objectives of the Roadmap.

Hon. David Michael, MLA
Minister for Mines and Petroleum

Contents

Executive Summary

While global growth in renewable energy capacity over recent years has been significant, it has become very clear more is needed to avoid increases to CO_2 emissions that will ultimately result in global warming reaching dangerous levels. CO_2 sequestration will be an instrument of increasing importance in the decarbonisation toolbox.

Accelerated mineral carbonation is an emerging sequestration technology, whereby CO_2 is reacted with metal-bearing materials, ultramafic rocks or alkaline waste and by-products in an engineered environment that mimics and accelerates the natural process of weathering, permanently locking the CO_2 as a carbonate product.

Ex-situ accelerated mineral carbonation achieves this using alkaline minerals in the form of mine gangue or tailings from mineral processing operations as the feedstock for the carbonation process. The CO_2 feedstock can be sourced from a point source of emissions or potentially via direct air capture technology to remove CO_2 from the atmosphere.

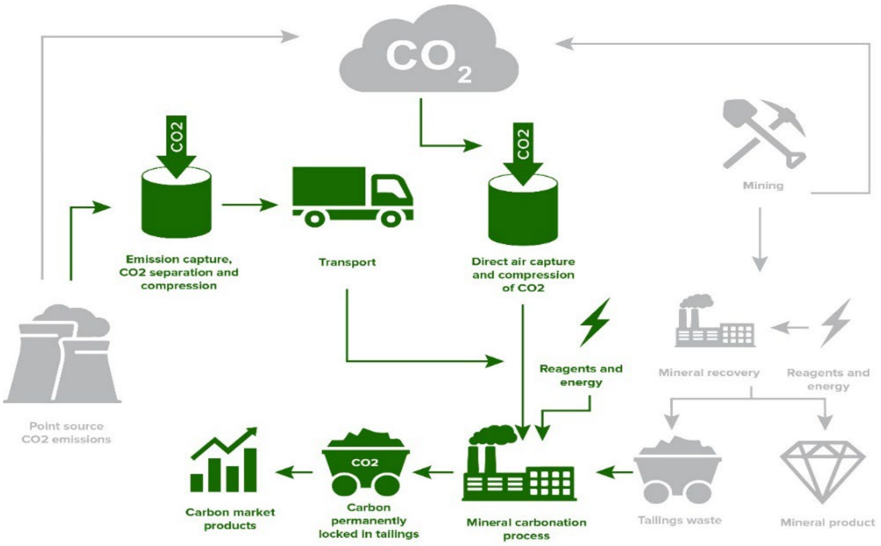
For over a century, Western Australia's minerals industry has provided feedstock to domestic and international, particularly Asian, metal manufacturing industries – industries that, by their nature, have significant emissions profiles.

Now these legacy waste streams – gangue and tailings – from Western Australian mining industry sectors provide an opportunity to permanently sequester CO_2 at the gigatonne scale using ex-situ mineral carbonation technology.

This Roadmap sets out a coordinated program of work to enable accelerated ex-situ mineral carbonation in Western Australia across four themes: science and technology, economic viability, social and environmental impacts and policy and regulatory needs.

Developed following a comprehensive literature review, together with extensive consultation with over 100 experts in mineral carbonation and related fields from across the globe, the Roadmap sets out, at a thematic and programmatic level, a plan to deliver an ex-situ mineral carbonation industry in Western Australia.

Figure ES1. High-level accelerated ex-situ mineral carbonation value chain



The case for governments and industry to invest in mineral carbonation in Western Australia is clear

Significant domestic decarbonisation targets need to be met…

The Australian and Western Australian Governments, as well as the mining industry have set clear and ambitious net emissions reduction targets, and the achievement of these targets will require sequestration to be part of the solution.

Western Australia faces a challenging energy transition paradigm…

Western Australia's rising emissions, electricity generation and heavy industry reliance on fossil fuels present a challenging domestic energy transition paradigm. While renewable generation will continue to grow in the State, this paradigm will result in long tail of natural gas dependency. The emissions generated from this dependency will need to be sequestered.

Western Australian research organisations and mining companies are leaders in the emerging global mineral carbonation community of practice…

Native capability in mineral carbonation science and related areas of scientific endeavour within the State's research organisations and industry is world-class.

Western Australia is a significant producer of critical minerals that will be more competitive if their waste products can be used to offset whole-of-supply-chain emissions…

The gangue and tailings highly suitable for ex-situ mineral carbonation are those associated with class 1 nickel production. This critical mineral is the feedstock for supply chains producing clean energy products such as electric vehicle batteries. The supply chains producing such products increasingly seek evidence of whole-of-supply chain emissions reduction.

Mineral carbonation presents a de-risked pathway to economic diversification…

Mineral carbonation presents an opportunity for the State to leverage off its significant minerals industry capability and assets, presenting a less risky pathway to economic diversification.

Mineral carbonation is an opportunity for First Nations economic participation…

Because most of the suitable gangue and tailings resources reside on First Nations traditional lands, mineral carbonation provides a potential economic opportunity for Western Australian First Nations.

Table ES1. Western Australian Mineral Carbonation Roadmap Themes and Programs

Themes	Programs	Sub-programs
Science and Technology Development of the basic and applied scientific research and technology required to deploy systems.	1. Target tailings and gangue characterisation	1.1 Standardised framework for assessing suitability for mineral carbonation
		1.2 Identification of priority mineral carbonation resources
		1.3 Selection of optimal resource(s) for pilot plant
	2. Pilot plant design and development	2.1 Process suitability decision tree
		2.2 Process design optimisation
	3. Direct air capture	3.1 Process feasibility
		3.2 Low-energy contactors for DAC system
		3.3 Point source capture and transportation as an interim solution
	4. Mineral carbonation and by- and co-products	4.1 By- and co-product identification
		4.2 By- and co product manufacturing systems
		4.3 By- and co-product LCA
Economic Viability Systems and product requirements for economic viability.	1. A financial framework for mineral carbonation in Western Australia	1.1 Marketability and associated pricing of products arising from carbonation process
		1.2 Beneficial offsets
		1.3 Capital cost, revenue and operating cost estimations
	2. Innovation in carbon credit markets	2.1 Application of derivatives
		2.2 Market integration
	3. Carbon embedded product innovation	3.1 New product opportunity scoping
		3.2 Market assessment
		3.2 Manufacturing assessment
Social and Environmental Effective management of positive and negative social and environmental externalities.	1. First Nations engagement	1.1 Social, cultural, and environmental impact mapping
		1.2 Traditional Ecological Knowledge (TEK) application framework
		1.3 Commercial frameworks for First Nations partnerships
	2. Community engagement	2.1 Socio-economic impact mapping
		2.2 Socio-economic multiplier analysis
		2.3 Socio-economic impact modelling
	3. Environmental impacts	3.1 Waste streams
		3.2 Tailings storage facility integrity
		3.3 Gangue and tailings as refugia
Policy and Regulation Policy and regulatory reform required to give effect to a mineral carbonation industry.	1. Policy case evidence	1.1 Industry development level economic impact modelling
		1.2 CO_2 abatement modelling
	2. Regulatory compliance and reform pathway	2.1 Inventory and analysis of Western Australian and Commonwealth legislation and regulations and associated policy and guidelines
		2.2 Reform and reform pathways
	3. Innovation in offsets regulation	3.1 Australian offsets products
		3.2 Emissions Lifecycle Assessment framework innovation
		3.3 Carbon embedded products

Introduction and Background 1

1.1. Overview

Recognition of climate change and the potentially catastrophic effects of global warming has accelerated over recent years.

However, despite the extent of scientific evidence as to the anthropogenic drivers of global warming, very significant investment in renewable energy and emissions reduction technology and multilateral international agreements to set policy to decarbonise the global economy, the current trajectory of global carbon dioxide (CO_2) emissions is such that global temperatures will rise to dangerous levels within this century.

It is abundantly clear global warming can only be contained through the deployment of renewable energy alone. Substantively compromising economic growth and, therefore, the well-being of humankind. While the energy transition from hydrocarbon fuels to renewable resources will remain the key driver for averting a climate disaster, in the medium term, this must be coupled with effective emissions capture at the point source, atmospheric CO_2 removal and permanent sequestration.

Technological solutions that mimic and accelerate the natural processes through which minerals form carbonates by absorbing atmospheric CO_2 using various waste products from mining and minerals recovery processes as the sequestration resource (known as mineral carbonation) have the potential to sequestrate carbon relatively permanently at gigatonne scale.

Meeting emissions reduction targets will be extremely challenging.

The growth of renewable energy over the past decade has consistently and dramatically outperformed nearly all expectations[1]. Driven by more robust government decarbonisation policies and evermore ambitious targets on the part of government and the private sector, the International Energy Agency estimates the current global capacity of renewables at 290 gigawatts (GW). It expects this capacity to increase to 4,800GW by 2026, a generation capacity equivalent to the present total hydrocarbon and nuclear generation facilities today. [2]

As impressive as this growth is, as illustrated in Figure 1, it is expected to be inadequate to reduce increased global carbon dioxide and other greenhouse gas emissions.

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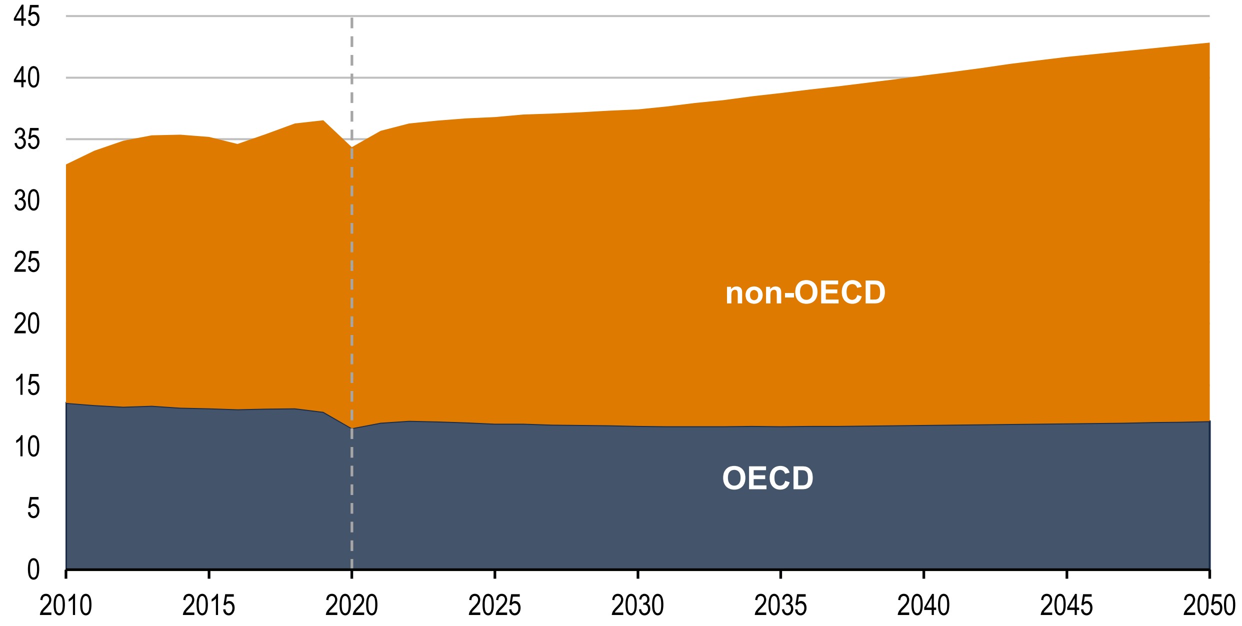
[1] Heineke, F., Janecke, N., Klarner, H., Kuhn, F., Tai, Humayan and Winter, R. (2022), Renewable- energy development in a net-zero world, McKinsey Electric Power & Natural Gas Practice, McKinsey & Company

[2] Conference of the Parties, Adoption of the Paris Agreement, December 12, 2015, UN Doc FCCC/CP/2015/L.9/Rev/1 (Dec 12, 2015)

Figure 1. *Global energy-related carbon dioxide emission (2010 to 2050)*[3] [4]



This predicament is driven by various factors, including the industrialisation of the developing world, switching costs and technical and economic limitations which constrain the ability of renewable energy systems to deliver dispatchable baseload energy.

These emission forecasts exist in a context whereby through multilateral agreements, policy, and legislation, national and sub-national governments and industries have set targets for mitigating global warming. Those targets are most relevant to Western Australia are summarised in the Table 1.

The principal instrument in the framework set out in Table 1 is the Paris Agreement, under which the parties have agreed to undertake rapid emissions reduction efforts by the best science, including emissions removal systems.

However, in its most recent assessment of progress, the United Nations Environmental Program determined the parties to the Paris Agreement remain significantly off track to meeting even the less ambitious objective of limiting global warming to 2°C above pre-industrial levels, with current policy settings projected to result in global warming of 2.8 °C over the course of this century.

To return to a trajectory where a temperature rise in the range of the Paris Agreement objectives is achievable, a 30 to 45 percent reduction in current emissions is required.[5] This will require a fundamental change to how emissions are managed.

> *'…incremental change is no longer an option: broad-based economy-wide transformations are required to avoid closing the window of opportunity to limit global warming to well below 2°C.'*[6]

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[3] US Energy Information Administration, International Energy Outlook 2021, Reference Case, October 2021 https://www.eia.gov/outlooks/ieo/

[4] NOTE: OECD is the Organisation for Economic Cooperation and Development

[5] United Nations Environment Programme (2022), The Closing Window: Climate crisis calls for rapid transformation of societies, United Nations

[6] Ibid, 5

Table 1. Emission reduction targets and instruments of relevance to Western Australia

Agreement	Target(s)	Parties	Instrument
Paris Agreement[7]	Limit global temperature increase this century to no more than 2.0 °C above pre- industrial levels, with an aspirational target of no more than 1.5 °C.	193 nation states (including Australia) and the EU, representing 98 percent of global greenhouse gas emissions.	Multilateral agreement ratified by national governments and parliaments that are party to the Agreement
Australian Government[8]	43 percent reduction on 2005 emission levels by 2030.	Australian government agencies and instrumentalities	*Climate Change Act 2022* (Cth)
Western Australian Government[9]	Net zero emissions by 2050	Western Australian Government agencies and instrumentalities	Policy
Australian Mining Industry[10]	Net zero emissions by 2050	Members of the Mineral Council of Australia	Aspirational agreement

With the People's Republic of China (PRC), the United States and India collectively representing over 50 percent of Scope 1 emissions in 2020, accountability is highly concentrated. However, Australia is not an insignificant emitter, with its 1.12 percent global emissions making it the World's 15th largest emitter.

Further, representing only 0.33 percent of the worldwide population, Australia's emissions are high from a per capita perspective, which is the result of the nation's:

- Energy generation profile - 75 percent of Australia's energy is produced from the combustion of black and brown coal and energy generation accounts for 78 percent of Australia's emissions;
- Emissions-intensive industry - industrial processes account for a further 20 percent of the nation's emissions.[11]

Coal-fired electricity generation currently accounts for less than 10 percent of Western Australia's energy mix and by 2030 will not be a component of the State's energy mix under current State Government Policy.[12.]

However, energy generation and industrial processes still account for 88 percent of Western Australia's emissions, the highest level in the nation. This is indicative of the significant dependency Western Australia and its industry has on natural gas as its primary energy source, accounting for nearly 55 percent of energy requirements across Western Australia.[13]

Within Australia, Western Australia is the equal third largest emitting jurisdiction on both a total and per capita emissions basis. This is illustrated in Figure 2.

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[7] Ibid, 2

[8] Climate Change Act 2022 (Cth)

[9] Western Australian Climate Policy: A plan to position Western Australia for a prosperous and resilient low-carbon future (2022), Western Australian Government, Perth

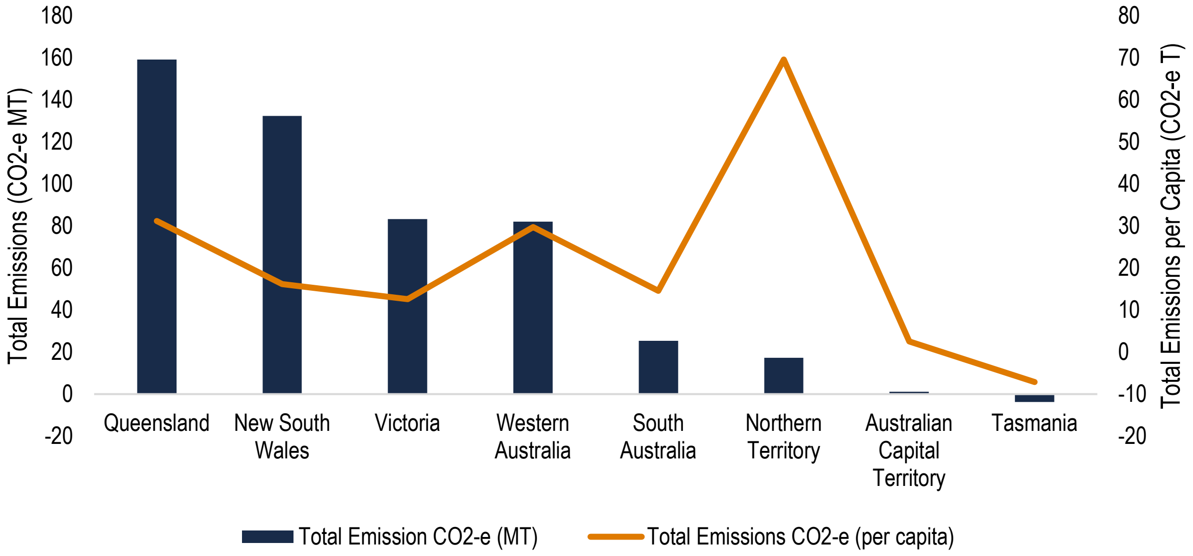
[10] Minerals Council of Australia (2021), Climate Action Plan, Minerals Council of Australia, Canberra

[11] Department of Climate Change, Energy, the Environment and Water (2022), Australia's National Greenhouse Accounts, Australian Government, Canberra

[12] McGowan, M. and Johnston, B, (2022), State-owned coal power stations to be retired by 2030, Media Statement (14 June), Department of Premier and Cabinet, Western Australian Government

[13] Ibid, 12

Figure 2. Australian jurisdictional emissions – total and per capita (2022) [14]



Facilitated by government and private investment in distribution infrastructure and the State's natural gas domestic reservation laws, Western Australia has capitalised on its significant natural gas endowments, facilitating an energy-intensive industry with a lower per unit emissions profile than the Eastern States.

While increased adoption of renewable energy platforms (currently accounting for around 2.5 percent of energy generation in Western Australia) will fill some of the supply gaps, the Western Australian Government's plan to retire all coal-fired generation in the State by 2030 will likely further increase demand for natural gas generation over the medium term and the carbon emissions from this will need to be offset.

1.2. What is Mineral Carbonation?

A naturally occurring process of carbon sequestration.

Around 99.8 percent of carbon on Earth – 1.8 billion gigatonnes – is stored and fixed in the Earth's crust, mantle, and core.[15]

Most of the carbon in the Earth's lithosphere exists in the form of hydrocarbons and carbonated minerals such as limestone, which is formed naturally through a process known as silicate weathering, whereby silicate minerals serve as the source of alkaline and alkaline-earth metals that naturally consume atmospheric CO_2 forming solid carbonate minerals.

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[14] Ibid, 11

[15] Suarez, C., Edmonds, M. and Jones, A. (2019), 'Earth catastrophes and their impact on the carbon cycle,' Elements, 15(5), 301-306

Weathering alkaline rocks is a geochemical process that occurs on a geological time scale.[16] Natural weathering is estimated to remove nearly 1.1 gigatonnes of carbon in the form of CO_2 from the atmosphere per annum and predominately stores it as bicarbonate ions in oceans or solid carbonate minerals.[17]

1.2.1. Accelerated Mineral Carbonation

Geochemical negative emission technologies such as accelerated mineral carbonation seek to harness and accelerate the natural weathering process.

The captured CO_2 is reacted with metal-bearing materials, ultramafic rocks or alkaline wastes/by-products from some industrial activities to form stable insoluble carbonate minerals, thereby 'permanently' locking atmospheric carbon in this carbonate product.[18]

It is a relatively permanent and safe form of sequestration that does not require ongoing monitoring.

Because carbonates of alkali metals such as sodium and potassium tend to be more soluble in water, the target metals for this purpose are alkaline-earth metals, particularly calcium and magnesium. In their natural state, these target metals can be found in relatively high concentrations in mafic and ultramafic rocks or processed waste from mining and minerals recovery operations.

Still at a relatively early stage of development, accelerated mineral carbonation processing routes can be broadly categorised as follows:

- ***In-situ mineral carbonatio***n: CO_2-rich fluids are injected into the subsurface under optimised conditions for accelerating the reaction of CO_2 with in-situ mineralisation to form carbonate minerals.
- ***Ex-situ mineral carbonation***: finely ground natural alkaline minerals and industrial alkaline wastes are reacted with concentrated CO_2 under forcing conditions (e.g., elevated temperature and pressure) to accelerate the reaction, producing a carbonated mineral product that can be stored, buried, or used for productive purposes. Ex-situ mineral carbonation is divided into two categories:
  (i) single-stage or direct carbonation and
  (ii) multi-stage or indirect carbonation.
- ***Surficial mineral carbonation***: or enhanced rock weathering (ERW), is the process by which powdered silicate rocks and minerals are spread over the land, coastal areas, or the ocean, whereby the carbonation reaction occurs at the Earth's surface without the assistance of an engineered reactor process.

With an abundance of silicate minerals around the world (see Figure 3), mineral carbonation has the potential to sequester more than 10,000 gigatonnes of carbon relatively permanently.

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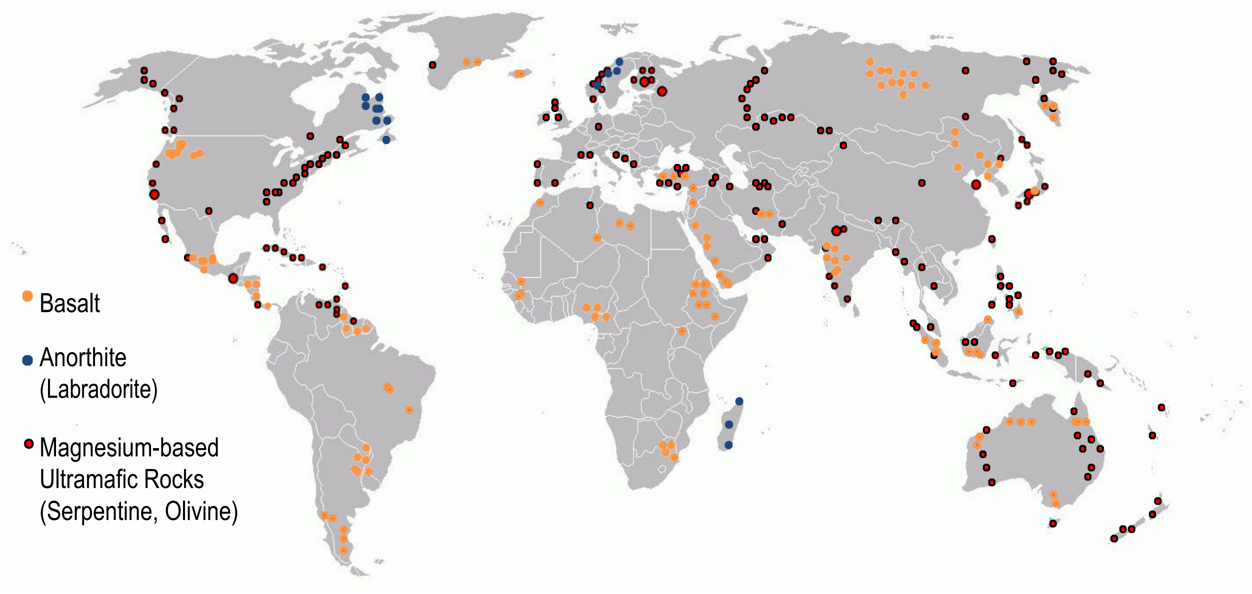
[16] Mazzotti, M., Abanades JC, Allam R, Lackner KS, Meunier F, Rubin E, Sanchez JC, Yogo K, Zevenhoven R. , (2005), 'Mineral carbonation and industrial uses of carbon dioxide', IPCC Special Report of Carbon Dioxide Capture and Storage, Chapter 7, Mineral carbonation and industrial uses of carbon dioxide, Cambridge University Press

[17] Ciais P, Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., Chhabra, A., DeFries, R., Galloway, J., Heimann, M. and Jones, C. (2013), 'Carbon and other biogeochemical cycles Climate Change 2013: The Physical Science Basis', *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* ed T F Stocker, D Qin, G K Plattner, M Tignor, S K Allen, J Boschung, A Nauels, Y Xia, V Bex and P M Midgley, Cambridge University Press, Cambridge

[18] Pandey, S., Srivastava, V. and Kumar, V. (2021), 'Comparative thermodynamic analysis of CO_2 based dimethyl carbonate synthesis routes', *The Canadian Journal of Chemical Engineering*, 99(2), 467-478

Figure 3. Mineral feedstock available for mineral carbonation[19]



The various methods of accelerated mineral carbonation that fall under these broad categories will have merit in different settings.

However, in the context of establishing effective procedures for capturing and permanently storing atmospheric carbon, in-situ accelerated mineral carbonation is likely to face socio-environmental perceptions associated with using depleted petroleum reservoirs for carbon sequestration, as well as the practice of hydraulic fracturing. Further, surficial mineral carbonation is a protracted process that, to be effective, requires an extensive footprint.

For these reasons, as well as circumstance that provide Western Australia with a competitive advantage the focus of this roadmap for mineral carbonation in Western Australia is ex-situ mineral carbonation.

1.2.2. Types of Ex-situ Mineral Carbonation

Ex-situ accelerated mineral carbonation involves reacting alkaline minerals that have been crushed and milled (which increases their surface area) with CO_2-rich gases in an engineered reactor to produce a carbonate mineral product, whereby the carbon is thermodynamically stable in that mineral matrix.

Feedstock can include minerals such as wollastonite, serpentine and olivine or waste streams from mining and recovering certain minerals that have already been crushed and milled. It is estimated these processes have the potential to permanently sequester between 9 and 17 gigatonnes of carbon per annum from mine tailings globally.[20]

Ex-situ accelerated mineral carbonation processes can be further categorised as direct and indirect and gas-solid and aqueous methods.

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[19] Park, A., Matter, P. and Gadikota, G. (2012), Geo-Chemo-Mechanical Studies for Permanent Storage of CO_2 in Geological Formations, DE-FE0002386

[20] Power, I., Harrison, A., Dipple, G., Wilson, S., Kelemen, P., Hitch, M. and Southam, G. (2013), 'Carbon mineralisation: from natural analogues to engineered systems,' Reviews in Mineralogy and *Geochemistry*, 77(1), 305-360

Figure 4. Types of ex-situ mineral carbonation[21]

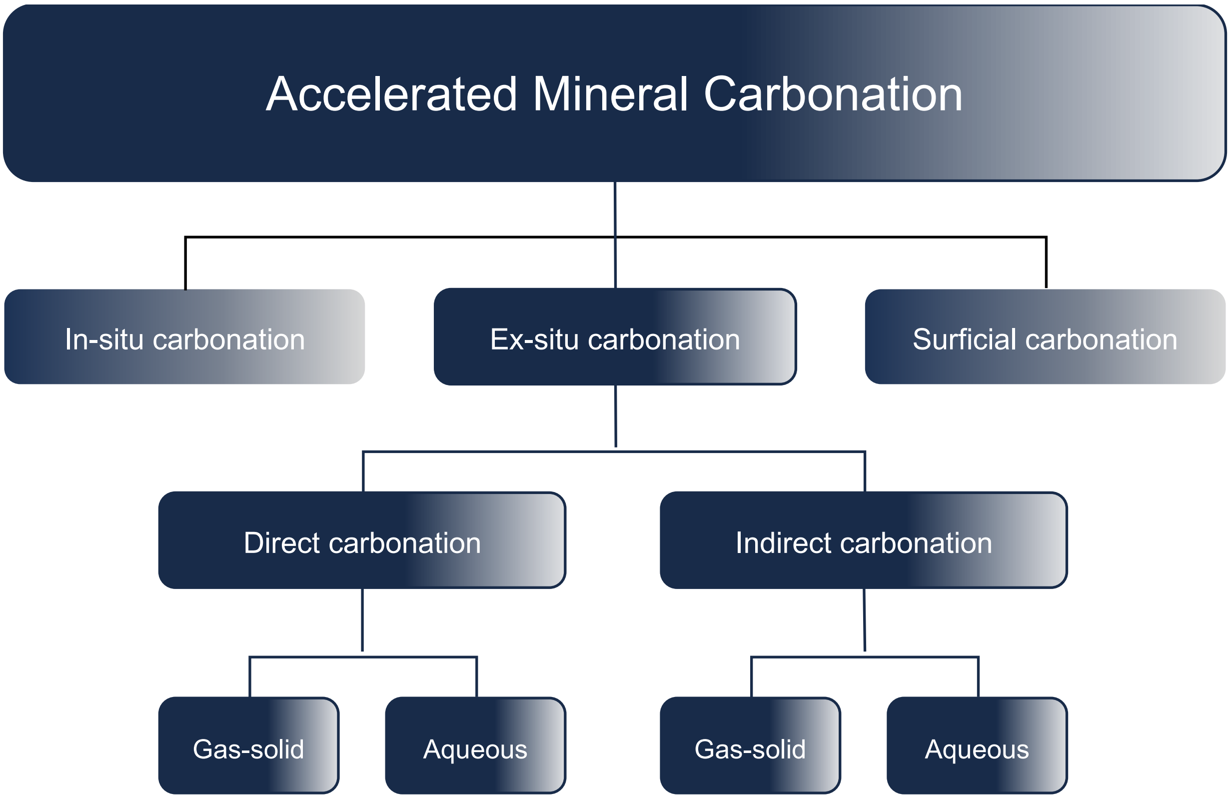

Figure 4 illustrates ex-situ mineral carbonation and its various pathways in the context of mineral carbonation processes more generally.

Direct carbonation

Direct carbonation describes a process route whereby a carbonate product is produced from a carbonation and mineral dissolution process in a single reactor. Upstream operations may include mineral pre-treatment and the extraction of reactive ions from the alkaline mineral feedstock. The benefits of direct carbonation include relative process route simplicity and minimal use of reagents.

Direct gas-solid carbonation is the simplest form of direct carbonation. Solid alkaline minerals contact gaseous CO_2 at a particular temperature and pressure. For optimal conversion rates, single-step gas-solid direct carbonation requires energy-intensive reaction conditions (340 bar, 500°C and 2 hours of contact time)[22], together with a reactor type that enables strong particle interactions between the two phases, such as a fluidised bed reactor.[23]

Direct aqueous carbonation is a process whereby in the presence of water, the gas-solid two-phase reaction scheme becomes a gas-liquid-solid multiphase reaction, which is conducive to the progress of the carbonation reaction. Part of the gaseous CO_2 dissolves in water and forms carbonic acid, which can further ionise.

This reaction causes hydrolysis of the mineral, which releases the magnesium or calcium ions and silica, with the bicarbonate and ions reacting to form a solid carbonate. This process results in a slower reaction. However, research has demonstrated reaction kinetics

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[21] Curtin University analysis

[22] Lackner, K., Butt, D., and Wendt, C. (1997), ‘Progress on binding CO_2 in mineral substrates’, Energy Conversion and Management, 38, 259-264

[23] Zevenhoven, R. and Fagerlund, J. (2010), Mineralisation of carbon dioxide (CO_2). ‘Developments and Innovation in Carbon Dioxide (CO_2) Capture and Storage Technology, Woodhead Publishing. 2: 433-462

can be improved by using additives or by altering temperature, solid-to-liquid ratio, CO_2 concentration, pressure, and particle size.[24] [25]

Indirect carbonation

Indirect carbonation describes a process route whereby the carbonate product is produced from a carbonation process that involves two or more stages. An essential processing stage in indirect mineral carbonation is the extraction of divalent metals, such as magnesium and calcium, from the solid matrix of the feedstock minerals.

The extracted metal ion is then processed into a carbonate via a reaction with CO_2. A potential benefit of indirect carbonation is that the extraction of metal ions in a separate stage provides the opportunity to produce pure metal carbonates because any impurities such as silica and unreacted minerals can be removed before the carbonate is precipitated, resulting in higher quality carbonate product.[26]

Indirect gas-solid carbonation is a process that includes a solid-solid metal extraction step at very high temperatures and pressures (up to 600 °C and 100 bar) or a metal dissolution step using an acidic solution. It also involves a final dry carbonation reaction in a pressurised bed reactor.[27]

Indirect aqueous carbonation is a process route comprising two or more mineral carbonation processes with dissolution and carbonation reactions being conducted in an aqueous environment, usually with various additives. A challenge associated with indirect aqueous carbonation is the recovery of additives. This needs to be improved due to its high energy consumption.[28]

1.2.3. Accelerated Ex-situ Mineral Carbonation Value Chain

This Roadmap's technical, economic, socio-environmental, and regulatory scope is for the entire value chain that will be needed to realise an accelerated ex-situ mineral carbonation industry in Western Australia. Figure 5 provides a high-level overview of that value chain.

Feedstock CO_2 is captured either from point source emissions such as industrial, mining, or mineral recovery processes that emit CO_2 as a waste product or directly from the atmosphere via a technology referred to as direct air capture (DAC).

The advantage of capturing CO_2 from a point source emission is the CO_2 is typically present in higher concentrations rendering its efficient capture more viable.

However, given the remote nature of the target mine gangue and tailings resources in Western Australia, there is unlikely to be adequate point source emissions near those resources, requiring CO_2 captured from other locations to be compressed and transported to the gangue and tailings resources (or vice versa) at a commercial scale.

DAC has two advantages: it removes legacy CO_2 emissions and can be near the sequestration resource. However, it is a relatively immature technology that still needs to be demonstrated at the scale required for gigatonne mineral carbonation to be viable.

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[24] Li, J. and Hitch, M. (2018), 'Mechanical activation of magnesium silicates for mineral carbonation: a review', Minerals Engineering, 128, 69-83

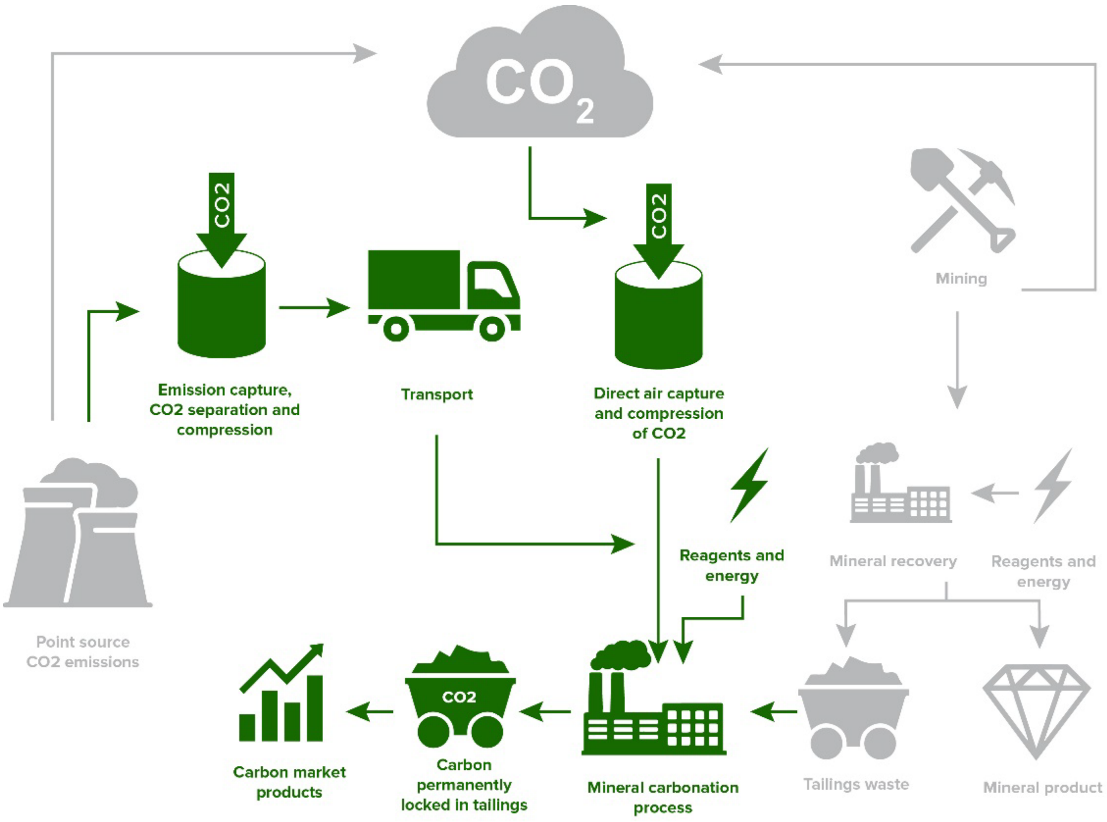
[25] Myers, C., Nakagaki, T. and Akutsu, K. (2019), 'Quantification of the CO_2 mineralisation potential of ironmaking and steelmaking slags under direct gas-solid reactions in flue gas', International Journal of Greenhous Gas Control, 87, 100-111

[26] Eloneva, S., Teir, J., Salmien, C., Fogelholm, J., Zevenhoven, R. (2008), 'Fixation of CO_2 by carbonating calcium derived from blast furnace slag', Energy, 33(9), 1461-1467

[27] Highfield, J., Lim, H., Fagerlund, J. and Zevenhoven, R. (2012), 'Activation of serpentine for CO_2 mineralisation by flux extraction of soluble magnesium salts using ammonium sulphate', RCS Advances, 2(16), 6535-6541

[28] Chakraborty, S. and Jo, B. (2018), Aqueous-based carbon dioxide sequestration, in Carbon Dioxide Sequestration in Cementitious Construction Materials, Woodhead Publishing

Figure 5. High-level accelerated ex-situ mineral carbonation value chain[29]



Once captured and compressed, CO_2 is delivered to a mineral carbonation plant, which is processed with tailings and mine gangue to form carbonate products. As discussed above, this can be a process immediately downstream from the mineral's recovery circuit or a separate process that uses gangue and tailings stockpiles as feedstock.

It could involve any methods described above, variants or a combination. The process will require energy and may require reagents.

The output of the process is a thermodynamically stable mineral carbonate in which the carbon is 'permanently locked.'

This product can potentially be securitised and sold into global carbon markets and converted into carbon-embedded products such as soil enhancers for agriculture, shotcrete for the mining industry or various construction industry products, albeit the creation and sale of such products, depending on their nature, potentially negates the ability to claim relative permanency of sequestration.

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[29] Curtin University analysis

1.3. The Challenge

Western Australia hosts resources of mine and mineral processing wastes highly suitable as feedstock for accelerated ex-situ mineral carbonation.

The scale of this resource is such that it could not only store all CO_2 emissions produced in Western Australia but also serve as a resource for offsetting national and international emissions and removing legacy CO_2 from the atmosphere.

In addition to the obvious benefits of reducing global warming and improving the environmental credentials of the Western Australian industry, this creates an opportunity for a new mineral carbonation industry in Western Australia.

However, some obstacles must be overcome for this opportunity to materialise.

Firstly, the ex-situ mineral carbonation technologies briefly described above and detailed in a subsequent chapter of this Roadmap remain at a developmental stage.

Secondly, research to date identifies mineral carbonation process technologies must be tailored for the specific feedstock and the carbonate product to be produced.

Thirdly, for a Western Australian mineral carbonation industry to develop, it must be economically viable and present a competitive use of mining and minerals recovery waste streams.

Fourthly, the environmental, social, and cultural externalities must be understood and managed.

Finally, an appropriate regulatory framework could facilitate the development of a mineral carbonation industry and its markets, regulate environmental, social, and cultural externalities, and create markets for its products.

Recognising this opportunity and the obstacles to be navigated, the Minerals Research Institute of Western Australia (MRIWA) commissioned Curtin University and its Western Australian School of Mines, Mineral, Energy and Chemical Engineering (WASM: MECE) to prepare, in consultation with other research organisations, industry, government and communities, this Western Australian Mineral Carbonation Roadmap.

The process for developing the Roadmap is outlined in Appendices A2. An extensive literature review was also completed to inform the deliberations.[30]

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[30] Mosallanejad, S., Bhatelia, T. and Hitch, M., (2022), *Roadmap to Decarbonise WA through Integrated Mineral Carbonation: Literature Review Report*, Curtin University and Minerals Research Institute of Western Australia

1.4. The Roadmap

The overall objectives of the Western Australian Mineral Carbonation Roadmap are to:

a. Develop and deploy a series commercial-scale ex-situ mineral carbonation pilot plant or plants in Western Australia to demonstrate technical and economic viability of different systems as the foundation of a new industry.

b. Establish a clear pathway for minimising negative social and environmental externalities and optimising benefits from positive social and environmental externalities associated with a mineral carbonation industry in Western Australia.

c. Investigate policy and regulatory drivers to give effect to a new mineral carbonation industry in Western Australia.

The Western Australian Mineral Carbonation Roadmap has been structured at thematic, programmatic, and sub-programmatic levels as illustrated in Table 2.

As with all strategic research plans, as early tasks in the sub-programs are conducted new knowledge will come to light that will affect the direction research and development takes under the Roadmap going forward.

Therefore, while detailed programming has been developed for the immediate term, plans are only outlined for later years of the Roadmap sub-programs.

Further, it is likely this Roadmap will be one of several subsequent Roadmaps required to give effect to a mineral carbonation industry in Western Australia as technology solutions develop.

Table 2. Western Australian Mineral Carbonation Roadmap Themes and Programs

Themes	Programs		Sub-programs	
Science and Technology Development of the basic and applied scientific research and technology required to deploy systems.	1.	Target tailings and gangue characterisation	1.1	Standardised framework for assessing suitability for mineral carbonation
			1.2	Identification of priority mineral carbonation resources
			1.3	Selection of optimal resource(s) for pilot plant
	2.	Pilot plant design and development	2.1	Process suitability decision tree
			2.2	Process design optimisation
	3.	Direct air capture	3.1	Process feasibility
			3.2	Low-energy contactors for DAC system
			3.3	Point source capture and transportation as an interim solution
	4.	Mineral carbonation and by- and co-products	4.1	By- and co-product identification
			4.2	By- and co product manufacturing systems
			4.3	By- and co-product LCA
Economic Viability Systems and product requirements for economic viability.	1.	A financial framework for mineral carbonation in Western Australia	1.1	Marketability and associated pricing of products arising from carbonation process
			1.2	Beneficial offsets
			1.3	Capital cost, revenue and operating cost estimations
	2.	Innovation in carbon credit markets	2.1	Application of derivatives
			2.2	Market integration
	3.	Carbon embedded product innovation	3.1	New product opportunity scoping
			3.2	Market assessment
			3.2	Manufacturing assessment
Social and Environmental Effective management of positive and negative social and environmental externalities.	1.	First Nations engagement	1.1	Social, cultural, and environmental impact mapping
			1.2	Traditional Ecological Knowledge (TEK) application framework
			1.3	Commercial frameworks for First Nations partnerships
	2.	Community engagement	2.1	Socio-economic impact mapping
			2.2	Socio-economic multiplier analysis
			2.3	Socio-economic impact modelling
	3.	Environmental impacts	3.1	Waste streams
			3.2	Tailings storage facility integrity
			3.3	Gangue and tailings as refugia
Policy and Regulation Policy and regulatory reform required to give effect to a mineral carbonation industry.	1.	Policy case evidence	1.1	Industry development level economic impact modelling
			1.2	CO_2 abatement modelling
	2.	Regulatory compliance and reform pathway	2.1	Inventory and analysis of Western Australian and Commonwealth legislation and regulations and associated policy and guidelines
			2.2	Reform and reform pathways
	3.	Innovation in offsets regulation	3.1	Australian offsets products
			3.2	Emissions Lifecycle Assessment framework innovation
			3.3	Carbon embedded products

Policy and Investment Case

2

2.1. Overview

The nature and scale of stockpiles of mine gangue and waste from minerals recovery operations in Western Australia, particularly the Goldfields Region of Western Australia, create an opportunity for the State to become a world leader in ex-situ mineral carbonation.

Developing this capability will be crucial for offsetting the State’s emissions profile and the environmental credentials of its mining industry. It will also result in a new sector for the State that serves customers across a range of markets nationally and globally.

2.2. Key Elements of the Policy and Investment Case

The interplay between the decarbonisation objectives and actions of government and industry, the nature of energy requirements of Western Australian industry and the State’s competitive domestic supply of natural gas, combined with an enormous domestic ex-situ mineral carbonation resource and opportunities for new industry, creates a compelling case for investment by government and industry in the implementation of this Roadmap.

This is illustrated conceptually in Figure 6 and summarised in the following subsections.

2.2.1. Vast Sequestration Resource

It's extensive, highly suitable sequestration resource underpins Western Australia's accelerated ex-situ mineral carbonation opportunity. Decades of mining mafic and ultramafic ore, particularly in the Goldfields Region, have resulted in mining gangue and minerals recovery tailings facilities that hold mineralisation suitable for permanently abating carbon through mineral carbonation processes at a gigatonne scale. Further, much of this resource is the product of nickel mining. This critical mineral is vital to manufacturing products that service the decarbonisation economy, providing the opportunity for Western Australian primary production to significantly contribute to positive lifecycle emissions assessments of products servicing the renewable energy sector, such as lithium-ion batteries, solar photovoltaic cells, and wind turbines.

Figure 6. Key elements of the policy case for investment in this Roadmap[31]

2.2.2. Ambitious Government and Industry Net Emission Reduction Targets

As summarised in Table 1, the Western Australian government and the mining industry have established ambitious net emissions reduction targets – net zero by 2050. Achieving this 'net' reduction will involve the ongoing transition from hydrocarbon fuels to renewable energy but will also require a significant sequestration effort.

The application of accelerated ex-situ mineral carbonation presents an opportunity to convert worthless mine waste into scalable sequestration resources.

2.2.3. A Challenging Domestic Energy Transition Paradigm

The energy-intensive nature of mining and minerals recovery operations renders Western Australia's industry emissions relatively intensive. While this emissions profile will be partly abated through the deployment of renewable energy systems and electrification of mining fleets, the reality is it will remain some time until the ultimate objective of renewable sources being able to supply the sustained delivery of electricity and heat required for efficient mining and minerals recovery operations becomes a reality.

In the case of Western Australia, this energy transition dilemma is exacerbated by the following:

- The competitiveness of many mineral recovery operations in Western Australia is underpinned by affordable natural gas supplied from plentiful reserves and historical investment in distribution

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[31] Curtin University analysis

infrastructure under a policy that requires gas producers to reserve 15 percent of production for sale into the domestic market.

- The Western Australian Government's commitment to retire coal-fired generation by 2030, which places greater dependence of the South West Integrated System (SWIS) on natural gas for dispatchable baseload in the short term.

In these circumstances, for the industry to continue to acquire this relatively cheap energy and for government to use natural gas to provide dispatchable baseload in the grid, both will increasingly need to demonstrate emissions offsets.

It is unlikely conventional balances such as tree planting alone will be able to meet these requirements.

2.2.4. A Unique Requirement for Mining Industry Environmental Credentials

Nationally, the mining industry is on a pathway to optimising its environmental credentials. However, the need to credibly offset emissions from mining and minerals recovery operations is particularly relevant to Western Australia's rapidly growing critical minerals industry.

This industry supplies mineral products to supply chains producing products of advanced manufacture, including those enabling decarbonisation.

With lifecycle emissions of these products increasingly under scrutiny, upstream suppliers that can effectively abate their emissions will have a competitive advantage and be increasingly sought out by downstream customers.

As discussed above, there is an immediate opportunity to achieve this in the nickel sector.

2.2.5. Achievable Economic Diversification

While Western Australian emissions are increasing [32] and the State demonstrates a high per capita emissions rate, it only accounts for under 1 percent of global emissions.

Enabling accelerated ex-situ mineral carbonation to become viable at an industrial level, the extent of the gangue and tailings resource suitable for accelerated carbonation in Western Australia implies there is potential for a Western Australian mineral carbonation industry to service carbon offset markets in other jurisdictions nationally and internationally.

Efforts to diversify an economy are more likely to succeed if they leverage an existing industry base and competitive advantage. For example, should accelerated ex-situ mineral carbonation becomes viable at an industrial scale, the enormous gangue, and tailings resources in Western Australia that is particularly suitable for accelerated carbonation, combined with potentially significant global demand for whole-of-supply-chain carbon offsets, could see an important new sector for the Western Australian economy.

Further, in addition to the sale of offsets, there could be an opportunity for a range of downstream products, including various carbon-embedded building materials and soil enhancement products that complement other major local industries such as construction and agriculture.

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[32] Department of Climate Change, Energy, the Environment and Water (2020), *State and territory greenhouse gas inventories annual emissions*, Australian Government, Canberra

2.2.6. First Nations Opportunities

Much of the mine gangue and tailings resources suitable for ex-situ mineral carbonation are on mining leases on First Nations' traditional lands.

With many pre-dating native titles and, in some instances, heritage legislation, there is little doubt these resources will have impacted traditional lands.

Mineral carbonation using these resources presents a potential opportunity for First Nations to participate in commercialisation while delivering environmental benefits to traditional lands and the global environment.

2.2.7. Local Capability

Several key Western Australian organisations or organisations with a significant Western Australia operational footprint are developing technical capability in mineral carbonation, including research organisations such as Curtin University and CSIRO, mining companies including BHP, Rio Tinto and Alcoa and chemical companies such as Wesfarmers.

There is also an emerging engineering, technology and services sector developing with a variety of carbonation technologies.

Theme One: Science and Technology

3

3.1. Overview

From the outset, it is essential to acknowledge that much of the knowledge and technology required to give effect to accelerated ex-situ mineral carbonation at an industrial scale is still to be acquired.

This capability will only be attainable through significant and sustained government and industry investment in applied scientific investigation and technology development along the entire mineral carbonation value chain and, in many instances, under a context specific to Western Australia's mineral sequestration resources and abatement needs.

3.2. Western Australian Sequestration Resources

Accelerated ex-situ mineral carbonation offers the prospect of converting stored gangue and tailings from certain mining and mineral recovery operations in Western Australia to carbon sequestration resources and potentially downstream carbon-embedded products of commercial value in other industries. However, a specific challenge facing the use of legacy mining gangue and recovery plant tailings as the carbonation resource is the heterogenic characteristics of mine and mineral recovery waste resources.

As an ore body is progressively mined and processed, the ore feedstock changes characteristics, including its specific mineralogy, water content, etc. Therefore, processes to optimise recovery from the changing ore characteristics change accordingly (e.g., by changing particle size and the type and volume of reagents).

This, in turn, results in an uneven distribution of mineralogies, gangue, water content, reagent waste, reaction products and mechanical properties across a mine waste resource. Further, in the case of legacy waste resources, because the tailings resource is exposed to the atmosphere, the surface and top layers tend to be more weathered than the covered tailings.

Finally, depending on the consistency of the throughput rate and changes in the characteristics of ore feedstock, weathering can be variable through the tailings resource.

Magnesium-silicate minerals are preferable to calcium-silicate minerals as they contain more reactive minerals per tonne of rock and are more readily available around the globe.

These are found primarily in the waste streams from the mining and processing mafic and ultramafic ore bodies. Gangue and tailings from several sectors of the Western Australian mining industry have been identified as suitable for mineral carbonation in this regard.

3.2.1. Mafic and Ultramafic Gangue and Tailings Resources

A significant portion of mineral production in Western Australia, particularly in the Goldfields Region, is mined from mafic and ultramafic ore bodies such as gold sulphide and nickel sulphide mines. The tailings from mineral recovery processes whereby the feedstock is a mafic or ultramafic ore are typically rich in magnesium and calcium silicates rendering them highly suitable for sequestration via accelerated mineral carbonation.

Operational processing of ultramafic ores generally must run high tonnages to be profitable, inevitably generating vast quantities of tailings demonstrating high magnesium oxide (MgO) concentrations suitable for mineral carbon sequestration.

Turning ultramafic tailings into a value-added product could make some marginal nickel projects economically feasible,[33] increasing Western Australia's capacity as a key upstream supplier of nickel minerals and chemical products to the upstream supply chain to manufacture products designed to decarbonise the economy.

In addition, some ultramafic nickel deposits contain chrysotile, also known as white asbestos. Carbonating these tailings provides additional benefits in the form of remediation of hazardous asbestos tailings[34] that can reduce the environmental impact of the waste.[35]

3.2.2. Red Mud (Bauxite Residue) Resources

Bauxite has been mined and refined into alumina in Western Australia since the 1960s when significant private investment in mining, logistics and refining infrastructure was facilitated by five separate state agreements between 1961 and 1978.

In 2022-23, Western Australia produced approximately 13.1 million tonnes of alumina, with a total value of approximately AUD 6.7 billion. This is produced across Alcoa's bauxite mining and refining operations (Huntley and Willowdale mines and Pinjarra, Wagerup and Kwinana refineries) and South 32 Worsley Alumina (Boddington mines and Worsley refinery).

Western Australian alumina production accounts for approximately 68 percent of Australia's and 9 percent of the world's alumina production.[36]

The Bayer process for refining bauxite into alumina produces a slurry of caustic alkaline waste representing approximately 35 to 40 percent of the bauxite feedstock. It is commonly referred to as 'red mud.' Alumina refining operations, including those in Western Australia, typically stockpile red mud on site or near the refining operations.

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[33] Hitch, M., Ballantyne, S., Hindle, S. (2010), 'Revaluing mine waste rock for carbon capture and storage,' *International Journal of Mining, Reclamation and Environment*, 24, 64-79

[34] Oskierski, H.C., Dlugogorski, B.Z. and Jacobsen, G., (2013). 'Sequestration of atmospheric CO_2 in chrysotile mine tailings of the Woodsreef Asbestos Mine, Australia: Quantitative mineralogy, isotopic fingerprinting and carbonation rates.' *Chemical Geology*, 358, 156-169.

[35] Xu, M., Dai, Z., Ford, F. and Lee, A. (2011), *Fibrous minerals in ultramafic nickel sulphide ores*, Canadian Institute of Mining, Metallurgy and Petroleum

[36] Department of Mines, Industry Regulation and Safety (20242), *Western Australian Mineral and Petroleum Statistics Digest 2022-23*, Western Australian Government

Historically, mineral carbonation[37] has been trialled and used to a limited extent to neutralise red mud by locking up alkalinity in an unreactive alkaline form.[38, 39, 40, 41] Alcoa has trialled mineral carbonation for this purpose at its Kwinana Refinery in Western Australia in 2007. A mineral carbonation plant was developed to process red mud to reduce long-term storage risk and potential adverse environmental impacts.

It achieved this by saturation of the red mud with CO_2 from the nearby CSBP ammonia plant[42], sequestering CO_2 (up to 70,000 tonnes per annum) and reducing the red mud's alkalinity to a less hazardous level (from pH 13 to pH of around 8). The resulting material was usable for making cement and concrete.

The lack of a financially viable source of CO_2 at the other two Alcoa alumina refineries, Wagerup and Pinjarra, delayed the implementation of the carbonation process at these two sites[43] Alcoa shifted focus to press filtration in pursuit of higher storage solids concentrations, which significantly increased the volume of recovered water treated and returned to the refinery.

Carbonate introduced into the recovered water before filtration was acceptable in combination with other benefits. However, carbonation of the higher volume of recovered water caused significant production losses in refinery..[44]

Any carbonate in the water returned to the primary refinery flowsheet is then causticised with lime (an overall greenhouse penalty), so red mud carbonation is then only viable if the majority of the CO_2 is retained with the solids (either precipitated or as entrained pore liquor) or in some way removed as a product. This also assumes some framework for recognising any CO_2 captured in this way.

3.2.3. Iron Ore

With an annual production of approximately 861 million tonnes per annum,[45] Western Australia is one of the world's largest iron ore producers.

The scope for using iron-rich minerals for mineral carbonation has yet to be explored to the extent calcium and magnesium-rich minerals have. However, in Western Australia, iron ore resources have two fundamental limitations.

Firstly, while Western Australia hosts some of the world's largest hematite and magnetite in-situ iron resources, these resources have far more value as feedstock to the regional steelmaking industry than sequestration resource.

Secondly, because the vast majority of iron ore production in Western Australia is exported as a minimally processed product, the waste stream is relatively small and less suitable for

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[37] NOTE: Because it is the liquor reacting in the carbonation process, rather than any residual mineralisation, the storage of carbon in red mud is not strictly speaking mineral carbonation. Nevertheless, there has been growing interest in exploring the carbonation of bauxite solid residue.

[38] Han, Y., Ji, S., Lee, P. and Oh, C. (2017), 'Bauxite residue neutralisation with simultaneous mineral carbonation using atmospheric CO_2', *Journal of Hazardous Materials,* 326, 87-93

[39] Dilmore, R., Lu, P., Allen, D., Soong, Y., Hedges, S., Fu, J., Dobbs, C., Degalbo, A. and Zhu, C. (2008), 'Sequestration of CO_2 in mixtures of bauxite residue and saline wastewater', *Energy and Fuels,* 22, 343-353

[40] Khaitan, S., Dzombak, D., Swallow, P., Schmidt, K., Fu, J. and Lowry, G. (2010), 'Field evaluation of bauxite residue neutralisation by carbon dioxide, vegetation and organic amendments', *Journal of Environmental Engineering,* 1045-1053

[41] Sahu, R., Patel, R. and Ray, B. (2010), 'Neutralisation of red mud using CO_2 sequestration cycle', *Journal of Hazardous Materials*, 182, 710-715

[42] Alcoa Australia Alumina Kwinana (2012), *Long Term Residue Management Strategy*, Alcoa, Western Australia (kwinana_refinery_ltrms_report_2012.pdf (alcoa.com))

[43] Tabereaux, A. (2019), 'Bauxite residue: in search of a greener red mud', *Light Metal Age*, March 11

[44] Alcoa of Australia (2013), *Long Term Residue Management Strategy: Partial Review*, Alcoa of Australia

[45] Department of Mines, Industry Safety and Regulation (2024), *Western Australian Minerals Statistics Digest: 2022-23*, Western Australian Government

mineral carbonation. Should further onshore processing of iron ore occur or the production of concentrate products from Western Australia's magnetite resources increase, tailings from iron ore may become a higher priority target for ex-situ mineral carbonation.

3.2.4. Other Potential Resources

Several other waste streams and resources have been identified as potential candidates for mineral carbonation in Western Australia, including:

- **Naturally occurring minerals**: surficial deposits of mafic or ultramafic alkaline rock could be mined, crushed, and ground as feedstock for an ex-situ mineralisation process. However, given the extensive resources of gangue and tailings that contain minerals suitable for carbonation and which have already been the subject of comminution, sourcing naturally occurring minerals as feedstock would add unnecessary cost and incur unnecessary ground disturbance.
- **Brines from salt production or desalination:** brines and other alkaline liquids from desalination processes, natural gas or oil extraction, or some industrial mining processes that contain carbonation-ready alkalinity may also be used to sequester CO_2.[46] [47]

  Each year, Western Australia produces approximately 11.6 million tonnes of salt from evaporative (solar) salt production facilities[48] located on the coast in the State's northwest. The brine by-product from this process is also suitable for mineral carbonation but is currently discharged back into the ocean.

  Western Australia is a significant manufacturer of desalinated seawater, with large municipal desalination plants operating in Kwinana and Binningup and smaller plants serving industrial customers in the northwest. The brine waste stream from these plants has also been identified as a potential candidate for mineral carbonation.[49]
- **Cement kiln dust (CKD):** is a fine, powdery material generated inside the cement kiln, where temperatures range between 800°C and 1000°C. CKD contains some reactive calcium oxide that is a potential means to reduce CO_2 emissions by forming carbonates. It can readily sequester CO_2 at ambient temperatures and pressures.[50]

  The cement industry is a significant emitter, accounting for approximately 7 percent of CO_2 emissions globally. In Western Australia, cement is manufactured in Kwinana, Munster, Kemerton, Karratha, Port Hedland, and Kalgoorlie. Kiln dust can be reacted with CO_2 emissions from cement plants to produce carbonated fillers for blending cement, representing another possible application for a product of mineral accelerated carbonation.[51]

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[46] Bang J., Yoo Y., Lee S., Song K. and Chae S. (2017), 'CO_2 mineralization using brine discharged from a seawater desalination plant', *Minerals,* 7(11), 207

[47] Woodall, C., McQueen, N., Pilorgé, H. and Wilcox, J. (2019), 'Utilization of mineral carbonation products: current state and potential', *Greenhouse Gas Science and Technology*, 9, 1096-1113

[48] Department of Mines, Industry Safety and Regulation (2024), *Western Australian Minerals Statistics Digest: 2022-23*, Western Australian Government

[49] Ho, J. and Izuka, A. (2023), 'Mineral carbonation using seawater for CO_2 sequestration and utilisation: a review', *Separation and Purification Technology*, 307

[50] Huntzinger, D.N., Gierke, J.S., Sutter, L.L., Kawatra, S.K. and Eisele, T.C. (2009), 'Mineral carbonation for carbon sequestration in cement kiln dust from waste piles', *Journal of Hazardous Materials,* 168(1), 31-37

[51] Pedraza, J., Zimmermann, A., Tobon, J., Schomacker, R. and Rojas, N. (2021), 'On the road to net zero emission cement: integrated assessment of mineral carbonation of cement kiln dust', *Chemical Engineering Journal*, 406

Research shows CKD can sequester greater than 80 percent of its theoretical capacity for carbon without any amendments or modifications to the waste.[52]

More detailed research, including material characterisation of pre- and post-carbonated CKD, is needed to better elucidate reaction pathways and their products.

- **Legacy asbestos tailings:** while the carbonation of legacy asbestos tailings can potentially reduce contamination and dust emissions[53], the hazardous nature of the feedstock and public concerns over disturbing asbestos tailings or using products produced from them potentially limits their suitability.
- **Other alkaline industrial wastes:** Many existing industries, such as steel and cement manufacturing, produce alkaline materials that can be used as feedstock in a mineral carbonation process.

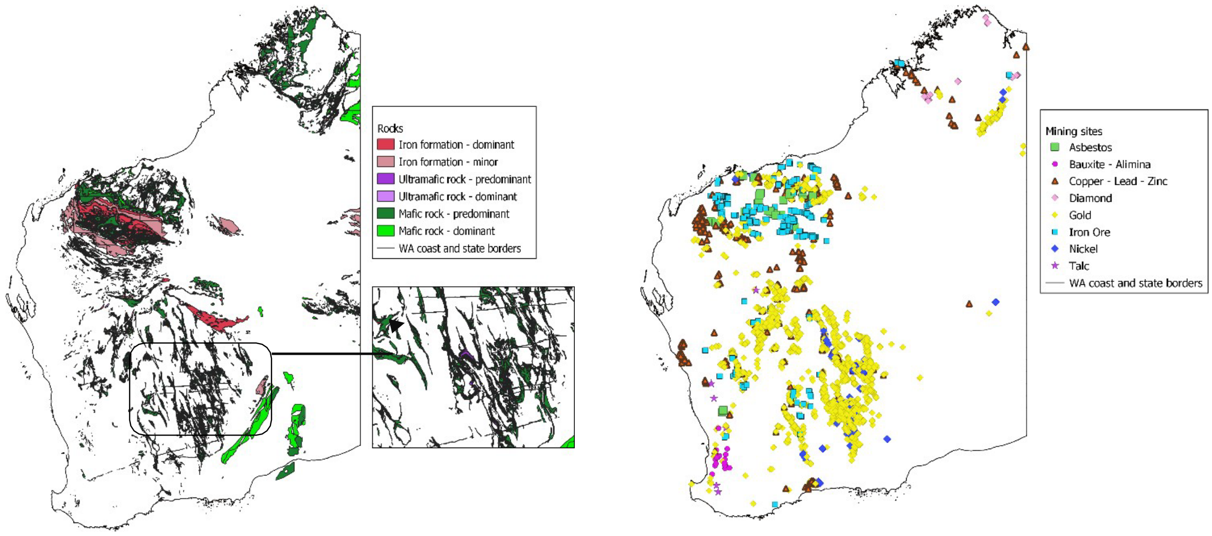
  Alkaline industrial solid wastes typically have high mass fractions of reactive oxides that may not require pre-processing, making them an attractive source material for mineral carbonation. Large-scale industrial waste streams and by-products such as coal or oil-shale-fired power plants, solid waste incinerators, demolition waste, cement plants, and steel and paper production processes are potential targets for mineral carbonation.

As outlined, while there are various potential resources, there is broad consensus mafic and ultramafic tailings and gangue are likely to be the most suitable for ex-situ mineral carbonation, which in the case of Western Australia, are typically associated with processing gold and particularly nickel sulphide ore bodies in the Goldfields Region.

Figure 7 illustrates the location of mafic, ultramafic, and iron-rich rocks and where those minerals are being mined in Western Australia.

Figure 8 illustrates the location of tailings storage facilities and gangue stockpiles comprised of minerals suitable for mineral carbonation.

Figure 7. (a) Location of mafic, ultramafic, and iron-rich rocks; and (b) Locations where mafic, ultramafic, and iron-rich rocks are being mined in Western Australia[54]



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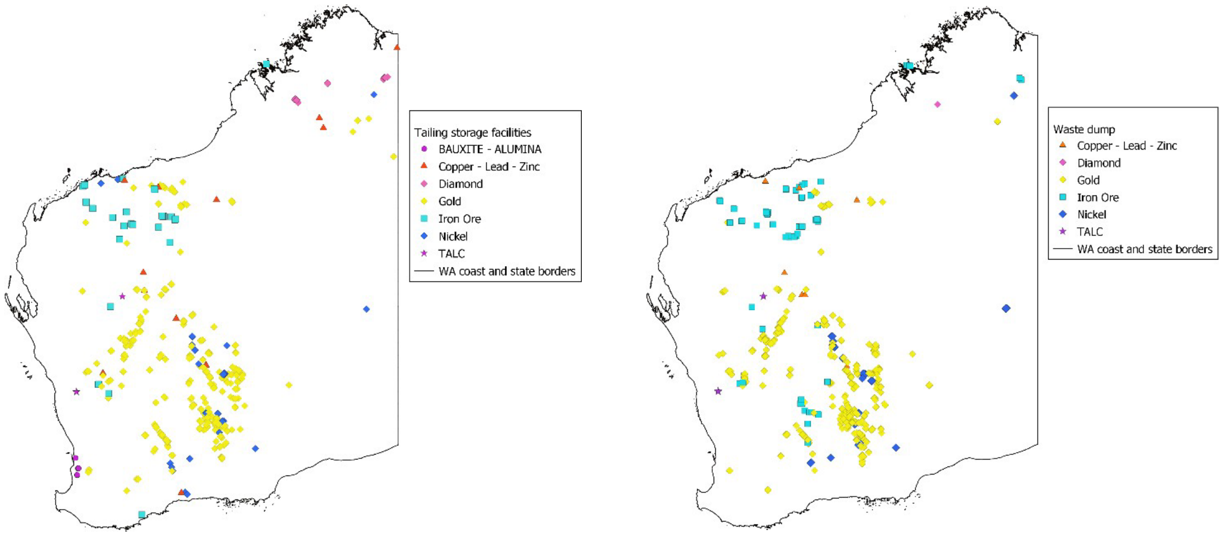
[52] Huntzinger, D. (2006), *Carbon dioxide sequestration in cement kiln dust through miner carbonation*, Dissertation, Michigan Technological University

[53] Azadi, M., Edraki, M., Farhang, F. and Ahn, J. (2019), 'Opportunities for mineral carbonation in Australia's mining industry', *Sustainability*

[54] Department of Mines, Industry Regulation and Safety (2022), *MINEDEX*, Government of Western Australia

Figure 8. (a) Location of tailings storage facilities; and (b) location of gangue and other mine waste materials prima facie suitable for mineral carbonation in Western Australia[55]



3.2.5. Characterisation is Key

Generally speaking, the extraction of mineral resources produces two main waste streams: gangue (rock from the mining process that contains too low a concentration of the target mineral(s) for efficient recovery and is rejected in advance of mineral processing) and tailings (the waste product from mineral processing or leaching).

Gangue is characterised by variability in particle sizes, ranging from microns to tens of centimetres and heterogeneity.[56] In contrast, tailings will demonstrate less variability in particle size (typically within a distribution like silty sands). However, they will still show heterogeneity because of changes in the use of reagents and the nature of the circuit over time and weathering.[57]

The key to mineral carbonation technology's success is selecting the best process route and conditions for each feedstock. In this regard, characterising each tailings material and assessing its carbonation reactivity is a crucial first step.[58]

Knowledge of the tailing's mineralogy is a valuable guide to potential, but it physically captures limitations to reactivity. A deeper understanding of the characteristics of legacy tailings resources can also be acquired through historical modelling operations and accessing historical plant records. However, because geochemistry is typically treated as commercial-in-confidence by operators, the necessary modelling inputs are generally outside the public domain.

Within the extensive resource of mafic and ultramafic gangue and tailings in Western Australia, specific resources will be more suited to carbon mineralisation than others. They can be identified and prioritised through modelling studies followed by laboratory testing.

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[55] Ibid, 54

[56] Paktunc, A. (1999) 'Characterisation of mine wastes for prediction of acid mine drainage,' IN: Environmental Impacts of Mining Activities, Springer, Berlin

[57] Bussiere, B. (2007) 'Hydro-geotechnical properties of hard rock tailings from metal mines and emerging geo-environmental disposal approaches,' Canadian Geotechnical Journal, 44(9), 1019- 1052

[58] NOTE: There are facilities in Western Australia that can conduct such assessments at a laboratory scale such as the John de Laeter Centre at Curtin University, Centre for Microscopy, Characterisation and Analysis at the University of Western Australia and the CSIRO's Australian Resources Research Centre.

3.3. Accelerated Ex-situ Mineral Carbonation Processes

As mentioned briefly in the introduction to this Roadmap, several accelerated mineral carbonation process routes need to be explored and developed. However, each of these presents benefits and drawbacks. Its suitability depends on the nature of the sequestration resource, availability of process inputs and the carbonate products required from the process.[59]

The following subsections provide an overview of these processes, the state-of-the-art in each cycle and their suitability to an accelerated ex-situ mineral carbonation industry in Western Australia.

The natural mineral carbonation process can be accelerated through direct or indirect methods and gas-solid reactions or aqueous routes within each process.

3.3.1. Direct Mineral Carbonation

Direct mineral carbonation refers to a processing system whereby minerals react in a single step with CO_2 to form carbonate using a single engineered reactor. The most straightforward reaction pathway consists of gas-solid and aqueous approaches.[60] While the process may involve pre-treatment of the feedstock and extraction of reactive magnesium and calcium ions from the alkaline mineral upstream from the reactor, the carbonation and mineral dissolution occur in a single reactor.[61]

3.3.2. Direct Gas-Solid Route

Direct gas–solid carbonation was first studied under high temperatures and pressure using minerals such as olivine and serpentine.[62] Gas-solid carbon mineralisation routes refer to processes with less than 0.2 percent moisture.[63] The reaction kinetics are slow and conversion poor.[64] Some enhanced outcomes have been achieved using heat-activated feedstock or injecting high-pressure or supercritical CO_2.[65]

However, these optimisation processes only add to the energy requirements of an already energy-intensive process. They were abandoned mainly as a research pathway for silicate minerals in favour of aqueous approaches.[66]

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[59] IEAGHG (2022), Mineral Carbonation Using Mine Tailings: A Strategic Overview of Potential Opportunities, IEA Greenhouse Gas R&D Programme

[60] Sanna, A., Uibu, M., Caramanna, G., Kuusik, R. and Maroto-Valer, M.M., (2014). 'A review of mineral carbonation technologies to sequester CO_2', Chemical Society Reviews, 43(23), 8049-8080

[61] Tamilselvi, D., Kandasamy, P. and Andimthu, R. (2016). 'Direct mineral carbonation of coal fly ash for CO2 sequestration, Journal of Cleaner Production, 112, 4173-4182

[62] Ibid, 22 [63] Lim, M., Ahn, H. and You, K. (2010) 'Environmental remediation and conversion of carbon dioxide (CO_2) into useful green products by accelerated carbonation technology', International Journal of Environmental Research and Public Health, 7(1), 203-228

[63] Lim, M., Ahn, H. and You, K. (2010) 'Environmental remediation and conversion of carbon dioxide (CO_2) into useful green products by accelerated carbonation technology', International Journal of Environmental Research and Public Health, 7(1), 203-228

[64] Wang, F., Dreisinger, D., Jarvis, M., Hitchins, T. and Dyson, D. (2019), 'Quantifying kinetics of mineralisation of carbon dioxide by olivine under moderate conditions', Chemical Engineering Journal, 360, 452-463

[65] Huijgen, W. and Comans, R. (2003), Carbon dioxide sequestration by mineral carbonation: literature review

[66] Saran, R., Arora, V. and Yadav, S. (2018) 'CO_2 sequestration by mineral carbonation: a review', Global Nest Journal, 20, 497-503

3.3.3. Direct Aqueous Route

Direct aqueous mineral carbonation involves dissolving the mineral and CO_2 in solution and precipitating carbonate minerals. In the presence of water, the gas-solid reaction scheme becomes a gas-liquid-solid multiphase reaction conducive to the progress of the carbonation reaction.[67] [68]

Direct aqueous mineral carbonation involves three steps:

1. *Dissolution of CO_2 in the aqueous phase*: whereby, firstly, CO_2 is dissolved in water to form carbonic acid (H_2CO_3), then dissociates into protons (H^+ or H_3O^+) and bicarbonate ions (HCO^-).
2. *Dissolution of the mineral into the aqueous medium* involves extraction of the alkaline earth metal from the mineral structure of the feedstock. The protons produced in the first step mentioned above hydrolyse the mineral, resulting in the liberation of magnesium/calcium cations and free silica and water formation. This is considered the rate-limiting step [69] due to the reprecipitation of amorphous silica on the surface of the mineral particles that inhibits further extraction of metal ions[70].
3. *Precipitation of a stable metal carbonate:* magnesium or calcium cations in the solution react with the bicarbonate ions to form a solid carbonate.

The conversion rate can be improved by mineral pre-treatments, which aim to either increase reactive surface area (comminution) or the reactivity of the mineral (e.g., through thermal activation) or by altering reaction conditions such as temperature, solid-to-liquid ratio, CO_2 concentration and pressure.[71] [72]

The energy penalties incurred by pre-treatments must be considered when assessing the feasibility of the mineral carbonation process for a particular feedstock.

3.3.4. Indirect Mineral Carbonation

The indirect route, also called multi-stage mineral carbonation, is a process that occurs across two or more stages. An essential step in an indirect mineral carbonation process is the extraction of divalent metals (magnesium and calcium) from the feedstock solid mineral matrix before reacting with CO_2. The extracted mineral then undergoes the carbonation process by reacting with CO_2.

In this route, it is possible to form relatively pure products (carbonates, iron oxides, silica) since this process removes impurities before the carbonation process. In addition, reaction rates are generally faster than direct carbonation, which can be advantageous in some product applications[73]. However, these processes are more complex and involve reagents that require financial, material, and energy resources to produce and regenerate.[74]

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[67] Li, J., Jacobs, A. and Hitch, M. (2019), 'Direct aqueous carbonation on olivine at a CO_2 partial pressure of 6.5 MPa', *Energy*, 173 902-910

[68] Benhelal, E., Rashid, M., Rayson, M., Brent, G., Oliver, T., Stockenhuber, M. and Kennedy, E. (2019), 'Direct aqueous carbonation of heat activated serpentine: discovery of undesirable side reactions reducing process efficiency', *Applied Energy*, 242, 1369-1382

[69] Huijgen, W.J., Witkamp, G.J. and Comans, R.N., (2005), 'Mineral CO_2 Sequestration by Steel Slag Carbonation', *Environmental Science & Technology* 39(24), 9676-9682

[70] Farhang, F., Rayson, M., Brent, G., Hodgins, T., Stockenhuber, M. and Kennedy, E., (2017), 'Insights into the dissolution kinetics of thermally activated serpentine for CO_2 sequestration' *Chemical Engineering Journal*, 330, 1174-1186

[71] Ibid, 24 [72] Wang, F., Dreisinger, D., Jarvis, M., Hitchins, T. and Dyson, D. (2019), 'Quantifying kinetics of mineralisation of carbon dioxide by olivine under moderate conditions,' *Chemical Engineering Journal*, 360, 452-463

[72] Wang, F., Dreisinger, D., Jarvis, M., Hitchins, T. and Dyson, D. (2019), 'Quantifying kinetics of mineralisation of carbon dioxide by olivine under moderate conditions,' *Chemical Engineering Journal*, 360, 452-463

[73] Ibid, 26

[74] Azdarpour, A., Asadullah, M., Mohammadian, E., Hamidi, H., Junin, R., and Karaei, M. (2015), 'A review on carbon dioxide mineral carbonation through pH-swing process,' *Chemical Engineering Journal*, 279, 615-630

Indirect carbonation has attracted significant attention, primarily due to its mild carbonation conditions, avoiding the high temperature and pressure operating conditions typical of direct carbonation processes.

3.3.5. Indirect Gas-Solid Route

Indirect gas-solid mineral carbonation involves an initial solid-solid metal extraction process operating at very high temperatures and pressures (up to 600˚C and 100 bar) or a metal dissolution process using an acid solution. A dry carbonation reaction follows this in a pressurised fluidised bed reactor[75].

3.3.6. Indirect Aqueous Route

Indirect aqueous mineral carbonation processes comprise two or more steps with dissolution and carbonation reactions conducted in an aqueous environment, typically in the company of various additives.[76]

Additives previously trialled to optimise processes, include acidic reagents and other solvents such as acetic acid[77], hydrochloric acid[78], ammonia salts[79] [80], ammonia and brine[81], molten salts[82] and bioleaching.[83]

However, each technique for the extraction of metals has its inherent benefits and drawbacks.

3.3.7. Biologically Enhanced Carbonation

Biogeochemical activities are crucial in natural calcium carbonate mineralisation as recorded in geological formations ranging from stromatolites, beach rocks, and cave speleothems to sediments.[84]

These processes have been mimicked in laboratory conditions for various engineering applications, including mineral carbonation harnessing the potential of biological agents.[85] Biological carbonation using plants and other

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[75] Olajire, A. (2013), ‘A review of mineral carbonation technology in sequestration of CO_2, *Journal of Petroleum Science and Engineering*, 109, 364-392

[76] Ibid 75

[77] Kakizawa, M., Yamasaki, A. and Yanagisawa, Y. (2001), ‘A new CO_2 disposal process via artificial weathering of calcium silicate accelerated by acetic acid’, *Energy*, 26(4), 341-354

[78] Arce Ferrunfino, G., Okamoto, S., Dos Santos, J., de Carvalho, J., Avila, I., Romero Luna, C. and Gomes Soares Neto, T. (2018), ‘CO_2 sequestration by pH-swing mineral carbonation based on HCl/NH_4OH system using iron-rich lizardite 1T’, *Journal of CO_2 Utilisation*, 24, 164-173

[79] Sanna, A., Dri, M. and Maroto-Valer, M. (2013), ‘Carbon dioxide capture and storage by pH swing aqueous mineralisation using a mixture of ammonium salts and antigorite source’, *Fuel*, 114, 153-161

[80] Jo, H., Park, S., Jang, Y., Chae, S., Lee, P. and Jo, H. (2014), ‘Metal extraction and indirect mineral carbonation of waste cement material using ammonium salt solutions’, *Chemical Engineering Journal*, 254, 313-323

[81] Huang, H., Shi, Y., Li, W. and Chang, S. (2001), ‘Dual alkali approaches for the capture and separation of CO_2’, *Energy and Fuels*, 15(2), 263-268

[82] Wendt, C.H, Lackner, K.S., Vaidya, R., Ziock, H-J. (1998) ‘Thermodynamic calculations for acid decomposition of serpentine and olivine in $MgCl_2$ melts-I: *Reaction Equilibria in $MgCl_2$ Melts*, Los Alamos National Laboratory Report, LA- 984529

[83] Power, I., Dipple, G. and Southam, G. (2010), ‘Bioleaching of ultramafic tailings by acidithiobacillus spp. for CO_2 sequestration’, *Environmental Science and Technology*, 44(1), 456-462

[84] Dhami, N., Mukherjee, A. and Watkin, E. (2018), ‘Microbial diversity and mineralogical – mechanical properties of calcitic cave speleothems in natural and vitro biomineralization conditions’, *Frontiers in Microbiology*, 9(40), 1-22

[85] Dhami, N., Mukherjee, A. and Reddy, M. (2013), ‘Biomineralisation of calcium carbonates and their engineered applications: a review’, *Frontiers of Microbiology*, 4:314

biological agents is considered an eco-sustainable approach for CO_2 mitigation.[86]

Amongst the different biological agents, microbial systems have gained immense interest in carbon capture, utilisation, and storage processes due to their faster growth, low risk and long-term storage in the form of carbonates.[87]

A range of microbial metabolic activities, including photosynthesis, urea hydrolysis, CO_2 hydration (via microbial carbonic anhydrase enzyme), and sulphate reduction, can capture CO_2 and lead to the precipitation of carbonates, as also found widely in Earth's crust.[88] [89]

Microbial enhanced carbonation (MEC) from mine tailings using photosynthetic and heterotrophic microbes and utilising microbial carbonic anhydrase enzyme has been the focus of some research studies[90] [91]. MEC has attracted lots of interest among researchers as an emerging, promising, and green technology for rapid carbon capture and storage that may represent a readily implementable and economically efficient alternative.

However, considering the direct link between mineral carbonation and MEC, the utilisation of this technology to obtain a sustainable environment and mining in WA requires further research.

3.3.8. Potential Process Improvements

The main technical constraints to efficient accelerated mineral carbonation are high energy intensity, slow reaction kinetics, low reaction conversion and complexities of the production chain and process adaptability.[92] While the mineral carbonation reactions are thermodynamically favourable, slow reaction kinetics still need to be improved for the development of commercial-scale mineral carbonation processes.

As summarised in Table 3, various methods of improving the speed and efficiency of the reaction have been examined.[93]

Of all the processes, those that revolve around direct or indirect aqueous mineral carbonation process routes are generally considered the most promising. However, the kinetics associated with even these more promising routes remain constrained by the formation of a silica-rich passivation layer while slowing the overall carbonation reaction by limiting further extraction of magnesium or calcium ions from the core of the mineral particles.

Research to date has explored several avenues for overcoming this barrier, including the using ultrasound as a focused energy source to enhance convection mass transfer, reduce diffusion barriers, activate precipitation sites, and control crystal growth and morphology.[94]

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[86] Rossi F, Olguín EJ, Diels L, De Philippis R. (2015), 'Microbial fixation of CO_2 in water bodies and in drylands to combat climate change, soil loss and desertification', *New Biotechnology*, 32(1), 109- 120

[87] Ibid, 77

[88] Ibid, 77

[89] McCutcheon, J.; Turvey, C.C.; Wilson, S.A.; Hamilton, J.L.; Southam, G. (2017), 'Experimental deployment of microbial mineral carbonation at an asbestos mine: potential applications to carbon storage and tailings stabilisation, *Minerals*, 7:10

[90] Ibid, 81

[91] Dhami, N. and Mukherjee, A. (2016), 'Micrographical, mineralogical, and non-mechanical characterisation of microbial carbonates from urease and carbonic anhydrase producing bacteria', *Journal of Ecological Engineering*, 94, 443-454

[92] Santos, R. and Van Gerven, T. (2011), 'Process intensification routes for mineral carbonation', *Greenhouse Gases: Science and Technology*, 1, 287-239

[93] Ibid, 53 [94] Santos, R., Francois, D., Mertens, G., Elson, J. and Van Gerven, T. (2013), 'Ultrasound intensified mineral carbonation,' *Applied Thermal Engineering*, 57, 154-163

[94] Santos, R., Francois, D., Mertens, G., Elson, J. and Van Gerven, T. (2013), 'Ultrasound intensified mineral carbonation,' *Applied Thermal Engineering*, 57, 154-163

A toolbox of design options will be required

Developing processes to achieve mineral carbonation, let alone technically and economically optimised sequestration, will require process designs specific to the resource that accommodate variability within the resource. Some technologies may involve numerous mechanical and chemical processes.

Therefore, developing ex-situ mineral carbonation systems is not a matter of picking a specific category of processing route but determining the specific processing requirements of a sequestration resource and using a combination of methods that optimises the carbonation process.

Table 3. Approaches to enhancing speed and efficiency of the mineral carbonation reaction[95]

Approach	Method	Benefits
Mechanical pre- treatment	High energy crushing and grinding of the mineral feedstock	Increases the overall specific surface area of the minerals per unit mass available for mineral carbonation
Thermal activation	Heating the mineral feedstock to temperatures above 630°C	Destabilises the crystal lattice, thus increasing the reactivity of the mineral and creating an even larger specific surface area.
Higher reaction temperatures	Operating temperatures above 100°C	Accelerates reaction kinetics.
Higher reaction pressures	Operating CO_2 pressure above 150 bar	Increases the activity of protons needed for metal extraction and counteracts the low solubility of CO_2 at high temperature.
Organic or inorganic reagents	Adding different substances as catalysts and additives to the reactants	Enhances the kinetics of the carbonation process and precipitation of the carbonate mineral.
Beneficiation	Upgrading of mafic content in the feedstock by cycloning-out quartz that may be present in the tailings	Enhanced reaction efficiency.
Multi-step process designs	Altering operating conditions between process stages	Provides the ability to control and optimise extraction and precipitation separately.

Minimisation of energy costs will be essential

The primary energy requirements for accelerated ex-situ mineral carbonation of mine gangue and tailings resources are associated with potential additional comminution requirements, stirring and mixing material through the mineral carbonation circuit and any heat and pressure required to activate the minerals and achieve efficient reactions.

Heterogeneity within a tailings resource implies further comminution of the tailings resource to achieve optimal particle surface area and to mix to achieve a more homogenous feedstock may be required for the mineral carbonation process, resulting in additional energy penalties that would need to be offset from an economic and in most cases, emissions perspective.

Regardless of the process route and its specifications, minimisation of energy costs is likely to be critical across all processes. In this

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[95] Curtin University analysis

regard, electrochemical and biological processes that do not require high reaction temperatures hold some potential but are at relatively early stages of development.

Direct coupling of renewable energy generation to accelerated mineral carbonation processes also holds some potential for reducing energy costs and emissions associated with the mineral carbonation process. However, most minerals suitable for mineral carbonation require a pre-treatment step in thermal activation at temperatures in excess of 600˚C.

Moreover, most aqueous mineral carbonation processes require a relatively dilute slurry (i.e., 15 percent or less solid content) at a temperature of between 80˚C and 180˚C (depending on the process route and type of feedstock) for efficient carbonation. With the potential exception of hydro-energy, renewable energy sources cannot continuously meet the energy required to move and heat the slurry at commercial volumes.

Laboratory scale research also indicates adding salts can accelerate carbonation reactions.[96] However, this results in a less pure carbonate product that can reduce the opportunity for it to have other commercial product applications and increase the volume and, therefore, the footprint of the carbonated mineral resource or sequestered asset. Other relatively simple processes to remove salts from the final product could resolve these issues[97].

While energy requirements remain a significant barrier to the economic viability of accelerated mineral carbonation, consideration will need to be given to the opportunity cost associated with using energy for this purpose, including using any renewable energy resources or energy recovered from upstream processes to reduce emissions associated with an active minerals production operation directly. Given the location of tailings and gangue resources and the temperature requirements of most functions, solar is likely to hold the most promise as a renewable resource.

Minimisation of reagents and optimal reagent recycling will be essential

In addition to the minerals to be converted to carbonates to give effect to sequestration, tailings resources also typically contain reagents and products of reagent reactions which were used in the recovery circuit. Further, the mineral carbonation process itself is likely to produce waste streams that include reagents and products of reagent reactions.

Understanding the entire lifecycle of reagents (lifecycle assessment) along the value chain will be crucial to understanding where reagents might be recoverable and recyclable (environmental and economic considerations) and the nature of waste streams and their natural potential ecological and social impacts, and how to manage those impacts.

3.4. Direct Air Capture Technology

A significant aspect of every mineral carbonation plant is the source of CO_2.

Essentially, CO_2 can be captured via two main methods: CO_2-rich, post-combustion industrial point sources, typically referred to as flue-gas capture, or from the atmosphere using a relatively immature technology known as direct air capture (DAC).

Flue gas suitability for a plant depends on the proximity of mineral feedstock and point-

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[96] Jo, H., Soo-Hee, P., Young-Nam, J., Soo-Chun, C. Pyeong-Koo, L., Ho Young, J. (2014), 'Metal extraction and indirect mineral carbonation of waste cement material using ammonium salt solutions,' *Chemical Engineering Journal*, 254, 313-323

[97] Eloneva, S., Mannisto, P., Said, A., Fogelholm, C. and Zevenhoven, R. (2011), 'Ammonium salt- based steelmaking slag carbonation: precipitation of $CaCO_3$ and ammonia losses assessment', *Greenhouse Gases: Science and Technology*, 1(4), 305-311

source emission. However, industrial wastes, including mine tailings, are geographically dispersed and far from any significant point source emission. In such cases, DAC can be considered a solution that offers a pathway to relatively concentrated sources of CO_2 with flexibility in location.

A typical DAC system consists of (1) blowers or fans, (2) a contactor (absorber) where the air comes into contact with a sorbent (solid or liquid) and (3) a regenerator where the captured and concentrated CO_2 is removed to regenerate the spent sorbent.

The absorber allows ambient air to be exposed to the sorbent and enables airflow through the system to increase adsorption (if the solid sorbent is used) or absorption (if the liquid sorbent is used) of CO_2 in the air.

DAC based on absorption typically uses aqueous hydroxy sorbents like alkali and alkali-earth hydroxides. In contrast, DAC based on adsorption employs a wide range of solid sorbents such as calcium, magnesium oxides, zeolites or metal-organic frameworks (MOFs). [98] Each method comes with its advantages and disadvantages.

There are currently around 19 DAC plants operating globally, capturing an average of 10,000 tonnes of CO_2 per annum, with a 1 million tonne per annum plant currently under development in the United States. [99] Current DAC systems typically employ solid-supported amine-based absorbents, with amine functional groups tethered to the cellulose surface, porous polymer networks and porous silica materials. To achieve moderate CO_2 absorption capacities, these chemical sorbents typically require elevated temperatures (>100˚C) to give effect to sorbent regeneration.[100]

Energy requirement, cost and scalability are the main challenges of DAC technology. DAC facilities can be co-located with renewable energy generation facilities to reduce associated emissions and transmission losses and CO_2 storage facilities to minimise transport costs and infrastructure. However, the current and projected costs of DAC are about 2 to 6 times higher than the desired costs, making them economically challenging to scale.

In a DAC system, blowers and absorbers account for about 70 percent of capital cost, and regenerators account for most of the operating cost. Regardless of the type of DAC system used, most costs in scaling up are associated with the contactor's efficiency.

Therefore, developing low-energy, low-cost DAC technology using novel contactors and novel sorbents is required to achieve carbon removal costs of <\$100/tonne of CO_2.

While DAC is still a relatively immature technology, interest in its potential application is increasing as jurisdictions seek to reduce their emissions to the bare minimum and compensate for residual emissions in pursuit of reduction targets.

Currently most efforts to develop economic storage solutions for CO_2 that could be captured from a future efficient and scalable DAC system focus on sequestration in abandoned oil and gas wells or other appropriate geological formations.[101]

However, unlike geological storage that requires high-purity CO_2, some alkaline minerals can react with lower-concentration CO_2. By combining low-purity CO_2 DAC with mineralisation, it may be possible to decrease

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[98] McQueen, N., Gomes, K.V., McCormick, C., Blumanthal, K., Pisciotta, M. and Wilcox, J., (2021), A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future, *Progress in Energy*, 3(3)

[99] https://www.iea.org/reports/direct-air-capture

[100] Madden, D., Hayley, S., Kumar, A., Chen, K., Sanii, R., Bajpai, A., Lusi, M., Curtin, T., Perry, J. and Zaworotko, M. (2017) ‘Flue-gas and direct-air capture of CO_2 by porous metal-organic materials’, *Philosophical Transactions of the Royal Society A*, 375

[101] Sodiq, A., Abdullatif, Y., Aissa, B., Ostovar, A., Nassar, N., El-Naas, M. and Amhamed, A., . (2023). ‘A review on progress made in direct air capture of CO_2.’, *Environmental Technology & Innovation,* 29, 102991

the overall cost of DAC substantially [102], facilitating economic carbon sequestration at gigatonne scale.[103]

Most significant *prima facie* suitable gangue and tailings resources in Western Australia are some (relatively un-serviced) distance from any major point sources of CO_2 emissions (such as major industrial areas like Kwinana). The logistical challenges, costs, and emissions associated with siting the facilities and transportation of the feedstocks often render implementing ex-situ mineral carbonation impractical. DAC of CO_2 near the gangue and tailings resources and accelerated mineral carbonation plant is considered a potential solution to this dilemma.

Low-altitude CO_2 concentration in the Earth's atmosphere averages approximately 400 ppm (0.04 percent). By comparison, post-combustion point source concentrations are more in the range of 0.15 atm, and industrial sources such as ammonia plants produce CO_2 over 99 percent purity. However, the physics of capturing large volumes of CO_2 from the atmosphere at scale from such low concentrations is challenging, with some experts considering the economic viability of DAC at the scale necessary to support commercial mineral carbonation unattainable.

Antagonists of the future of DAC as a source of CO_2 for commercial-scale mineral carbonation advocate capture from already concentrated sources of CO_2 such as flue gasses will be the only way a commercial-scale application can be brought forward if achieved at all. In this regard, the current state-of-the-art is generally considered to be oil and gas industry processes for capturing CO_2, such as amine-based processes used to reduce the CO_2 content of natural gas.

In addition, point source emissions are already hot, which also presents the potential to reduce energy associated with achieving optimal reaction temperatures in the carbonation process.

Alternative avenues for investigation include using Direct Seawater Capture, albeit the ability of seawater to capture CO_2 is capped by its acidity. This would not resolve the economic challenge of transporting the captured CO_2 to the gangue and tailings resources. Another potential avenue includes using the inland desalination value chain as the source of emissions, with numerous desalination plants operating in proximity to Western Australian gangue and resources.

Regardless of the challenges, a specific pillar of the Roadmap is to create a capability that can extract CO_2 from the atmosphere to offset what is currently a global emissions trajectory that, if not significantly averted shortly, will very likely result in the Paris Agreement emissions targets not being reached and therefore, significant future global warming.

For these reasons, the Roadmap will focus on identifying pathways for the technical and economic viability of DAC. Depending on development pathways and timing, point source capture is likely to be a primary source of CO_2 for a Western Australian mineral carbonation pilot plan while research is undertaken on DAC.

Potential Process Improvements

The focus on improving DAC is in three areas – contactor, sorbent, and regeneration – to improve the technology's capture rates and regeneration aspects.

The most developed DAC concepts separate CO_2 from the air by either absorption or adsorption [104]. DAC based on absorption typically uses aqueous hydroxy sorbents like alkali and alkali-earth hydroxides. By contrast, DAC based on adsorption can employ a wide range of solid sorbents (such as zeolites or metal-organic frameworks (MOFs)), which have lower heats of adsorption (45−70 kJ/mol)

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[102] Bui, Mai, and Niall Mac Dowell, eds. (2022) Greenhouse Gas Removal Technologies, Chapter 7, *Royal Society of Chemistry*

[103] Ragipani, R., Sreenivasan, K., Anex, R.P., Zhai, H. and Wang, B., (2022), 'Direct Air Capture and Sequestration of CO_2 by Accelerated Indirect Aqueous Mineral Carbonation under Ambient Conditions', *ACS Sustainable Chemistry and Engineering*, 10(24), 7852-7861

[104] Ibid 98

compared to the heat of reaction of sodium hydroxide and calcination reaction (+200 kJ/mol).[105]

Potential merits of CO_2 capture via the adsorption route are highlighted by researchers, including avoiding (1) high equipment corrosion rate, (2) high energy consumption in regeneration, and (3) the need for a large absorber volume. However, these processes also have other energy and cost components, and the conclusion for energy and economic analysis may vary for such operations.

In designing an adsorption-based separation process, the choice of adsorbent plays a crucial role.[106] Although novel materials like metal-organic frameworks (MOFs) have caught attention due to their high CO_2 loading capacity and selectivity, their synthesis's high cost and complexity hinder their large-scale application.

On the other hand, there is a lack of reliable adsorption properties and relatively considerable uncertainty in the reported adsorption measurements of conventional materials like Zeolites, which affects the evaluation of these materials for applications such as DAC with a low concentration of CO_2 (~400 ppm).

Pressure, temperature and Vacuum Swing Adsorption technology, have been widely studied for CO_2 capture from low-pressure gas mixtures (carbon dioxide capture from air or flue gas) at laboratory and pilot-scale levels.[107] Various process configurations have been investigated, which differ by the type of adsorbent, distinct cycle steps and their sequence, operating conditions (temperature, pressure, flow velocity, etc.), and cycle step times.

Improvements continue to be sought in both adsorbents and process cycles to reduce energy consumption further and enable the use of moderate regeneration conditions that can be easily achieved on a large scale. Optimising purity–recovery and energy productivity provide critical insights into the impact of the adsorption properties of the adsorbents on the process performance.

Trade- offs invariably exist in the performance of Pressure Swing Absorption systems. Therefore, it is unlikely any design choice for exploiting the adsorbent properties for a particular feed gas condition will be optimal for all performance variables.

3.5. Research and Development Priorities

The focus of the Science and Technology Theme of this Roadmap is to develop the scientific knowledge and technology necessary to design, implement and operate a series of commercial-scale ex-situ mineral carbonation pilot plant or plants in Western Australia to demonstrate technical viability of different systems using mine gangue and tailing resources.

Table 4 outlines the approaches required to enhancing the speed and efficiency of the mineral carbonation reaction.

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[105] Sinha, A., Darunte, L.A., Jones, C.W., Realff, M.J. and Kawajiri, Y., (2017), ‘Systems Design and Economic Analysis of Direct Air Capture of CO_2 through Temperature Vacuum Swing Adsorption Using MIL-101(Cr)-PEI-800 and mmen-Mg2(dobpdc) MOF Adsorbents’, *Industrial & Engineering Chemistry Research*, 56(3), 750-764

[106] Zhu, X., Xie, W., Wu, J., Miao, Y., Xiang, C., Chen, C., Ge, B., Gan, Z., Yang, F., Zhang, M. and O'Hare, D., (2022), ‘Recent advances in direct air capture by adsorption,’ *Chemical Society Reviews*, 51(15), 6574-6651

[107] Deutz, S. and A. Bardow (2021), ‘Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption’ *Nature Energy*, 6(2), 203-213

Table 4. Science and Technology Theme

Program	Sub-program	Intent	Timeframe - Years		
			1-3	3-5	5-10
1. Target tailings and gangue characterisation	1.1 Standardised framework for assessing the suitability of tailings and gangue resources for mineral carbonation	Development of technology and methodology for the cost-effective, rapid, and accurate assessment of specific gangue and tailings resources in Western Australia as targets for ex-situ mineral carbonation.	✓		
	1.2 Identification of priority mineral carbonation resources	Applied geochemistry program using the technology and methodology developed in Program 1.1 to characterise and prioritise gangue and tailings resources in Western Australia for mineral carbonation.	✓		
	1.3 Selection of optimal resource(s)	Development of criteria to select the optimal resource(s) from the targets identified in Program 1.3 as potential subjects for the pilot plant.	✓		
2. Pilot plant design and development	2.1 Process suitability decision tree	Development of a decision framework that identifies the most suitable process route(s) that will optimise the technical success and economic viability of carbonation of the priority targets identified in Program 1.2	✓		
	2.2 Process design optimisation	Based on the process route(s) identified in Program 2.1 and the gangue and tailings resource selected under Program 1.3, optimise pilot plant reaction efficiency, cost minimisation and 'green mining' credentials.		✓	
3. Direct air capture	3.1 Process feasibility	Feasibility study to examine the techno-economic challenges of capturing adequate amounts of CO_2 from atmosphere compared to the point source emissions and transporting it to (most likely) Goldfields' site and determine the economic baseline with which DAC must compete	✓		
	3.2 Low-energy contactors for DAC system	Development of low-energy contactors for integration with the mineral carbonation process to permanently lock the CO_2 by integrating it with mineral carbonation. Integration with Program 2.1 and Program 2.2		✓	✓
	3.3 Point source capture and transportation: an interim solution	Based on finding from Program 3.2, extend the use case to further reduce energy and cost of point sources capture for interim solution.	✓	✓	
4. Mineral carbonation by and co-products	4.1 By and co-product identification	Drawing from outcomes of Programs 1.3 and 2.2 identify possible products that could be developed from the carbonated product, including specific standards that they may be required to meet in their specific market application.	✓	✓	
	4.2 By and co-product manufacturing systems	Drawing on outcomes from Programs 4.1 and 1.2 identify and design downstream process for manufacturing the products identified in Program 4.1.		✓	✓
	4.3 By- and co-product lifecycle assessment	Drawing on the outcomes from Programs 4.1 and 4.2 establish frameworks for lifecycle assessment of the carbon emissions embedded in those products.	✓	✓	

Theme Two: Economic Viability

4

4.1. Overview

In the absence of significant ongoing public subsidisation, for mineral carbonation to become an industry in Western Australia it will have to demonstrate economic characteristics to attract private capital investment.

These investment decisions will be determined not only by the commerce directly attributable to a mineral carbonation project (i.e., capital required to establish and maintain mineral carbonation operations, its direct revenue and operating expenses and thereby, financial return on investment) but also the broader economic implications including opportunity cost associated with potential alternative uses of gangue and tailings resources and consequences for an organisation's license to operate and access to product and factor markets.

Currently, the direct commerce of ex-situ mineral carbonation at scale is not viable, and the full ambit of wider economic dividends that can be accrued needs to be demonstrated. The purpose of this Theme of the Roadmap is to identify the drivers of the commerce and economics of ex-situ mineral carbonation in the Western Australian context as a basis for informing the ongoing direction of technology development and regulatory reform and as a basis for communicating the benefits of an ex-situ mineral carbonation industry to industry, governments, and the public.

4.2. Creating Multidimensional Value from Gangue and Tailings

Historically considered a necessary cost and negative externality associated with the mining and minerals recovery process, deriving value from gangue and tailings resources has recently become of greater interest to industry.

While the safety and environmental impact of particularly tailings storage facilities remains of paramount importance to industry, regulators, and communities (see the section on the Social and Environmental Theme), several trends toward recognising and creating value from these legacies of mining and minerals recovery operations are emerging:

- **Minerals recovery**: increasing in-situ scarcity of some minerals, combined with advances in minerals recovery technology and gangue and tailings resources that are, in today's terms, relatively rich in minerals for which demand has recently escalated (e.g. critical minerals), has seen an increased focus on opportunities to reprocess gangue and tailings resources to recover valuable minerals that remain in gangue and tailings that are a legacy from historical mining and mineral recovery operations.

- **Reagent recovery:** a greater focus by the mining industry on principles of the circular economy and escalating reagent costs has driven investment in the recovery and re-use of reagents and other additives that would have historically been discharged to tailings storage facilities.
- **Alternative uses of lands:** Gangue stockpiles and tailings storage facilities can have substantial physical footprints and usually render the land they are on unusable for other purposes. This sterilises that land for future minerals exploration, mining, and other uses, such as deploying renewable energy generation infrastructure such as wind or solar photovoltaic farms.
- **Restoration of traditional lands:** many Western Australian mining and mineral recovery projects were approved and commenced operations well before the recognition of First Nations land and cultural rights under various contemporary state and Commonwealth legal instruments. As a result, gangue stockpiles and tailings storage facilities will have significantly impacted traditional lands and potentially culturally significant sites. Restoring and returning these lands to traditional custodianship is a potential alternative use of these resources and an important consideration on mine closure.

Using gangue and tailings resources to store carbon as a stockpile of carbonated minerals or to produce a potential range of carbon-embedded products is a use of such resources that will compete with these other alternative uses. Its ability to do so will be primarily influenced by its full ambit of economic, social, cultural, and environmental returns compared to these different applications.

4.3. Commerciality of Accelerated Ex-situ Mineral Carbonation

While the full range of economic benefits will weigh on private sector decisions to invest in mineral carbonation, a detailed understanding of the commerciality of the mineral carbonation process as a distinct business unit, in most cases, will be a crucial element of the decision.

At the very least, there will be a limit to any financial loss that might be incurred to give effect to mineral carbonation, regardless of the broader array of economic benefits that may accrue.

When considering the commerciality of the ex-situ mineral carbonation process, there are three broad financial metrics – capital costs, operating costs, and revenue.

4.3.1. Critical Capital Cost Drivers

The initial capital cost associated with establishing and sustaining the mineral carbonation process is cited as one of the most significant barriers. It includes:

- Investments in stand-alone plants or retrofitting additional processing circuits to existing minerals recovery plants to facilitate the mineral carbonation process and, in some cases, manufacture carbon-embedded products.
- Infrastructure to capture, transport, and store CO_2 and mineral feedstock (gangue or tailings).
- Additional energy generation facilities are needed if the site does not currently have excess energy generation capacity.

Investment is required to sustain the mineral carbonation plant and associated infrastructure.

4.4. Critical Operating Cost Drivers

The primary operating cost considerations are reagents, logistics and energy.

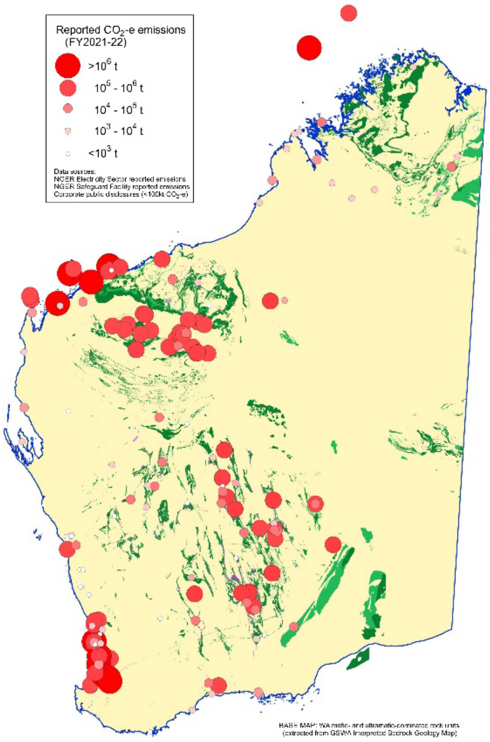
Energy

Mineral carbonation operations incur energy cost penalties through four critical aspects of the process:

- **Capturing and facilitating CO_2 feedstock:** while the CO_2 itself is a relatively free resource (either emitted as waste from an industrial process or available in the atmosphere), capturing CO_2 from either source, compressing it and delivering it to a mineral carbonation facility incurs cost. While DAC at scale is cost prohibitive, potentially, so is the notion of transporting large volumes of CO_2 via road, rail or pipeline from significant point source emissions in Western Australia to relatively remote gangue and tailings resources.

  As demonstrated in Figure 9, reported CO_2 emissions in Western Australia occur in those areas that have been deemed *prima facie* suitable for ex-situ mineral carbonation, providing a source of CO_2 feedstock as the technology developments on direct air capture occur.
- **Comminution:** optimising mineral carbonation reactions often requires maximisation of the surface area of the feedstock mineral. Tailings resources have the advantage they have already been ground and milled. However, gangue resources do not demonstrate this characteristic and tailings resources may require further comminution for optimal mineral carbonation reactions. All comminution processes incur energy penalties.

Figure 9. Western Australian jurisdictional emissions on mafic and ultramafic bedrock FY2021-22 [108]



- **Heat and pressure:** some mineral carbonation processes require preheating feedstocks or reactions under high temperatures and pressures. The exothermic nature of the carbonation reaction provides some energy penalty relief concerning any temperature requirements for the response. Still, more is needed to offset the energy required for the high temperature and pressure reaction associated with some mineral carbonation processes.
- **Materials handling and mixing:** gangue and tailings need to be moved from their current storage facilities to the mineral carbonation plant, through the processing circuit (including mixing) and to a carbonated stockpile or for further processing into products.

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[108] Image supplied by Department of Mines, Industry Regulation and Safety, Geological Survey of Western Australia

Reagents

Most mineral carbonation processes require reagents to give effect to or optimise the mineral carbonation reaction. Discussed in the Science and Technology Theme section, this can include a wide range of chemicals that need to be sourced, transported, and appropriately stored.

Logistics

The extent to which logistics is a significant operating cost driver depends on the structure of the mineral carbonation operation. Logistics costs will be minimised where the CO_2 capture, gangue or tailings resource and mineral carbonation plant are nearby.

Conversely, a mineral carbonation project transporting large volumes of CO_2, tailings, or gangue over large distances will likely incur heavy logistics cost penalties.

Logistics costs associated with transporting reagents and other inputs and potentially carbon-embedded products to market will be a cost factor for all mineral carbonation projects.

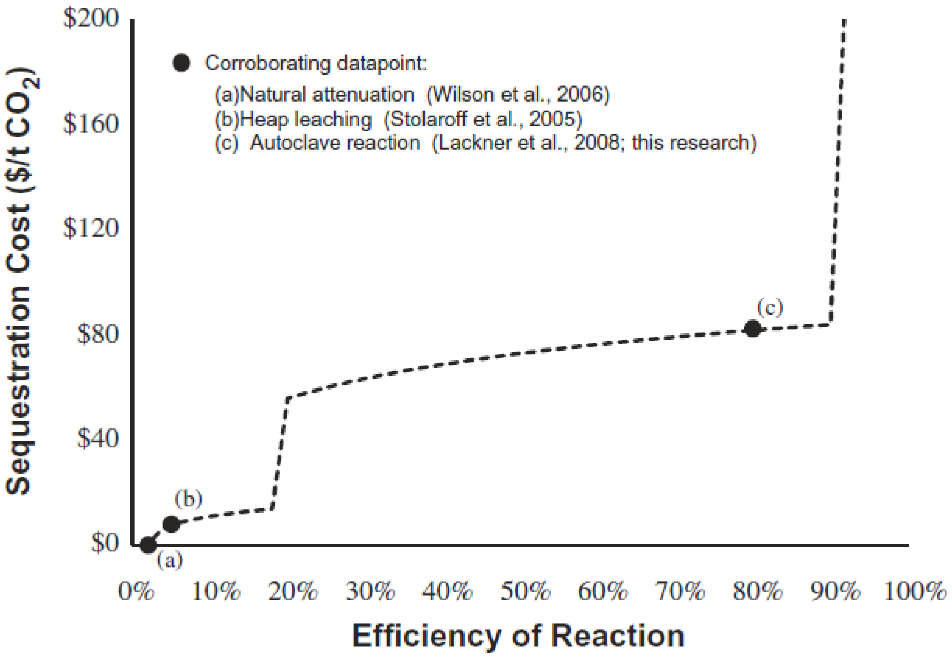
4.4.1. Total levelised costs of mineral carbonation

Total levelised costs of mineral carbonation refer to the life-of-asset capital, sustaining and operating costs of a mineral carbonation project as a ratio of the total carbon sequestered from the project, measured as the total cost per tonne of carbon sequestered.

As illustrated in Figure 10, achieving higher carbonation reaction efficiency rates requires more significant engineering intervention levels, dramatically increasing both operating and capital costs, leading to higher total levelised cost.

Table 5 summarises several estimates of costs associated with the mineral carbonation process derived from trials and modelling. This includes costs related to DAC, which are discussed further below.

Figure 10. Conceptual model of mineral carbonation costs[109]



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[109] Hitch, M. and Dipple, G. (2012), 'Economic feasibility and sensitivity analysis of integrating industrial-scale mineral carbonation into mining operations', *Minerals Engineering*, 39, 268-275

Table 5. Mineral carbonation cost estimate

Mineral Carbonation Process	Cost Estimate
Chemical costs (principally a variety of acids) associated with early trials of carbonating ultramafic nickel tailings from the Hitura nickel mine in Finland.	USD$600 to $1,600 per tonne of CO_2 sequestered[110]
Red mud mineral carbonation total cost.	USD $147 per tonne of CO_2 sequestered[111]
Point source CO_2 capture – estimate of cost of 90 percent CO_2 capture from a 532 MW coal-fired power plant.	USD $11 to $21 per tonne of CO_2 captured[112]
Direct Air Capture (DAC) - estimate of the range in total costs associated with DAC using existing technology.	USD $250 to $1,000 per tonne of CO_2 captured[113]
Direct Air Capture (DAC) – estimate of total costs in 2030 based on technology development trajectory and renewable energy.	USD $125 per tonne of CO_2 captured[114]

4.4.2. Critical Revenue Drivers

Three potential revenue streams are associated with an ex-situ mineral carbonation project – carbon credit markets, product premiums, and carbon-embedded by or co-products.

Carbon credit markets

The principal source of revenue associated with mineral carbonation is the potential to create carbon credits that can be used to offset any future charge placed on the emissions generated by mining and mineral recovery operations or securitised and traded on a compliance or voluntary carbon offset market.

The Australian Clean Energy Regulator regulates the Australian compliance market for carbon offsets. An Australian Carbon Credit Unit (ACCU) is a unit issued to an entity by the Australian Clean Energy Regulator and registered on the Australian National Registry of Emissions Units. Each ACCU represents 1 tonne of CO_2 equivalent stored or avoided by a project.

The price of carbon offset units and the liquidity in carbon offset markets is currently very much determined by the decarbonisation policy settings of a jurisdiction. This is evident in the price delta between markets and comparable volatility.

Table 6 presents a snapshot in time of carbon offset unit prices across various markets, demonstrating both the current volatility of these markets and variability in the pricing of carbon units.[115]

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[110] Teir, S., Kuusil, R., Fogelholm, C. and Zevenhoven, R. (2007), 'Production of magnesium carbonates from serpentine for long-term storage of CO_2', *International Journal of Mineral Processing*, 85(1), 1-15

[111] Sahu, R., Patel, R. and Ray, B. 'Neutralisation of red mud using CO2 sequestration cycle', *Journal of Hazardous Materials,* 179(1-3), 28-34

[112] Reddy, K., John, S., Weber, H, Argyle, M., Bhattacharyya, P., Taylor, D., Christensen, M., Foulke, T. and Fahlsing, P. (2011), 'Simultaneous capture and mineralisation of coal combustion flue gas carbon dioxide (CO_2), *Energy Procedia*, 4, 1574-1583

[113] Breyer, C., Fasihi, M. and Aghahosseini, A., (2020) 'Carbon dioxide direct air capture for effective climate change mitigation based on renewable electricity: a new type of energy system sector coupling', *Mitigation and Adaptation Strategies for Global Change* 25(1), 43-65

[114] Ibid, 104

[115] CarbonCredits.com

Table 6. Volatility and price differentials in the international carbon offset market

Carbon offset market	Last traded price	Price change (YTD)
	Compliance markets	
European Union	€88.99	+10.93%
California	USD$29.03	-9.34%
Australia	AUD$33.50	-34.31%
New Zealand	NZD$83.25	+21.62%
Republic of Korea	₩11.57	-54.13%
People’s Republic of China	RMB8.30	+6.60%
	Voluntary Markets	
Aviation Industry Offset	USD$2.89	-63.88%
Nature Based Offset	USD$4.35	-69.11%
Tech Based Offset	USD$1.16	-77.17%

Product premiums

Where an ex-situ mineral carbonation project is owned and operated by a mining and minerals recovery project whose primary business is the mining, recovery and sale of a specific mineral commodity, there is potential for markets to pay premiums for those commodities where their primary production can demonstrate a meaningful and verifiable contribution to product lifecycle emissions abatement.

While these are emerging markets, they are likely to grow, particularly in the case of critical minerals that are inputs to the manufacture of products that facilitate decarbonisation, such as lithium-ion batteries, solar photovoltaic cells, and wind turbines, as well as commodities that are feedstock to emissions-intensive manufacturing such as steelmaking.

By-products and co-products

Finally, the mineral carbonation process can be developed such that rather than producing a stockpile of carbonated gangue or tailings as the sequestration resource, it produces carbon-embedded products that have value in various applications.

These include products for the construction industry, such as cement fillers and other building materials, or the agricultural sector, such as soil improvers, albeit the market for these products is yet to be tested.

4.5. Direct Air Capture

To remove CO_2 at the scale of the sequestration resource available in the form of gangue and tailings resources in Western Australia suitable for mineral carbonation, DAC will need to be economically viable, which implies costs of less than \$100 per tonne of CO_2 at gigatonne scale by 2050.

As summarised in Table 6, current systems demonstrate costs in the range of \$250 to \$1,000 per tonne of CO_2 captured and, with the future coupling of renewables, could reduce to \$125 per tonne of CO_2 by 2030[116]. For example, the current state-of-the-art DAC facility is widely considered to be Carbon Engineering’s facility in Texas, United States,

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[116] Breyer, C., Fasihi, M. and Aghahosseini, A. (2020), ‘Carbon dioxide direct air capture for effective climate change mitigation based on renewable electricity: a new type of energy system sector coupling,’ *Mitigation and Adaption Strategies for Global Change,* 25(1), 43-65

which can capture 500,000 tonnes of CO_2 from the atmosphere per annum. Between 30 and 40 percent of the cost of operating a DAC system is in the energy associated with the fans and blowers and regenerating the absorbers/contactors.

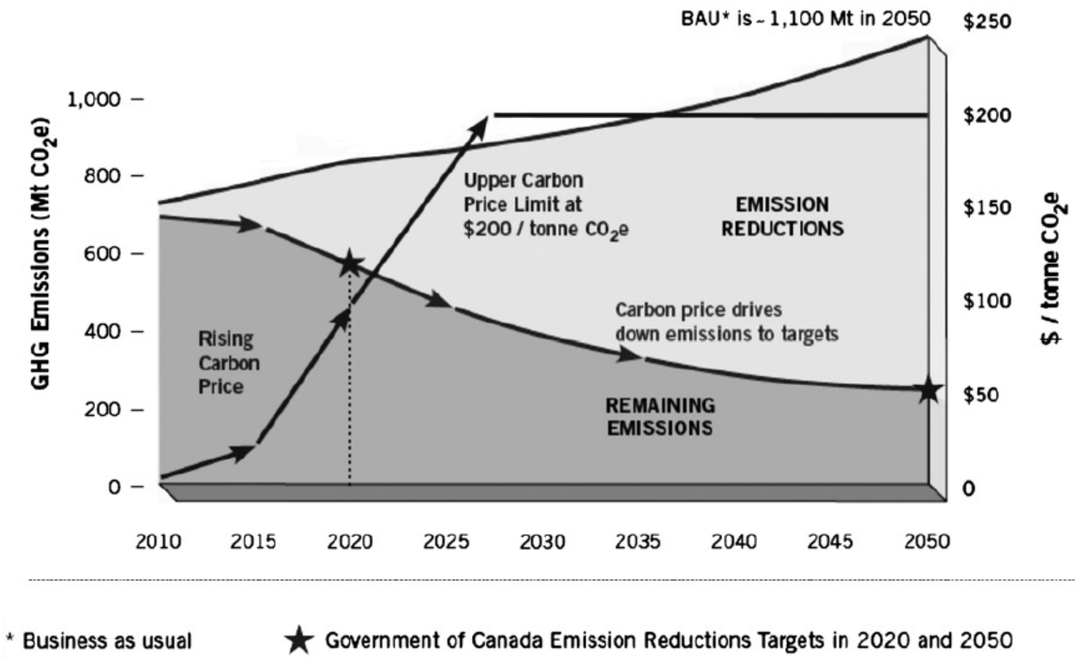
4.6. Broader Economics of Accelerated Ex-situ Mineral Carbonation

4.6.1. Mitigating Future Costs

There is little doubt companies will continue to face escalating costs associated with their emissions and other environmental externalities. As illustrated in Figure 11, prices, taxes or other penalties or charges governments will be required to place on emissions to achieve meaningful reduction will be significantly higher than they currently are. This will particularly be the case in jurisdictions that do not currently impose any direct charge on emissions, such as Australia.

Furthermore, the notion of governments applying taxes or charges for storing gangue and tailings is within the realm of possibility. Companies that invest now in mitigating these future costs may accrue a first- mover advantage in the form of lower prices and early offset market access.

Figure 11. Requirement for market-based incentives to achieve deep emissions reductions[117]



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[117] Ibid 109

4.6.2. Underwriting Future Cashflows

Similar to the inevitability of future government charges is the response of product, capital, and insurance markets to emissions-intensive operations. Increasingly, a commercial operations' viability will depend on the enterprise demonstrating to its customers, financiers, and insurers they have adequately abated emissions and managed other environmental externalities.

Further, those that go beyond minimum requirements may achieve price premiums for their products and more favourable pricing on inputs such as finance and insurance. Companies that invest in these initiatives now may achieve first-mover advantage and mitigate associated risks concerning the surety of future cash flows.

Access to markets

Consumers and business customers increasingly seek products that demonstrate carbon neutrality, positive abatement, and other environmental benefits. Further, it is likely that nation-states will increasingly apply levies to imported products that need to adequately offset emissions, like the carbon border tax that the European Union has proposed for some imports, such as carbon-intensive steel, aluminium, cement, fertilisers, and electricity.[118]

Access to finance

Increasingly financiers seek assurance concerning their investments' emissions profile and other environmental credentials. Examples of capital market responses include a USD 1 billion sustainability-linked senior note issued to Newmont. The net interest rate payable on the facility is related to achieving specific 2030 ESG objectives, including emissions targets.[119]

Access to insurance

Environmental risk is an increasingly important factor in assessing insurance risk and pricing. Businesses that must adequately address their emissions and other ecological risks will face ever-increasing premiums and potential denial of access to insurance. By way of example, the insurance industry is working on developing frameworks for insurance-associated emissions standard.[120]

4.7. Research and Development Priorities

The focus of the Economic Viability theme of this Roadmap is to develop the commercial and economic knowledge that underpins an understanding of the financial and economic metrics that must be achieved for ex-situ mineral carbonation to be viable in Western Australia that, in turn, will inform technology development pathways and policy and regulation.

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[118] Abnett, K. and Twidale, S. (2021), ‘EU proposes world’s first carbon border tax for some imports,’ *Reuters*, 14 July

[119] Newmont (2021), ‘Newmont closes sustainability – linked senior notes offering of $1 billion at 2.600%’, *New York Stock Exchange Announcement*, 20 December 2021

[120] Partnership for Carbon Accounting Financials (2022), *Insurance-associated Emissions: The Global CHG Accounting and Reporting Standard, Part C*

Table 7. Economic Viability Theme

Program	**Sub-program**	**Intent**	**Timeframe - Years**		
			1-3	**3-5**	**5-10**
1. A financial framework for mineral carbonation in Western Australia	1.1 Marketability and associated pricing of products arising from carbonation process	Identify specific products that can be produced during carbonation and determine their economic fundamentals (supply / demand and pricing).	✓		
	1.2 Beneficial offsets	Determine and quantify obviation benefits e.g. carbon trading costs, market pricing premium for products.	✓		
	1.3 Capital cost, revenue and operating cost estimations	Consider revenues, capex, and costs, formulate the most appropriate methodology, including discount rates, to gauge the economic attractiveness of carbonation.		✓	
2. Innovation in carbon credit markets	2.1 Application of derivatives	Engage with market regulators to gauge appropriateness of tradeable carbonation derivative products to ensure market-driven pricing applies, initially locally and internationally over time.	✓	✓	
	2.2 Market integration			✓	✓
3. Carbon embedded product innovation	3.1 New product opportunity scoping	Develop an integrated economic model that will assess the attractiveness of co- and/or by-product generation and sales through advancing the carbonation process to deliver additional products.	✓		
	3.2 Market assessment			✓	
	3.3 Manufacturing assessment			✓	

Theme Three: Social and Environmental

5

5.1. Overview

The intended outcome of a Western Australian mineral carbonation industry is a net social, environmental and ultimately economic benefit.

However, as with most anthropogenic activity, the mineral carbonation process and its value chain produce negative externalities and potentially impact legacy measures undertaken to minimise the negative externalities of other industrial activity and value chains.

Understanding the social and environmental impacts of the Western Australian mineral carbonation industry and developing responses to mitigate these will be vital in achieving net benefits.

5.2. First Nations Interests

From a First Nations engagement perspective, the prospect of ex-situ mineral carbonation is unique.

In most, if not all instances, gangue and tailings resources will be located on the traditional lands of specific Traditional Owners.

Given the precise location of gangue and tailings resources that have been deemed *prima facie* suitable for ex-situ mineral carbonation, a potential future mineral carbonation industry will intersect primarily with the legal rights and interests of a very discrete set of Traditional Owners as illustrated in Figure 12.

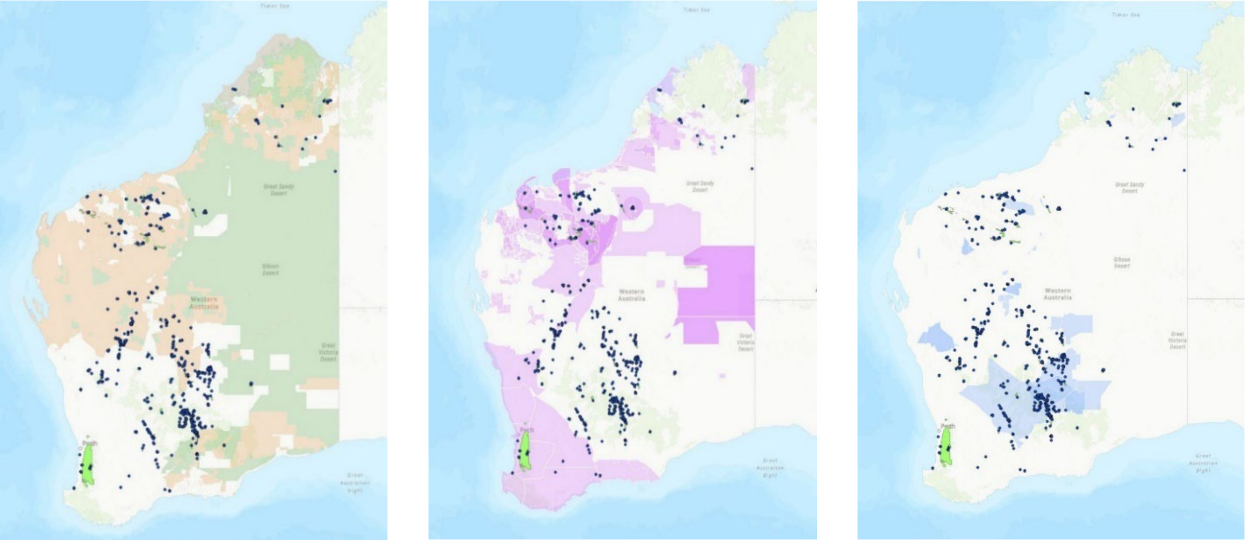
Some of these First Nations interests are still to be recognised by Federal Court determination following the *Native Title Act 1993* (Cth).

Today, most gangue and tailings resources will reside on relatively complex tenure that may include mining leases, state agreements and native title and could be close to conservation estates.

Any proposed change to the use of the land subject to these tenure arrangements will likely trigger extensive legislative economic, social, cultural, and environmental consultation requirements.

Understanding the information needs of the specific Traditional Owners as it relates to mineral carbonation and ensuring the programs support the development and presentation of this knowledge to build capability is a key tenet of this Roadmap.

Figure 12. Western Australian gangue and tailings resources suitable for mineral carbonation and First Nations land interests[121]



a) Gangue and tailings resources suitable for mineral carbonation and native title determinations

b) Gangue and tailings resources suitable for mineral carbonation and registered Indigenous Land Use Agreements

c) Gangue and tailings resources suitable for mineral carbonation and registered native title claims

5.2.1. Range of First Nations Aspirations

Understanding the specific aspirations of relevant First Nations Groups and working with them to understand the opportunities presented by using legacy gangue and tailings resources to give effect to mineral carbonation is a key area of research need.

5.2.2. Traditional Knowledge

'Traditional knowledge' refers to the practices, know-how, skills, and innovations developed by First Nations communities over millennia. As summarised in Table 8, the World Intellectual Property Organisation (WIPO) describes three types of First Nations intellectual property.

Working closely with Traditional Owners to ensure opportunities for the appropriate application of Traditional Knowledge are incorporated into the programs and sub-programs of work will be important.

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[121] Australian Venture Consultants (2022), derived data sourced: Department of Mines, Industry Regulation and Safety (December 2022), TENGRAPH/Mineral Titles Online, WA State Government; Native Title Tribunal (December 2022), Native Title Vision, Commonwealth Government

Table 8. Types of First Nations Intellectual Property[122]

Definition	Challenges to the Existing Framework
Traditional Knowledge	Knowledge resulting from intellectual activity in traditional context, including know-how, practices, skills, and innovations
Traditional Cultural Expression	Also known as 'folklore' this includes music, dance, art, designs, names, signs and symbols, performances, narratives, and architecture.
Genetic Resources	Biological materials that contain genetic information of value, and are capable of reproducing or being reproduced, including medicinal plants, agricultural crops, and products of animal husbandry

5.3. Community-Wide Social Impacts

5.3.1. Directly Affected Communities

The most immediately affected communities will be those near the gangue and tailings resources most suitable for ex-situ mineral carbonation. These are illustrated in Figure 13.

The communities most likely impacted by a Western Australian mineral carbonation industry can be broadly categorised as southwest industrial areas and central and northern Goldfields settlements.

Southwest Industrial Areas

The southwest industrial areas of relevance are Kwinana, Pinjarra, Wagerup and Collie. They are of particular significance because they are locations variably characterised by relatively significant point source CO_2 emissions and potential sequestration resources, primarily in the form of Red Mud.

Kwinana is an urban, diversified industrial area that has supported Western Australian industry in areas such as chemical and petroleum import, manufacture and storage, power generation, seawater desalination, fabrication, shipbuilding, and minerals refining for over 60 years.

Most of the Kwinana Industrial Area is the subject of Strategic Industrial Area zoning. While relatively small in scale, by international standards, Kwinana is recognised as demonstrating world-leading levels of industrial symbiosis.[123]

Wagerup and Pinjarra are synonymous with bauxite mining and alumina refining operations and are situated in areas characterised by small regional townships, rural industries, and natural bushlands.

However, Collie is a unique case in that its potential mineral carbonation sequestration targets are tailings at coal mine sites, who are drawing closer to closure. Townships in this area are seeking opportunities for diversification required to underwrite their ongoing viability.

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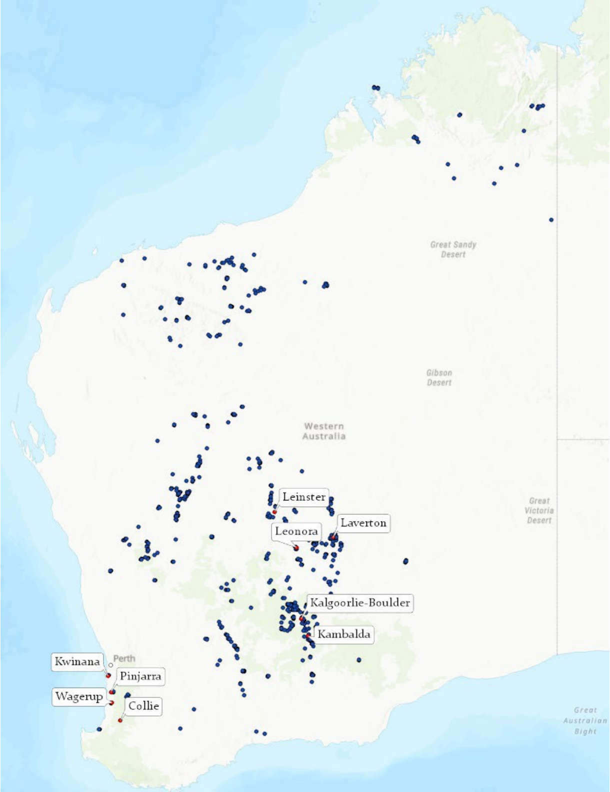
[122] https://www.nla.gov.au/sites/default/files/2023-09/nla-icip-protocol-2023.pdf

[123] Harris, S. (2007), 'Industrial symbiosis in the Kwinana Industrial Area (Western Australia),' *Measurement and Control*, 40

Figure 13. Ex-situ mineral carbonation resources and Western Australian communities[124]



Central and Northern Goldfields

While minerals processing plants, smelters and refineries in the central and northern Goldfields represent potential point source emissions of CO_2, the quantity emitted by these plants is unlikely to be adequate in the context of the scale of the possible mineral carbonation sequestration resources associated with operations in these areas.

As such, the impacts of a future mineral carbonation industry in the central and northern Goldfields are likely to be derived from mineral carbonation and product plants, stockpiles of carbonated products, transported CO_2 and potentially DAC plants.

Table 9 summarises the main settlements in the central and northern Goldfields region.

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[124] Australian Venture Consultants (2022), derived data sourced: Department of Mines, Industry Regulation and Safety (December 2022), TENGRAPH/Mineral Titles Online, WA State Government; Native Title Tribunal (December 2022), Native Title Vision, Commonwealth Government

Table 9. – Key Central and Northern Goldfields Settlements

Settlement	Population (2021)[125]	Overview
Kalgoorlie-Boulder	29,068	Western Australia's 4th largest regional centre and central government, community, and industry service centre for the Goldfields Region.
Laverton	4,818	Rural residential and administrative centre for the Shire of Laverton.
Kambalda	2,468	Rural residential area and service town for local mining and pastoral operations
Leonora	1,588	Rural residential area and service town for local mining and pastoral operations
Leinster	716	Rural residential area and service town for local mining and pastoral operations

5.3.2. Negative externalities

The main negative externalities associated with a future mineral carbonation industry that will need to be managed are those typically associated with a mineral processing-oriented plant, such as noise, built form, dust, odours, hazards associated with processing systems, their waste streams and transport of inputs and products, impacts on culture and heritage, and competing land, labour, and other resource (such as water) users.

In addition to the energy it consumes and any reaction waste products, the main externalities of DAC systems are noise associated with the giant fans used to source air in large volumes and the potential impact of those fans on local bird populations.

5.3.3. Positive externalities

The main positive externalities associated with a future mineral carbonation industry are related to the diversification of the local economy and the strengthening of the local mining industry's environmental credentials. This creates opportunities for employment, new enterprise development and ESG provenance.

Mineral carbonation represents a significant opportunity to demonstrate a circular mining economy in practice, creating environmental and economic opportunity from the legacy of mining operations lifecycle assessment (LCA) of emission, reagents, energy, and other factors that have environmental and social impacts.

Standardised frameworks for assessing and reporting LCA will be necessary as an evidence base to convince communities of this.

In addition, there is an opportunity to demonstrate the natural link between mineral decarbonisation and the development of carbon-embedded products for large emitting industries like cement manufacturing.

5.3.4. Impacts on the Broader Community

A future mineral carbonation industry has two significant impacts on the broader community. The first is the apparent benefits of reduced atmospheric CO_2 via capture from point source emissions or DAC. The second pertains to the possible impact of carbon-

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[125] Australian Bureau of Statistics (2022), *Population Census 2021*, Australian Government, Canberra

embedded products that might be produced from a mineral carbonation process and used in various applications.

Suppose carbonated products are produced from the carbonated gangue or tailings resource (such as building materials or agricultural inputs), in that case the impact of those products on the broader community must be considered. At a minimum, this means those products must meet regulatory standards concerning any residual contaminants such as heavy metals, asbestos, radionuclide or other radioactive materials, or other pollutants. Ideally, these products should be void of contaminants that may raise community or environmental concerns concerning their use.

5.4. The Integrity of Tailings Storage Facilities

Gangue stockpiles and particularly tailings storage facilities are significant negative externalities associated with the mining industry with their unique risk profile, which extends beyond mine life and, therefore, generation of positive cashflows associated with the operations.

Because compromised tailings facilities can present significant risks to human safety and the environment, ensuring the geotechnical and geochemical integrity of tailings storage facilities is of the utmost importance to mining operations and regulators and is a crucial focus of mine completion criteria.

5.4.1. The Structural Integrity of Tailings Storage Facilities

In circumstances where carbonated tailings materials are returned to the Tailings Storage Facility, there will need to be assurances the altered mineralogy does not compromise the structural integrity of the Tailings Storage Facility

5.4.2. Containment of Drainage Waters

Of particular importance are drainage waters. Contaminated drainages such as acid mine drainage (AMD), contaminated neutral drainage (CND), or alkaline drainage produced by weathering of metal sulphides exposed to water and oxygen can have significant environmental impacts [126] that reach well beyond the immediate site of a gangue stockpile or tailings storage facility.

Several factors, including the mineralogy, surface area, drying and wetting cycles, microbial activity and temperature of the gangue or tailings, determine the chemistry of drainage waters.[127, 128]

Tailings can contain heavy metals, toxic elements, and mineral groups. The carbonation process can fix and immobilise hazardous components and mineral groups in

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[126] Kandji, E., Plante, B., Bussiere, B., Beaudoin, G. and Dupont, P. (2017), 'Kinetic testing to evaluate the mineral carbonation and metal leaching potential of ultramafic tailings: a case study of the Dumont Nickel Project, Amos, Quebec,' *Applied Geochemistry*, 84, 262-276

[127] Stillings, L., Foster, A., Koski, R., Munk, L. and Shanks, W. (2008), 'Temporal variation and effect of rainfall on metals flux from the historic Beatson mine, Prince William Sound, Alaska, USA', *Applied Geochemistry*, 23, 255-278 Bowes, D., Ptacek, C., Jambor, J. and Weisener, C. (2013) 'The geochemistry of acid mine drainage' IN *Treatise on Geochemistry*, 2nd Edition

[128] Bowes, D., Ptacek, C., Jambor, J. and Weisener, C. (2013) 'The geochemistry of acid mine drainage' IN *Treatise on Geochemistry*, 2nd Edition

carbonate forms and some cases, produce environmentally benign minerals.[129] A mineral carbonation process that results in the safe and environmentally sound removal or reduction of tailings may benefit mining companies.

5.4.3. Ecosystem Services of Gangue Stockpiles and Remediated Tailings

Another environmental consideration that applies to mineral carbonation is the potential ecosystem services role gangue stockpiles and remediated tailings storage facilities might perform, such as refugia for various flora and fauna, particularly in the context of the impact that historical mining and associated land clearing may have had on the ecosystems that support them and the local prevalence of particular species.

5.5. Research and Development Priorities

The focus of the Social and Environmental Theme of this Roadmap is to develop a detailed and specific understanding of the likely social and environmental impacts of a mineral carbonation industry in Western Australia and the process that can be used to mitigate negative socio-environmental externalities and capitalise on positive socio-environmental externalities.

Table 10. Social and Environmental Theme

Program	Sub-program	Intent	Timeframe - Years		
			1-3	3-5	5-10
1. First Nations	1.1 Social, cultural, and environmental impact mapping	Ensure First Nations people have the capability to engage equitably in discussions on ex-situ mineral carbonation technology and can be aware of the risks and opportunities it presents, enabling Free, Prior and Informed Consent and Access and Benefits Sharing.	✓		
	1.2 TEK application framework		✓	✓	
	1.3 Commercial frameworks for First Nations partnerships		✓	✓	✓
2. Community Engagement	2.1 Socio-economic impact mapping	Ensure positive and negative externalities are identified and quantified on an evidence-base, so that communities are well informed, negative impacts are adequately mitigated and opportunities optimally capitalised on.	✓		
	2.2 Socio-economic multiplier analysis		✓		
	2.3 Socio-economic impact modelling		✓		
3. Environmental impacts	3.1 Waste streams	Develop an early understanding of the net impact of ex-situ mineral carbonation on cumulative impacts on the environment that may result from waste streams from the process, compromised or improved tailings facilities integrity and any function that gangue or tailings facilities may perform as refugia.	✓		
	3.2 Tailings Storage Facility Integrity		✓	✓	✓
	3.3 Gangue and tailings as refugia		✓	✓	✓

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[129] Azadi, M., Edraki, M., Farhang, F. and Ahn, J. (2019), 'Opportunities for mineral carbonation in Australia's mining industry', *Sustainability*

Theme Four: Policy and Regulatory

6

6.1. Overview

Commercialising mineral carbonation systems and developing a viable mineral carbonation industry in Western Australia will require some regulatory reform at the Commonwealth and jurisdictional levels. This will be needed for activities along the value chain, including approved methodologies for creating Australian Carbon Credit Units, standards for carbon-embedded products in other industries, management of negative externalities associated with the carbonation process and potential transportation of large volumes of CO_2 and tailings.

6.2. The Potential Ambit of Regulatory Reform

The legislative framework that applies to the mineral carbonation value chain is extensive and incorporates Commonwealth and jurisdictional (Western Australian) legislation and regulation, as well as potential international regulations and industry standards. Table 11 summarises critical Western Australian and Commonwealth legislation to be assessed.

6.3. Reform Priorities

6.3.1. Optimally Effective Offset Instruments

For revenue opportunities associated with accelerated ex-situ mineral carbonation to be optimised, there may need to be reform in sequestration methods approved by the Clean Energy Regulator (CER), as well as the existing Australian Carbon Credit Unit (ACCU) and the proposed Safeguard Mechanism.

Clean Energy Regulator Approved Methodology

A significant challenge facing the viability of accelerated ex-situ mineral carbonation is the lack of a CER approved method for this system of offsetting carbon emissions.

The CER is increasingly preferencing developing approved methodologies from operating processes rather than theoretical modelling.

While given the emerging nature of mineral carbonation, it is expected the resulting approved method will continue to evolve as the technology advances, early incorporation of credits for avoidance in the approved form will likely be critical to the economic viability of mineral carbonation.

Table 11. Examples of legislation requiring assessment

	Western Australia	Commonwealth
Carbon Capture and storage	*Greenhouse Gas Storage and Transportation Bill 2022*	*National Greenhouse and Energy Reporting Act 2007*
Gas transmission	*Petroleum Pipelines Act 1969 Gas Standards Act 1972* *Gas Supply (Gas Quality Specifications) Act 2009*	
Land use	*Conservation and Land Management Act 1984* *Petroleum and Geothermal Resources Act 1967* *Mining Act 1978* *Petroleum (Submerged Lands) Act 1982 Land Administration Act 1997* *Carbon Rights Act 2003* *Planning and Development Act 2005*	
Environmental and cultural	*Aboriginal and Cultural Heritage Act 2021* *Environmental Protection Act 1986*	*Environment Protection and Biodiversity Conservation Act 1999* *Native Title Act 1993*
Carbon markets		*Carbon Credits (Carbon Farming Initiative) Act 2011* *Carbon Credits (Carbon Farming Initiative) Regulations 2011* *Carbon Credits (Carbon Farming Initiative) Rule 2015*
Product markets	*Building Act 2011*	
General	*Work Health and Safety Act 2020* *Dangerous Goods Safety Act 2004*	

Australian Carbon Credit Unit timeframes

With the maximum period of storage valued under an ACCU currently only 25 years, a unique opportunity that should also be a target of early reform to the approved CER method for mineral carbonation is incorporating the additional value of the relatively permanently locked nature of mineral carbonation.

Safeguard mechanism

The Safeguard Mechanism requires Australia's largest greenhouse gas emitters to keep their net emissions below an emissions limit (a baseline). Still under development by the CER, it is proposed that the Safeguard Mechanism revolves around the following:

- Gradual reduction of baselines to help Australia reach net zero emissions by 2050
- Introduction of credits for facilities that emit less than their baseline
- Provision of tailored treatment to emissions-intensive, trade-exposed facilities so businesses are not disadvantaged compared to international competitors and emissions do not increase overseas.

To benefit from the proposed Safeguard Mechanism, ex-situ mineral carbonation must be approved.

6.3.2. International and Complementary Market Integration

In developing carbon market opportunities for accelerated ex-situ mineral carbonation, there is opportunity for the sector to not confine itself to Australian carbon markets and explore options for both accrediting units under international frameworks, as well as voluntary markets and particularly as global emissions increase, the supply of sequestration assets decrease, and carbon prices rise accordingly.

As with all carbon market products, the credit will be created at the point of sequestration, which will most likely be the gangue or tailings resource and, therefore, most likely the property of a mining company. Therefore, commercial frameworks that consider the unique nature of an ex-situ carbonated sequestration asset will need to be established to transfer the carbon credit benefit to a third party.

Carbon credit markets for mineral carbonation should seek to extend beyond the mining industry to other naturally related sectors. For example, if carbon-embedded building products can be produced from carbonated products, the construction industry, which accounts for significant global emissions, would, *prima facie*, be a natural customer.

6.3.3. Synergy With Other Gas Regulation Reform

As Western Australia navigates the energy transition, legislation and regulation about generating and transmitting of energy and energy products will require reform.

Understanding those areas of regulation preventing ex-situ mineral carbonation are necessary.

6.3.4. Lifecycle Assessment frameworks

As regulators and markets expand their assessments of emissions and other environmental and social impacts beyond Scope 1, standardised lifecycle assessment (LCA) frameworks for reporting on Scope 1, 2, and 3 emissions will need to be developed.

Because mineral carbonation has application in mitigating Scope 1 emissions and through the potential application of DAC, Scope 2 and 3 emissions, the design of LCA frameworks that maximise the role of mineral carbonation in offsetting the full scope of emissions will likely prove vital for economic viability.

6.3.5. Carbon-Embedded Product Market Regulation

Where the ex-situ carbonation process produces carbonated products for a commercial application rather than merely a stockpile of carbonated minerals, regulatory reform will likely be required from two perspectives.

Firstly, in circumstances where the carbon sequestered in the product has been claimed as an offset directly or through a securitised instrument, there will need to be regulatory mechanisms that ensure the integrity of the offset once the carbonated product has been sold.

Secondly, where the carbonated product is sold into a regulated market, such as building products, it must comply with regulations and standards that apply to those regulated markets, or that regulation will require reform.

6.3.6. Research and Development Priorities

Policy and Regulation Theme of this Roadmap focuses on developing a compelling policy case for investment in ex-situ mineral carbonation in Western Australia and identifying areas of regulatory reform necessary to facilitate an ex-situ mineral carbonation industry in Western Australia.

Table 12. Policy and Regulation Theme

Program	Sub-program	Intent	Timeframe - Years		
			1-3	3-5	5-10
1. Policy case evidence base	1.1 Industry development level economic impact modelling	Develop evidence to support a policy and investment case for developing a mineral carbonation sector in Western Australia that can be advocated to government, industry and the community with confidence.	✓		
	1.2 CO_2 abatement modelling		✓	✓	✓
2. Regulatory compliance and reform pathway	2.1 Inventory and analysis of Western Australian and Commonwealth legislation and regulations and associated policy and guidelines	Ensure all legislative, regulatory, policy and guidelines that are relevant to establishing and growing a mineral carbonation industry in Western Australia are understood, with compliance built into process and value chain design and any reform that is required can be advocated for early and on an evidence basis.	✓		
	2.2 Reform pathways		✓	✓	✓
3. Innovation in offsets regulation	3.1 Australian offsets products	Ensure legislation, regulation, policy and guidelines are suited to new and innovative carbon offset products will be produced from a Western Australian mineral carbonation industry.	✓		
	3.2 Emissions Lifecycle Assessment framework innovation		✓	✓	
	3.3 Carbon embedded products		✓	✓	✓

Appendices

A1. Abbreviations and Glossary of Terms

Atmosphere (atm)	A unit of measure of pressure whereby 1 atm is equivalent to the average air pressure at sea level at a temperature of 15°C.
Basalt	A dark-coloured, fine-grained, igneous (volcanic) rock that is low in silica content and comparatively rich in iron and magnesium
Brine	Water with a salt concentration greater than 35 parts per thousand (3.5 percent)
Carbon Dioxide (CO_2)	Chemical compounds comprised of molecules that each have one carbon atom covalently bonded to two oxygen atoms. Present in many industrial emissions it has a ‘greenhouse’ effect by absorbing infrared radiation. Since industrialisation it has increased from 280ppm to 420ppm in the Earth’s atmosphere.
Curtin University (Curtin)	An institute of higher education with campuses in Western Australia, Malaysia, Singapore, Dubai, and Mauritius.
Western Australian School of Mines, Mineral, Energy and Chemical Engineering (WASM: MECE)	A world-leading resources industry tertiary education and research institution operated by Curtin University.
Direct Air Capture (DAC)	A system whereby CO2 (or other targets) is removed and captured from a feedstock of atmospheric air.
Gangue	Minerals that typically consist of common silicate, oxide, carbonate and sulphate minerals that are necessarily extracted as part of the mining process, but which do not contain sufficient concentration of valuable metals to economically warrant recovery processing.
Gigatonne	1 billion tonnes
Greenhouse gases	A gas that absorbs and emits radiant energy within the thermal infrared range, causing a ‘greenhouse’ effect that heats the Earth. The primary greenhouse gases are water vapour (H2O), carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O) and Ozone. At natural levels, they perform a critical role in regulating temperatures on Earth. However, because of artificially high levels that are derived from anthropogenic sources, they are a vital cause of global warming.
Renewable energy	Energy in the form of heat and electricity that is produced from natural renewable resources such as wind, solar or hydro resources.

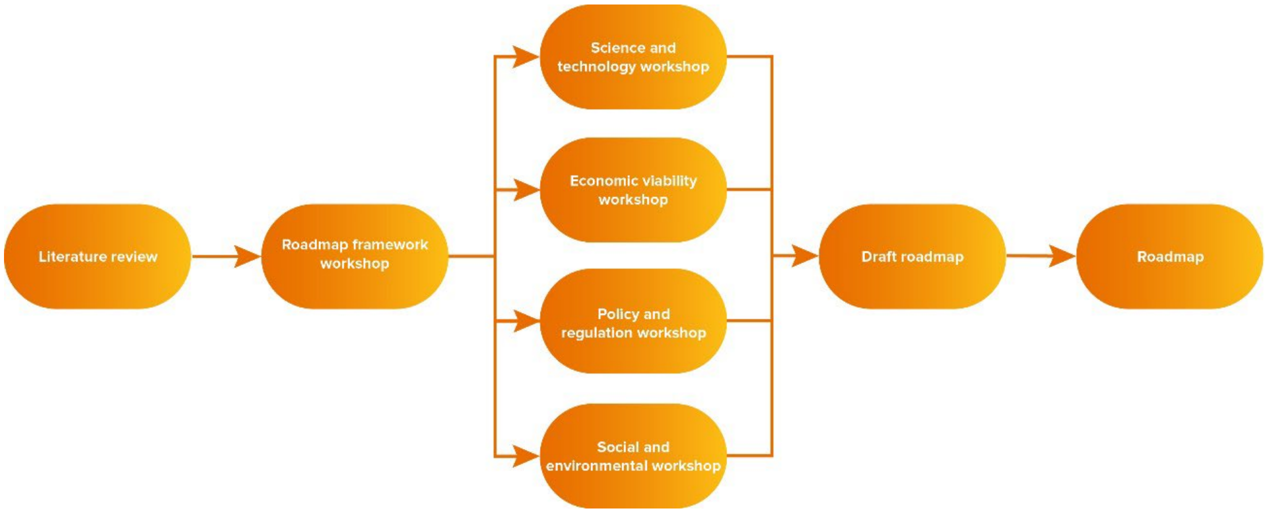
Hydrocarbons	Compounds comprised exclusively of carbon and hydrogen, which can be used to generate heat and electricity via combustion, which releases CO2. Key hydrocarbons include petroleum products such as crude, ULP, diesel and kerosene; coal; and natural gas. Hydrocarbon resources are often known as 'fossil fuels'.
Lithosphere	The rigid outermost rocky shell of a terrestrial planet or natural satellite, which in the case of Earth, is comprised of the crust and the portion of the upper mantle that behaves elastically on time scales of up to thousands of years.
Mafic rock	Silicate mineral or igneous rock rich in magnesium and iron.
Mineral	A solid inorganic substance with a definite chemical composition and crystal structure.
Minerals Research Institute of Western Australia (MRIWA)	A Western Australian Government Statutory Authority that is charged with providing grants to research organisations to develop science and technology that benefits the Western Australian minerals industry.
Olivine	Magnesium iron silicate mineral common in the Earth's subsurface.
Parts per Million (ppm)	A unit of measure of concentration, whereby a concentration of 1 ppm is equivalent to 0.0001 percent.
Serpentine	A large group of hydrous magnesium iron phyllosilicate minerals, resulting from the metamorphism of the minerals that are contained in mafic to ultramafic rocks. Chrysotile, antigorite, and lizardite are three of the primary serpentine minerals.
Scope 1 emissions	Greenhouse gas emissions released to the atmosphere as a direct result of an activity, or series of activities at a facility level.
Scope 2 emissions	Greenhouse gas emissions released to the atmosphere from the indirect consumption of an energy commodity.
Scope 3 emissions	Indirect greenhouse gas emissions other than Scope 2 greenhouse gas emissions that are generated by the wider economy.
South West Integrated System (SWIS)	An electricity generation and distribution system servicing the Perth Metropolitan Area and the southwest of Western Australia, which incorporates around 75 percent of the State's population and much of its industry.
Ultramafic rock	Rocks usually composed of greater than 90% mafic minerals with very low silica content (less 45%).
Wollastonite	Calcium inosilicate mineral that can contain small amounts of iron, magnesium and manganese substituting for calcium.

A2. Roadmap Development Process

Recognising this opportunity and the obstacles to be navigated for a mineral carbonation industry to develop in Western Australia, the Minerals Research Institute of Western Australia (MRIWA) commissioned Curtin University and its Western Australian School of Mines, Mineral, Energy and Chemical Engineering (WASM: MECE) to prepare, in consultation with other research organisations, industry, government and communities, this Western Australian Mineral Carbonation Roadmap, that will see the development of a commercial scale ex-situ mineral carbonation plant operating in Western Australia and a clear pathway for the development of a mineral carbonation industry in the State.

The following Figure 14 illustrates the process used to develop this Roadmap.

Figure 14. The Western Australian Mineral Carbonation Roadmap development process



A comprehensive review of academic and industry literature on mineral carbonation, mineral carbonation processes and the economic viability of mineral carbonation was undertaken to understand specific strategies that may underpin a Western Australian mineral carbonation industry, the state-of-the-art in mineral carbonation processes and issues about economic viability and potential social and environmental externalities[130].

Based on this literature review, WASM: MECE facilitated an online workshop attended by over 120 experts in mineral carbonation and mineral carbonation technology. This workshop identified and debated current opportunities and challenges associated with mineral carbonation in the global context and established a framework for the Western Australian Mineral Carbonation Roadmap (see following subsection).

After the Roadmap Framework Workshop, four separate workshops were held to deeply explore the themes that underpin the Roadmap frameworks – science and technology, economic viability, policy and regulation and social and environmental issues. These

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[130] Ibid, 30

workshops were facilitated by and attended by global experts in each thematic area. Summary reports from these workshops were produced and provided to participants for feedback and comment.

The information from the literature review and the workshop process was then synthesised into a draft Roadmap, which has been reviewed by all workshop facilitators, with their input incorporated into the final Roadmap.

Individuals and organisations that have contributed to the development of this Roadmap are listed below.

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