Enabling mine closure and transitions: Opportunities for Australian industry

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Authorship

This report was authored by Dominic Banfield, Anthea Moisi, Jose Francisco Carranceja, Jasmine Cohen and Vivek Srinivasan.

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CRC TiME

Part of the Australian Government's flagship CRC Program, the Cooperative Research Centre for Transformations in Mining Economies (CRC TiME) brings together diverse stakeholders to help re-imagine and transform mine closure and transitions for the better. It is the world's only dedicated research focused on what happens after mining ends.

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Foreword from the Minister

Mining has been key to Australia's economic development since the very first coal exports from our continent in 1802, and is at the heart of our reputation as a modern, trading nation.

Now, Australia is again looking to its miners to support our nation and the world through the transition to a cleaner future on the path to net zero emissions by 2050.

The path to net zero runs through the resources sector.

If we are to reduce emissions, we will need to mine more.

We will need more minerals to build the wind turbines, batteries, solar panels and transmission lines needed for the energy transition.

But as we undertake this enormous task, we must also ensure we are improving the way we go about mine closures once we have put those resources to good use.

Just like exploration and investment in new projects, mine closure is a normal part of the lifecycle of all mines.

This report estimates almost 240 existing mines will close by 2040. In addition to this there are many thousands of unrehabilitated mines in Australia.

The way we have gone about closing and rehabilitating mines has changed radically over past decades.

There is now a much greater understanding of the risks and opportunities associated with rehabilitation processes, not just for local communities but also for the social licence of resource companies themselves.

As we open more mines there will inevitably be growth in demand for expertise in mine closures and rehabilitation.

This will bring immense opportunity for both workers and communities, including for First Nations communities.

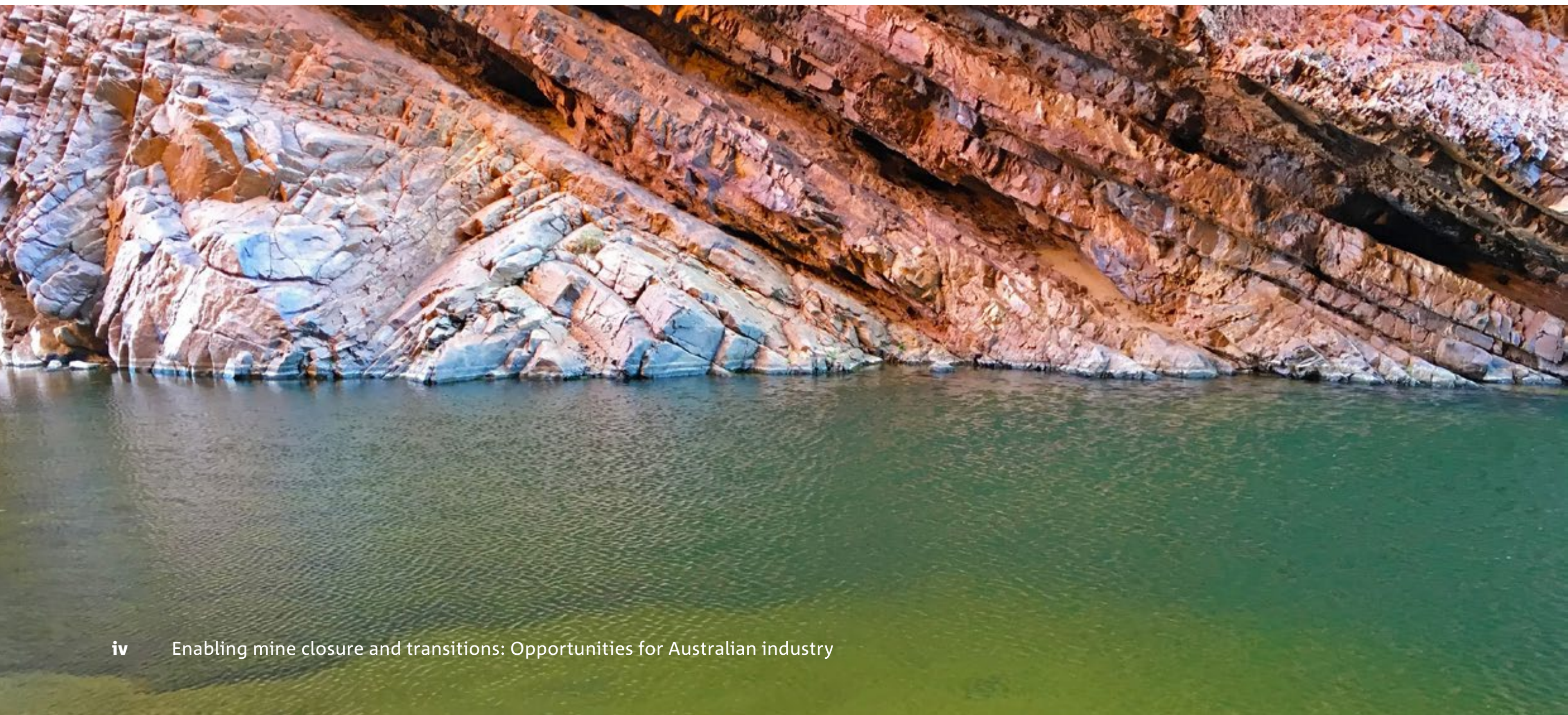
Just as Australia has a world leading reputation for our Mining, Equipment and Technology Services, we can become a major exporter of skills and expertise in mine closure and rehabilitation services.

The Albanese Government is committed to working with industry to address challenges in this sector, to make the most of opportunities and to create jobs.

We will ensure our mining and energy sectors remain strong and sustainable for current and future generations.

This report is a significant milestone in the ongoing conversation of how we make the world's greatest mining industry even better.

Hon Madeleine King MP
Minister for Resources
Minister for Northern Australia
Member for Brand



Foreword from CRC TiME

I am pleased to introduce this landmark report, *Enabling mine closure and transitions: Opportunities for Australian industry*.

Based on novel economic analysis and broad stakeholder engagement, it establishes a compelling case for coordinated action to help unlock new domestic and global opportunities for Australian enterprises while helping solve the mine closure and transition challenge.

A significant opportunity for Australia

CRC TiME brings together diverse partners to help reimagine and transform what happens after mining ends for the better. Our work covers all aspects of transformations in mining economies.

An important goal is supporting further growth of the specialist part of the mining equipment, technology and services (METS) sector supplying what we describe as 'mine closure solutions'.

These businesses – which include regionally based, export-focused and Indigenous enterprises – are involved in the diversity of activities and strategies required to optimise environmental, social and governance (ESG) outcomes post-mining.

Demand for these specialist solutions is growing.

In this report, CSIRO has identified almost 240 Australian mines that are projected to close by 2040, with conservative estimates of annual expenditure on mine closure and remediation activities at these mines alone ranging from $4 billion to $8 billion annually.

This is in addition to ongoing requirements ensuring mines are prepared for and progressing integration of closure at 2,200 active mines, as well as investment in tens of thousands of unrehabilitated legacy sites .

Beyond land rehabilitation to asset repurposing and waste recovery

This report also provides the first comprehensive mapping of opportunities for growth in Australia's mine closure solutions industry.

Existing and emerging opportunities across four categories were identified, namely:

- **Engagement and partnership**, such as solutions that enable effective engagement, co-design and mutually beneficially partnerships between industry and regional and First Nations communities.
- **Waste reduction and recovery**, such as solutions that enable cost-effective reduction, reuse and recycling of mine wastes. This includes recovery of critical and other minerals.
- **Mine rehabilitation**, such as solutions that improve performance or cost-effectiveness of land rehabilitation activities. This includes biodiversity and revegetation activities.
- **Land use transitions**, such as businesses specialise in identifying, assessing and developing post-mining land uses (i.e energy generation).

Critically, the mapping process highlights both the diversity of opportunity as well as the additional social, economic and environmental value that can arise from innovative solutions.

Enabling actions

As outlined in the report, Australia could leverage the domestic mine challenge to position itself as a leading global supplier of mine closure solutions.

For CRC TiME, this report represents a major step forward in unlocking this potential. Yet further cooperation and targeted action is needed.

We look forward to engaging widely about the enabling actions identified that will support the growth of Australia's mine closure solutions industry. We also see partnering on targeted studies of opportunities for Indigenous, regional and export-focused businesses as a priority.

Dr Guy Boggs
Chief Executive Officer
Cooperative Research Centre for Transformations in Mining Economies (CRC TiME)

This report

Objectives

The project's objectives are to:

- Identify growth opportunities for Australian businesses to provide mine closure solutions that address closure risks, and deliver social, environmental and economic value, including opportunities for Indigenous businesses.
- Identify actions to support industry development and encourage export opportunities for Australian MCS providers.

Definitions

This report uses the term *mine closure and transitions* to describe strategies and activities related to the completion of mining activities, rehabilitation of mined land, and the establishment of post-closure land uses. These activities include engagement and partnerships, waste reduction and resource recovery, mine rehabilitation and land use transitions. *Mine closure solutions* describe equipment, technology or services that support and enable these activities. Companies that provide these solutions are referred to as *MCS providers*. Please refer to Appendix A for a complete glossary of terms used in this report.

Methodology

Interviews and workshops

This report was developed in consultation with **114** individuals from **62** relevant organisations during scoping and delivery. The focus of consultations was on industry participants including miners, MCS providers (including Indigenous businesses), researchers, and government stakeholders. Consultations with mining communities (including Traditional Owners and other Indigenous stakeholders) are outside the scope of this project. Stakeholders provided direction and input by participating in:

- **Interviews:** Individual organisation consultations were undertaken with targeted stakeholders involved throughout the mine closure and transition cycle. These consultations were used to identify challenges faced during mine closure and transition, opportunities for Australian business and emerging solutions from MCS providers, and the barriers and enabling actions for industry growth.
- **Workshops:** Two workshops were undertaken with targeted stakeholders to refine and test findings from the interviews. The first of these workshops was used to define mine closure challenges and opportunities. The second was used to explore enabling actions that could support the growth of the MCS industry.

Novel economic analysis

This report developed two approaches to showcase the economic opportunity of mine closure and evidence of the scale of the opportunity for MCS providers. The first approach explores the opportunity of mine closure broadly from a top-down approach based on the number of Australian mines projected to close by 2040. The second approach explores the scale of the potential market for environmental remediation technologies in the mining sector.

Executive summary

Improving the outcomes of mine closure and transitions is a critical challenge for Australia and the mining industry. This report explores opportunities for Australian businesses to supply equipment, technology and services-based solutions that help solve the industry's mine closure challenges.

Australia has a growing demand for solutions that support the mining industry to optimise the social, environmental and economic outcomes of mine closure and transitions

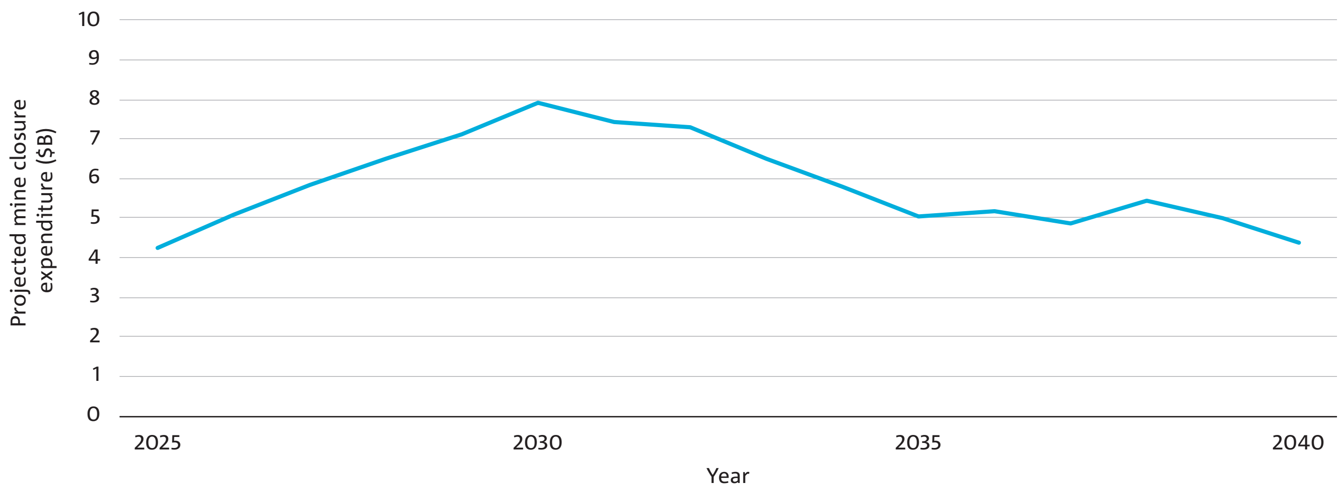
This report estimates that expenditure on mine rehabilitation and closure activities could exceed $4 billion each year, with almost 240 existing Australian mines expected to close by 2040. Mining will continue to play a critical role in Australia and the global economy by providing the mineral commodities essential to society and achieving net-zero emissions by 2050. With increasing demand for many minerals, over 2,200 active mines and tens of thousands of unrehabilitated mines in Australia, there will be an ongoing demand for innovative mine closure solutions that mitigate social, cultural, environmental and economic risks and reduce the costs of rehabilitation and other activities. In addition, there is an emerging demand for mining transition solutions such as resource recovery and post-closure land use that optimise value for both local communities and miners.

This demand will create valuable opportunities for mine closure solutions (MCS) providers, including Australia's world-class mining equipment, technology, and services (METS) industry and a broad range of other businesses such as plant nurseries, drone operators, software developers, environmental services providers, and specialist consultants. This demand can also create business and employment opportunities for Indigenous and regional communities.

Australia can leverage domestic mine closure challenges to become a global supplier of solutions that improve outcomes and reduce the costs of mine closure and transitions

Over the last 20 years, stakeholder awareness of the liabilities and risks associated with mining has increased significantly. The social dimensions of mine closure are also increasingly recognised as an important factor in the mining life cycle, especially during closure. However, despite the increasing focus on mine closure and transitions, there are very limited examples of successful mine closure, relinquishment and post-mining land use in Australia. Safe, cost-effective, and sustainable solutions will be needed to address the complex economic, environmental, and social challenges posed by mine closures.

Expenditure on mine rehabilitation and closure activities is projected to exceed $4 billion each year



This report explores opportunities for Australian MCS providers across four categories of mine closure solutions: engagement and partnership, waste reduction and recovery, mine rehabilitation, and land use transitions. For each of these categories, industry consultations, workshops and desktop research identified challenges facing mine closure practitioners and related opportunities for Australian businesses to supply mine closure solutions.

Engagement and partnerships

Solutions that enable effective engagement, co-design, and mutually beneficial partnerships to improve social performance, reduce social and governance risks and optimise outcomes.

Challenges	Opportunities
Effective engagement	• Facilitation services for complex stakeholder engagements • Tools to support data-driven engagement, governance, and decisions • Tools for the effective and inclusive communication of complex information
Co-design and partnerships	• Facilitation and capability development services to support sustainable partnerships with communities • Data management solutions to support transparency, governance, co-design and delivery of mine closure outcomes

Waste reduction and resource recovery

Solutions that enable cost-effective reduction, reuse, and recycling of mine waste to minimise closure liabilities, residual risk, and ongoing maintenance costs.

Challenges	Opportunities
Waste reduction	• Low-impact and precision mining technologies
Repurposing mineral waste	• Waste-derived materials and products
Resource recovery	• Technologies to characterise and recover minerals from waste
Recycling non-mineral waste	• Cost-effective and responsible recycling services for mining equipment and infrastructure

	Mine rehabilitation
	Solutions that improve the performance or cost-effectiveness of mine rehabilitation activities to ensure that mined land is safe, stable, non-polluting and able to support an appropriate land use.
Challenges	**Opportunities**
Physical stability	• Enhanced data collection with remote technology for landform design and monitoring • Resilient landform construction products and engineering solutions • Thickening and dewatering technologies to stabilise tailings • Technology solutions to optimise the movement of excavated materials
Hydrological systems	• Engineered solutions for hydrological system restoration, stabilisation and water quality management • Technology to monitor and model the long-term impacts of mining on surface and groundwater systems
Pollutant management	• Prevention and monitoring technologies to mitigate hazardous pollutants • Improved pollutant remediation technologies
Revegetation and biodiversity	• Modelling and monitoring technologies to measure biodiversity impacts • Cost-effective treatment technologies to enhance the quality of disturbed topsoil • Sustainable native seed collection services for revegetation • Weed removal systems to reduce labour intensity and prevent potential hazards

	Land use transitions
	Solutions that address challenges preventing the establishment of post-closure land uses on mined land to generate lasting economic, social, or environmental value and offset the costs of managing ongoing liabilities.
Challenges	**Opportunities**
Post-closure land use	• Businesses specialising in identifying, assessing, enabling and developing of post-closure land uses

Enabling actions can support continued growth of Australia's MCS industry

To enable this opportunity, stakeholders will need to take coordinated and targeted action to address key barriers to developing the MCS industry. These actions are designed to support the growth of a sustainable and productive ecosystem of Australian MCS providers, irrespective of their specific closure solutions. Most actions require collaboration, and a subset of identified measures will require leadership from multiple stakeholders.

Government and industry stakeholder actions to enable growth of Australia's MCS industry

Multi-stakeholder actions

1. Increase visibility of mine closure challenges and opportunities to support partnerships and innovation with MCS providers.
2. Develop and implement methods that value the social and environmental outcomes of mine closure and transitions.
3. Encourage collaborative research and support demonstration of innovative mine closure solutions.

MCS industry actions

4. Develop a coherent MCS industry identity and aligned strategy.
5. Broaden customer base through adaptability, interoperability and export.
6. Align solutions with evolving stakeholder expectations and miner requirements.
7. Strengthen commercialisation and business development skills of emerging providers.

Mining industry actions

8. Embed performance indicators that increase the focus on mine closure and transitions within mining companies and drive uptake of effective solutions.
9. Ensure that procurement policies allow new market entrants and small companies to provide innovative mine closure solutions.

Government actions

10. Review regulatory barriers to novel mine closure and transition solutions.
11. Support MCS industry capability development and export opportunities.

1 Introduction

Improving the outcomes of mine closure and transitions is a critical challenge for the global mining industry that presents an opportunity for Australian businesses. This report explores opportunities for Australian businesses to supply equipment, technology and service-based solutions that can address mine closure challenges and improve social, environmental and economic outcomes. The report also identifies enabling actions to support this industry's growth.

Improving the outcomes of mine closure is critical to the future of Australian mining

Mining has contributed significantly to Australia's economic prosperity for well over 100 years. It will continue to play a critical role in providing the mineral commodities essential to society and achieving net-zero emissions by 2050. However, mining is a temporary land use that can have mixed impacts on local and regional communities and environments. When mine closure does not adequately address these impacts, it can diminish the already low levels of trust in the mining industry.[1] Miners, regulators, and communities have become increasingly aware of the social and environmental effects of mining and mine closure and identified the importance of addressing these issues to rebuild trust in the sector.[2]

Over the last 50 years, Australia's approach to mined land rehabilitation and closure has broadened. From an initial focus on undertaking rehabilitation only within mine sites to meet environmental compliance standards, leading practice now seeks to understand cumulative regional impacts and undertake progressive rehabilitation.

However, it has only been in the last 20 years that stakeholder awareness of the liabilities and risks associated with mining has increased, and the social dimensions of mine closure have begun to receive attention.[3] This has led to an increased focus on identifying and developing sustainable post-closure land use opportunities for mined land to support economic and social transitions for mining communities.[4] Industry bodies, governments and research institutions have developed many standards, frameworks and guidelines to support leading practice closure and encourage post-closure land use.[5]

Despite this increased focus on mine closure and transitions, there are extremely limited examples of successful mine relinquishment and repurposing in Australia.[6] Previous studies have found that Australia has tens of thousands of inactive and unrehabilitated mine sites but only 15 examples of repurposed mined land.[7] There is also evidence that mine closure implementation has not consistently kept up with leading practices.[8] Consulted stakeholders suggested a confluence of reasons why this has been the case, including inconsistency of regulation between states and territories, a slow pace of regulatory reform, and cost-cutting incentives in mining companies leading to underfunding of mine closure activities and the use of care and maintenance arrangements to delay closure.

1 A 2017 survey by CSIRO found that the Australian public has low levels of trust in the mining industry and its regulation, despite understanding the importance of the mineral resources sector. Moffat K, Pert P, McCrea R, Boughen N, Rodriguez M, Lacey J (2017) Australian attitudes toward mining: Citizen Survey – 2017 Results. CSIRO, Australia. <https://publications.csiro.au/publications/publication/PIcsiro:EP178434>

2 Environmental, Social and Governance risk has been identified as the top risk for the mining and metals sector for the last 5 years. EY (2023) Top 10 business risks and opportunities for mining and metals in 2023. https://www.ey.com/en_au/mining-metals/risks-opportunities; ATSE (2017) Addressing the environmental impacts of Australian mining's past and future. <https://www.atse.org.au/research-and-policy/publications/publication/addressing-the-environmental-impacts-of-australian-minings-past-and-future/>

3 Unger CJ, Everingham J-A, Bond CJ (2020) Transition or transformation: shifting priorities and stakeholders in Australian mined land rehabilitation and closure, Australasian Journal of Environmental Management, 27:1, 84-113, DOI: 10.1080/14486563.2020.1719440

4 Keenan J, Holcombe S (2021) Mining as a temporary land use: A global stocktake of post-mining transitions and repurposing. The Extractive Industries and Society, 8(3), p.100924.

5 For example, ICMM (2019) Integrated Mine Closure: Good Practice Guide (2nd edition) <https://www.icmm.com/en-gb/guidance/environmental-stewardship/2019/integrated-mine-closure> and Department of Industry, Science, Energy and Resources (2016a) Mine Closure: Leading Practice Sustainable Development Program for the Mining Industry. Australian Government. <https://www.industry.gov.au/sites/default/files/2019-05/lpsdp-mine-closure-handbook-english.pdf>

6 In 2017, the Australia Institute was not able to identify any examples of major, modern open cut mines completing rehabilitation to the point where the site could be relinquished: Campbell R, Linqvist J, Browne B, Swann T, Grudnoff M (2017) Dark Side of the Boom: What We Do and Don't Know about Mines. The Australia Institute. <https://australiainstitute.org.au/report/dark-side-of-the-boom/>

7 Over 80,000 inactive and unrehabilitated sites were identified in: Werner TT, Bach PM, Yellishetty M, Amirpoorsaeed F, Walsh S, Miller A, Roach M, Schnapp A, Solly P, Tan Y, Lewis C (2020). A geospatial database for effective mine rehabilitation in Australia. Minerals, 10(9), p.745; Keenan J, Holcombe S (2021)

8 Keenan J, Holcombe S (2021)

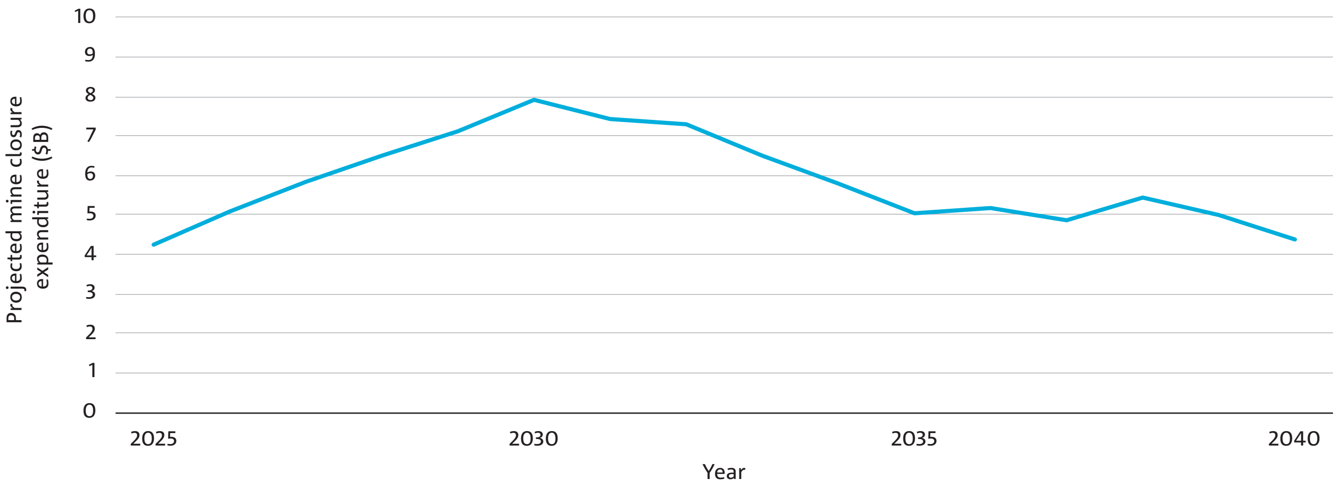
Future mine closures in Australia will create demand for mine closure and transition solutions

Closing mine sites and managing their associated risks is complex and expensive. Mine closure practitioners need safe, cost-effective, and sustainable solutions to address the complex economic, environmental, and social challenges of future mine closures and historic mines. This creates opportunities for a diverse range of Australian businesses and could lead to new export opportunities to support the global mine closure and remediation market.

Expenditure on mine closure is expected to grow in the coming decades. Around 240 Australian mines are expected to end their economically productive life between 2021 and 2040.[9] This report estimates that the annual expenditure on mine rehabilitation and closure related to these mines alone could exceed $4 billion (see Figure 1 and Appendix B).[10]

With increasing demand for many minerals, over 2,200 active mines and tens of thousands of unrehabilitated mine sites in Australia, there will be an ongoing need for innovative mine closure solutions that mitigate environmental, social and economic risks and reduce the costs of rehabilitation and other activities.[11]

Figure 1: Projected expenditure on mine closure activities for known Australian mine sites closing (2025–2040)[12]



9 See Appendix B for further information. CSIRO Futures calculation; S&P Global Market Intelligence 2023, S&P Capital IQ Pro, Asset Data, Metals & Mining Properties, Australia.

10 CSIRO Futures calculation based on conservative assumptions; S&P Global Market Intelligence 2023, S&P Capital IQ Pro, Asset Data, Metals & Mining Properties, Australia.

11 S&P Global Market Intelligence 2023, S&P Capital IQ Pro, Asset Data, Metals & Mining Properties, Australia; Werner et al. (2020)

12 CSIRO Futures calculation (see Appendix B); S&P Global Market Intelligence 2023, S&P Capital IQ Pro, Asset Data, Metals & Mining Properties, Australia.

Graph displays a 5-year moving average trendline, so 2021–2024 data points are omitted. 2025 data point is interpreted as average expenditure from 2021–2025 and so on.

Identifying opportunities for Australian industry

Australian businesses can become a leading supplier of mine closure solutions to domestic and international mines. Many mine closure activities are already supported or delivered by Australia's mining equipment, technology, and services (METS) industry,[13] with approximately a quarter of companies in this $100 billion industry already offering mine closure and remediation solutions.[14] Many other diverse businesses, such as plant nurseries, drone operators, software developers, environmental services providers and specialist consultants also provide mine closure solutions.

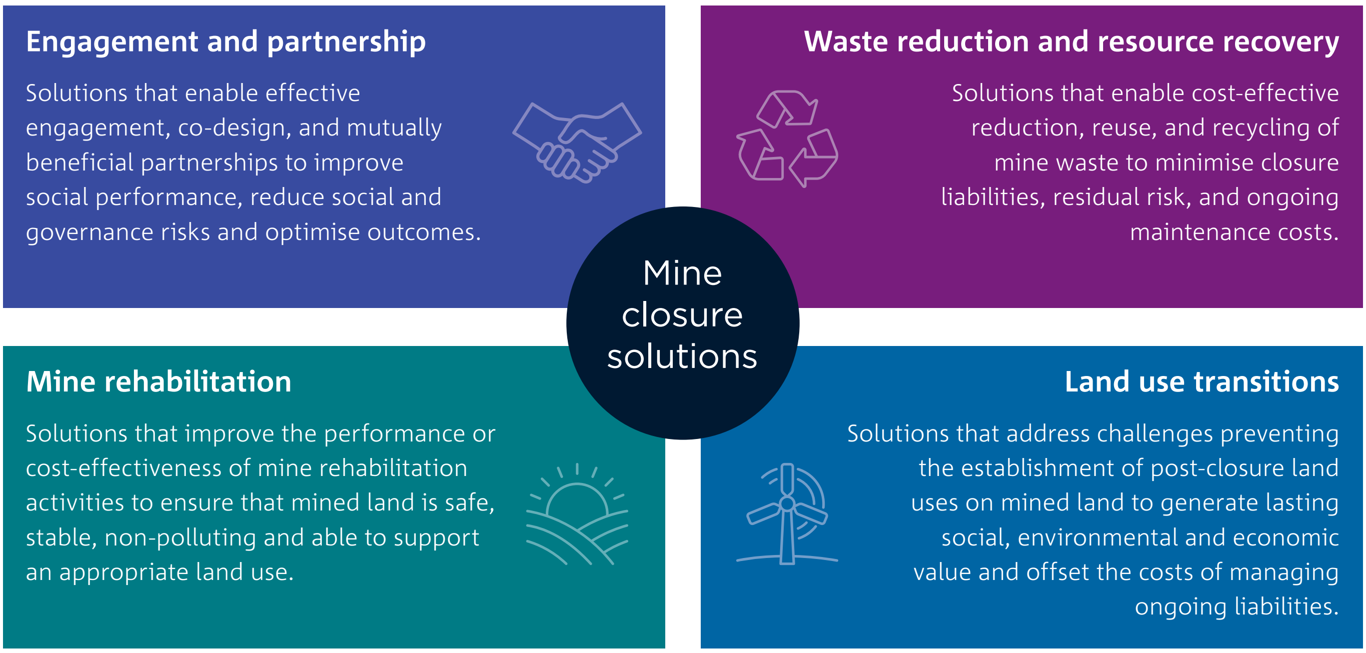
Mine closure can provide business and employment opportunities for Indigenous peoples and organisations across the span of MCS services. There are also opportunities to incorporate local and Indigenous knowledge into rehabilitation activities and mine transition planning. In addition, mining transition opportunities such as resource recovery and post-closure land use can optimise social, environmental and economic value for all stakeholders.

New mine closure solutions are required to help optimise closure and transition costs and outcomes. This report explores opportunities for Australian MCS providers in four categories of mine closure solutions: engagement and partnership, waste reduction and recovery, mine rehabilitation, and land use transitions (see Figure 2).

For each category, desktop research, and consultations and workshops with targeted stakeholders identified challenges facing mine closure practitioners and related opportunities for Australian businesses to supply mine closure solutions (Sections 2–5). A selection of enabling actions is also identified to help Australian businesses capture these opportunities (see Section 6).

The report focuses on challenges that affected a wide selection of mines, and on solutions with limited availability or adoption in Australia. The report should not be interpreted as an exhaustive description of mine closure related challenges and solutions in Australia.

Figure 2: Categories of mine closure solutions explored in this report



13 While this report recognises that the METS industry does not account for all businesses delivering mine closure activities, this term is used to align to industry standard.

14 26% of 619 Australian METS businesses reported operating at the closure and remediation part of the mining lifecycle. Cumulative revenue for all respondents was $114B for the 2018-19 financial year. Austmine (2020) 2020 National METS Survey. <https://austmine.imiscloud.com/Web/Public/News/Reports_Pages/National-METS-Survey-2020.aspx>

2 Engagement and partnerships

Supporting effective engagement and partnership development in the mine closure ecosystem is essential to improving the mining industry's social performance, addressing the trust deficit, and optimising mine closure and transition outcomes for local communities and regions.[15] Collaboration with partners and stakeholders during closure planning and throughout implementation underpins the success of mine closure. This engagement is critical to provide a voice to communities, including Aboriginal and Torres Strait Islander communities, affected by the legacy of closed mines.

Mine closure and transitions affect diverse stakeholders with different values and perspectives on the definition of successful mine closure (see Table 1). These perspectives can change over time and differ significantly across regions of Australia. As such, meaningful and respectful engagement is required to promote mutual understanding and to clarify expectations related to mine closure.

Facilitating engagement and partnerships with diverse stakeholder groups can be a significant challenge for mine closure practitioners. Addressing this requires the implementation of mechanisms that enable effective dialogues and mutually beneficial partnerships. Consultations with mining and government stakeholders identified establishing effective engagement, co-design and partnerships as challenges that could benefit from mine closure solutions provided by Australian businesses (see Table 2).

Table 1: Examples of stakeholders and desirable mine closure and transition outcomes

STAKEHOLDER	DESCRIPTION	EXAMPLES OF DESIRED OUTCOMES
Miners	Mine closure practitioners plan and manage mine closure activities, including stakeholder engagement.	• Satisfy regulatory conditions, achieve relinquishment and meet shareholder expectations • Minimise expenses, address liabilities and retrieve funds held by government
Communities	Local community stakeholders (including Indigenous communities and groups) may be directly and indirectly affected by mining and mine closure through its impact on local communities, economies and environments.	• Mitigate safety, health and environmental risks • Protect cultural, social and environmental assets • Create and sustain economic and employment opportunities • Recognise heritage
Governments	State and territory governments regulate most aspects of mine closure, with the Australian Government involved in some elements of rehabilitation, closure and abandoned mine management. Local governments are engaged in discussions between miners and communities.	• Ensure mining companies achieve agreed mine closure outcomes (e.g., safe, stable, and non-polluting land) • Mitigate the risk of abandoned assets and ongoing liabilities to the government • Optimise social, environmental, and economic outcomes for communities and local economies
Other industries	Local industries and businesses may be impacted by mining and mine closure and potential users of mined land post-closure.	• Develop new industry opportunities from mine closures and transitions • Ensure sustainability of local businesses after the transformation of the mining economy

Table 2: Summary of engagement and partnerships related challenges and opportunities

Challenges	Opportunities
Effective engagement	• Facilitation services for complex stakeholder engagements • Tools to support data-driven engagement, governance, and decisions • Tools for the effective and inclusive communication of complex information
Co-design and partnerships	• Facilitation and capability development services to support sustainable partnerships with communities • Data management solutions to support transparency, governance, co-design and delivery of mine closure outcomes

15 ICMM (2022) Integrating Community Engagement across the Business Tools for Social Performance. <https://www.icmm.com/en-gb/guidance/social-performance/2022/tools-for-social-performance>

2.1 Effective engagement

Solutions that aid in communicating complexity and facilitating effective and inclusive engagement can improve social performance and governance for mine closure. Opportunities include:

- Facilitation services for complex stakeholder engagements
- Tools to support data-driven engagement, governance, and decisions
- Tools for the effective and inclusive communication of complex information

The success of mine closure and transition planning and implementation requires meaningful engagement of diverse stakeholders. However, managing effective communication and engagement around the complexities implicit in mine closure activities is challenging. Mine closure practitioners must successfully engage diverse stakeholders to explore and manage the social, environmental, economic and technical challenges associated with closure and transition opportunities. Consulted mining stakeholders noted that engagement skills and experience vary amongst closure practitioners, and the support of skilled consultants with relevant expertise is often required.

Opportunities

Facilitation services for complex stakeholder engagements

Stakeholders suggested that mine closure practitioners would value access to skilled consultants who can facilitate effective dialogue and complex engagements. Specialised providers focused on managing effective engagements can improve a mining company's social performance throughout the life of mine, delivering shared value for all stakeholders. The complexity of closure processes requires ongoing engagement to understand and align various stakeholder expectations and objectives. The input of many stakeholders, including local communities, Traditional Owner Groups and other Indigenous stakeholders, is essential to inform mine closure planning.

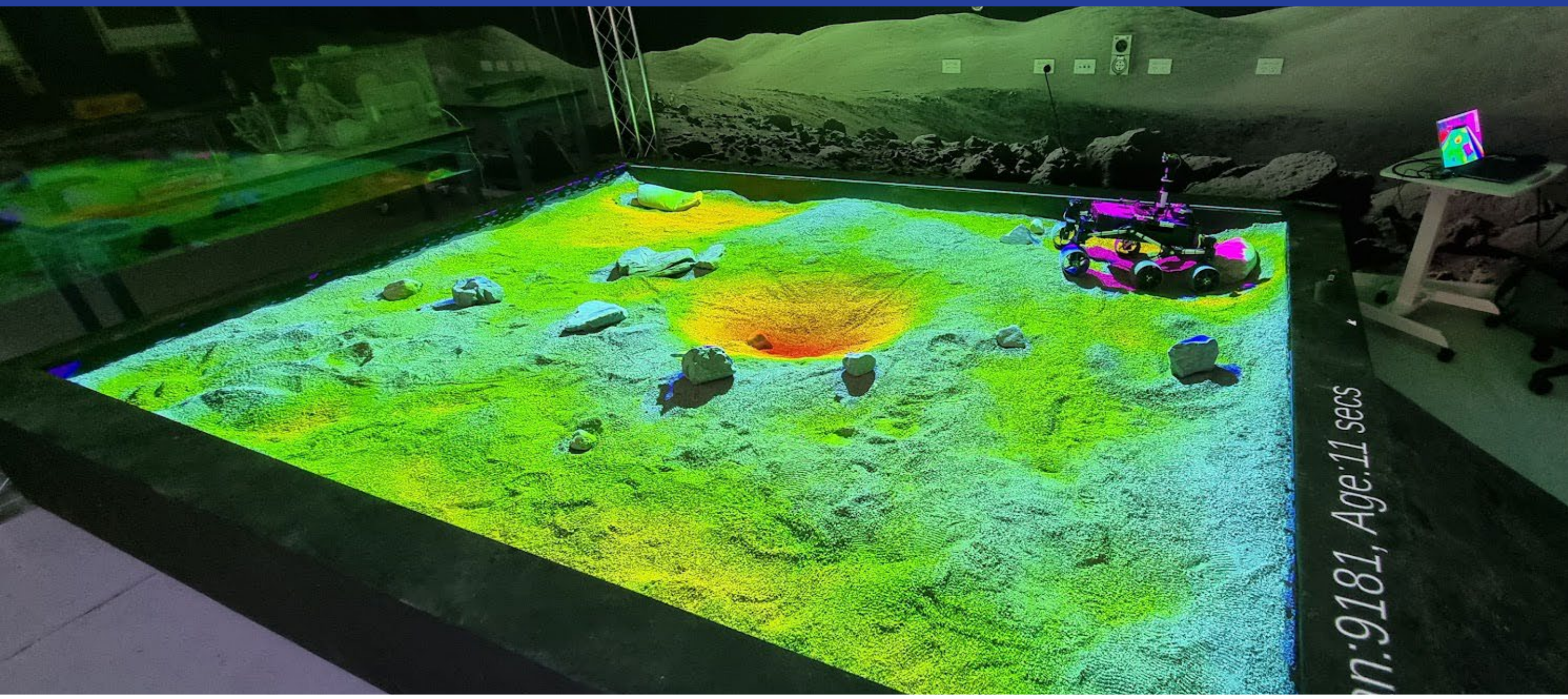
This opportunity includes providing skilled facilitation and training services to build miners' engagement capabilities and to strengthen communication and collaboration between mining operators and communities. Examples of Australian businesses focused on engagement training include TEH & CO[16] and Greenfields Consulting.[17]

MCS providers supporting effective management of stakeholder relationships can play an integral role in enabling successful closure outcomes. Any facilitation by consultancies must recognise the necessity of tailored approaches for different groups and of acting as a neutral third party to build confidence and trust between parties. Culturally appropriate consultation services are especially important in enabling respectful decision-making in partnership with Indigenous landholders, communities, businesses, and organisations. Carey Group Holdings is an Indigenous-owned civil and engineering service provider that offers Indigenous engagement support by managing Indigenous business procurement opportunities as well as recruitment, training, employment and mentoring for Indigenous workers. The Indigenous affairs team aim for culturally appropriate best practice and economic development through partnering the Carey group with emerging Indigenous businesses.[18]

16 Teh & Co (n.d) Empowering people to drive sustainable development <https://kteh.com.au> (accessed 29 August 2023)

17 Greenfields (2023) The Greenfields Story <https://greenfieldschange.com.au/about/> (accessed 29 August 2023)

18 Carey Group (2023) Indigenous Engagement. <https://careygroupholdings.com.au/indigenous-engagement/> (accessed 13 September 2023)



Tools to support data-driven engagement, governance, and decisions

Collecting and analysing social and economic data can support identification and management of risks and opportunities relating to mine closure activities. This can improve informed, collaborative decision-making for closure plans and opportunities. Engaging, collecting and assessing social and economic data over time can help closure practitioners understand, record and respond to stakeholder expectations, concerns and approvals. This can also support transparency and enable enhanced engagement approaches.

Socio-economic impact assessments and social engagement tools can aid in creating a deep and clear understanding of a mine's socio-economic footprint and integrating social and economic data into closure planning**.** A socio-economic impact assessment includes assessment, management and monitoring of social and economic impacts of a mine, including providing baseline stakeholder data.[19] A meaningful and independent assessment can be a crucial input into managing complex stakeholder relationships over the life of a mine. One example of a company using data and social science to inform stakeholder and partner engagement is CSIRO spin-out Voconiq, which uses data software to collect, aggregate and analyse social insights.[20]

Tools for the effective and inclusive communication of complex information

MCS providers that provide solutions that effectively communicate complex and technical information associated with mine closure activities can support inclusive stakeholder engagement and informed decision-making. For example, dynamic modelling can be used to present multiple closure scenarios and allows focus on attributes that impact the desired outcomes for a specific stakeholder group. Sentient's MAVI tool is one example of an Australian company developing visual modelling tools for stakeholder engagement. The tool provides interactive maps that overlap topic datasets and can provide animations to orient stakeholders on the location within a mine site.[21]

Enabling non-technical partners and stakeholders to understand opportunities and challenges can foster understanding stakeholder trust and generate mutual value while managing expectations and planning requirements. This enables stakeholders to provide informed consent and approval for closure-related planning decisions. At a regional level, these tools can also be used to understand, monitor, manage and communicate the cumulative impacts of closure activities from multiple mine sites.

19 Munday J (2020) Guide to Social Impact Assessment. Environment Institute of Australia and New Zealand Inc. <https://static1.squarespace.com/static/5fd84a533ea9e15de736ac0b/t/60541d0d7db8ef1e23ce6d4c/1616125212404/Guide+to+Social+Impact+Assessment.pdf>)

20 Voconiq (2023) Engagement Science. <https://voconiq.com/engagement-science/> (accessed 29 August 2023)

21 Sentient Computing (2022) MAVI – INTERACTIVE COMMUNICATIONS TOOL <https://sencom.com.au/products/mavi/> (accessed 29 August 2023)

2.2 Co-design and partnerships

Solutions that enable the development and maintenance of inclusive community partnerships can address the trust deficit in mining companies and enable better mine closure outcomes through collaborations. Opportunities include:

- Facilitation and capability development services to support sustainable partnerships with communities
- Data management solutions to support transparency, governance, co-design and delivery of mine closure outcomes

A history of poor inclusion of partners and stakeholders in closure decision-making and implementation has led to a trust deficit between industry and communities. Creating and sustaining an open, constructive and ongoing dialogue between mining companies and community partners can help to build trust, encourage long-term collaboration, and create shared value.[22] Shaping mine closure activities through co-design, including post-closure land use, can improve the legacy of mines, meet social, cultural and community expectations, and help uphold the mining company's social performance.

In particular, the global mining industry has often failed to adequately consult or gain Indigenous communities' consent for operations in regions, including around closure activities. A history of poor relationships with companies and governance structures highlights the need to build trust, implement authentic engagement practices, and develop genuine mutually beneficial partnerships with Indigenous communities. The foundations of this approach should be based on free, prior and informed consent.[23]

This is particularly important when establishing closure plans, completion criteria setting, and undertaking rehabilitation activities.[24] Stakeholders noted that leading practices for Indigenous partnerships include addressing the power imbalance between communities and mining companies, procurement targets for local communities and ensuring communities are involved in decision-making throughout the life of the mine.[25] Doing so presents an opportunity for Australian businesses, particularly local Indigenous businesses, to develop improved partnerships with Indigenous communities.

22 Everingham J, Svobodova K, Mackenzie S, Witt K. (2020). 'Participatory processes, mine closure and social transitions'. Centre for Social Responsibility in Mining. University of Queensland, Brisbane.

23 As described in: United Nations (2007) United Nations Declaration on the Rights of Indigenous People (A/RES/61/295). <https://social.desa.un.org/issues/indigenous-peoples/united-nations-declaration-on-the-rights-of-indigenous-peoples>

24 Holcombe S, Elliott V, Keeling A, Berryman M, Hall R, Ngaamo R, Beckett C, Moon W, Hudson M, Kusabs, N, Ross River Lands Office. (2022) Indigenous Exchange Forum: Transitions in Mine Closure. St Lucia: Centre for Social Responsibility in Mining, University of Queensland.

25 Holcombe et al. (2022)

Opportunities

Facilitation and capability development services to support sustainable partnerships with communities

While mining companies continue to develop capabilities in partnering with local communities, including Aboriginal and Torres Strait Islander groups, there is an opportunity for service providers that can provide culturally sensitive engagement, business development, facilitation, and training programs. Community members have diverse interests, values and expectations. As such, respectful and informed engagement will be required to promote mutual understanding and develop meaningful partnerships. This may also require the use of interpreters at times. These engagements can be vital in determining and delivering opportunities for post-closure economic development and land use (see Section 5), including reusing existing infrastructure for communities.

Indigenous-led facilitation and training services may be especially well placed to enable culturally sensitive and mutually beneficial collaborations with Aboriginal and Torres Strait Islander communities. Australian businesses can provide short to medium-term support and capability-building for the industry while also implementing training programs to build internal capabilities of mine closure practitioners. Australian company Linking Futures is an example of an Indigenous-owned business seeking to develop cross-cultural understanding in complex stakeholder relationships, by training commercial and collaborative capabilities of businesses.[26]

Data management solutions to support transparency, governance, co-design and delivery of mine closure outcomes

Co-design and delivery of closure outcomes rely on collection and access to meaningful, relevant, and timely data to inform stakeholder decision-making, enhance governance processes, and facilitate a two-way dialogue between stakeholders.[27] Collaboration and partnerships are critical to improving closure outcomes and developing plans for mining transitions that satisfy local community expectations.

Businesses delivering software solutions can improve data transparency through improved collection and access. These solutions can also facilitate a two-way exchange of information, where mining operators provide information on sites and other stakeholders input ideas and concerns. Improved collection and access can ensure accurate measurement of progress against objectives and support management of outcomes from co-designed solutions. For example, K2fly offers a cloud-based solution for heritage management that captures data from multiple sources and spatially integrates this for visualisation, analysis, and change detection. This software tool is designed to enable improved stakeholder engagement and heritage management, particularly with Traditional Owner groups.[28]

26 Linking Futures Pty Ltd (n.d) Our Capabilities – Linking Futures <https://linkingfutures.com.au/our-services/> (accessed 29 August 2023)

27 Everingham et al (2020)

28 K2fly (2023) K2fly Heritage Management A Stakeholder & Preservation Solution. <https://k2fly.com/solutions/heritage-management/> (accessed 29 August 2023)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3 Waste reduction and resource recovery

Effective waste management throughout the mining life cycle is critical to managing a mining company's ongoing liabilities posed by environmental and safety risks. Mining generates diverse waste streams such as waste rock, overburden, tailings, wastewater, equipment, infrastructure and processing by-products (including sludge, chemical reagents, solvents and metallurgical processing waste).[29]

Traditional mining methods typically rely on mass extraction of ore and surrounding rock, followed by extensive processing to recover targeted minerals. These processes create large volumes of waste, especially for projects with a high strip ratio (the ratio of waste and overburden to ore) such as open-pit mining. The global mining industry is estimated to produce around 100 billion tonnes of waste each year.[30] Poorly managed waste can create environmental and safety risks and ongoing liabilities long after ceasing mining operations.

By applying circular economy and waste management hierarchy principles (see Figure 3), proactively managing mining waste can reduce risks and liabilities during closure. Consulted mining stakeholders noted the importance of exploring other waste management opportunities before defaulting to engineered disposal and containment solutions. Stakeholders indicated that there are opportunities for Australian businesses to develop innovative solutions to improve mining companies' waste management practices. Consultations identified four challenges that require deploying solutions that enable enhanced waste reduction and resource recovery on mine sites (see Table 3).

Figure 3: Waste management hierarchy

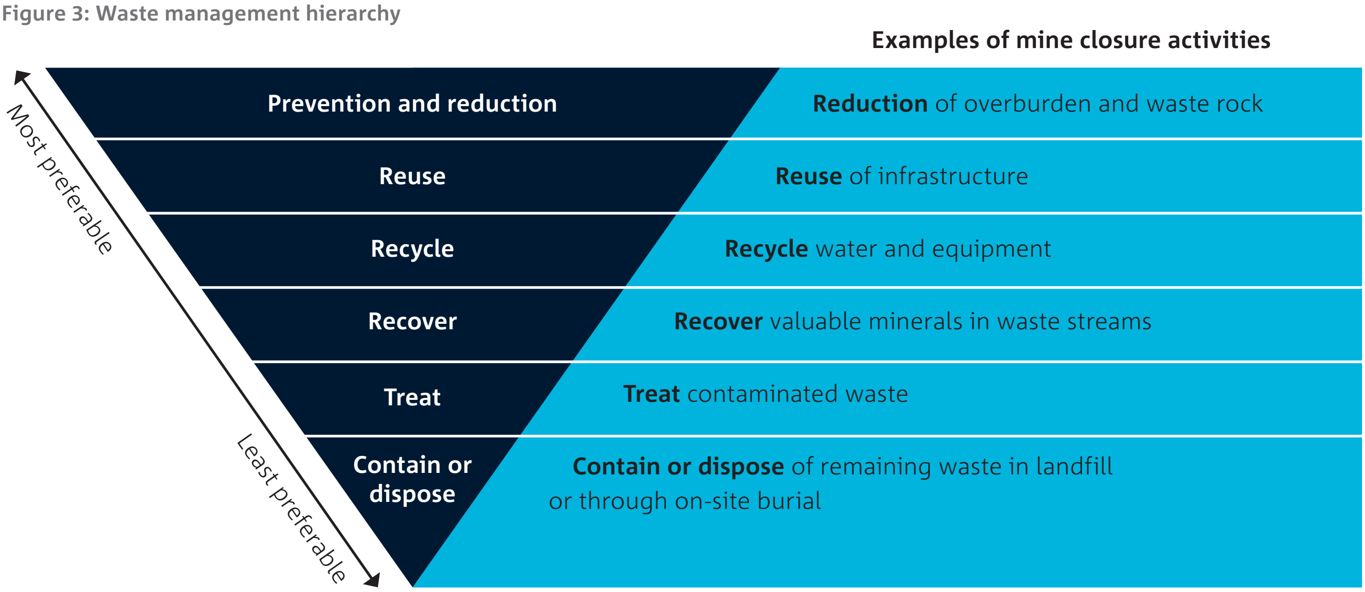


Table 3: Summary of waste reduction and resource recovery related challenges and opportunities

Challenges	Opportunities
Waste reduction	• Low-impact and precision mining technologies
Repurposing mineral waste	• Waste-derived materials and products
Resource recovery	• Technologies to characterise and recover minerals from waste
Recycling non-mineral waste	• Cost-effective and responsible recycling services for mining equipment and infrastructure

29 MiningNewsWire (2020) Mining Waste Management and Disposal Methods. <https://www.miningnewswire.com/mining-waste-management-and-disposal-methods/> (accessed 29 August 2023)

30 Vuillier et al, (2021) The Future of Mining with Zero Mine Waste'. The Southern African Institute of Mining and Metallurgy (SAIMM), Global tailings Standards and Opportunities for the Mine of the Future, Rustenburg, South Africa

3.1 Waste reduction

Solutions that enable efficient and precise mineral extraction and processing can reduce the volume of waste generated during mining production and reduce the associated waste management liabilities at closure. Opportunities include:

- Low-impact and precision mining technologies

Significant volumes of mine waste are generated throughout the mining life cycle and require resource-intensive management activities to reduce the risks they may present. Waste accumulation and increased risk of waste-related hazards present a more complex burden at closure. For example, excess tailings can increase risks associated with environmental contamination by toxic substances and physical instability of tailings storage facilities (TSF). Early interventions that prevent or reduce wastes can help miners avoid some of the costs and risks of waste management during closure.

Waste reduction practices need to be considered throughout the life of mine. By implementing waste hierarchy principles during the extraction phases, mining projects can consider waste sources and reduction opportunities throughout the mining value chain. New mining projects may implement innovative mining methods with significant waste reduction potential, while existing operations will require solutions that reduce waste by optimising select processes to ensure continued production.

Opportunities

Low-impact and precision mining technologies

Developing and deploying novel mining technologies can increase the precision of and degree of selectivity associated with mineral extraction, reducing waste volumes and related closure liabilities. In-situ recovery, in-line and in-mine recovery and modular mines (see Table 4) can reduce the footprint of operations and minimise excavation, movement, and waste rock processing. In-situ recovery and modular mining may also reduce equipment and infrastructure-related waste compared to conventional mining approaches.[31] Due to the transformative nature of these technologies, they are well-suited for implementation in new mining projects. Economic limitations and impacts on productivity may constrain the integration of these technologies within already operating mines.

For operational mine sites, targeted process optimisation and readily implementable solutions can improve waste reduction practices with minimal disruption to production. The International Council on Mining and Metals (ICMM) published the *Tailings Reduction Roadmap* in 2022, outlining a strategic direction for developing and adopting technologies for reduced tailings and waste production.[32] The ICMM roadmap outlines tailings reduction technologies with high Technology Readiness Levels and fast-scaling potential that can be implemented while developing more transformative mining processes or designs. These include greater characterisation technologies such as continuous sorting, batch sensing, and mining machines.[33] For example, Novamera (US) has developed mobile surgical mining technology that can be integrated with conventional drilling equipment. Their technology can be used to reduce overall waste generated through data-driven ore vein mapping and smart drilling systems, resulting in a minimal environmental footprint.[34]

Commercially mature technologies, such as optimised blasting and precision comminution, can also improve efficiency and reduce waste creation. Furthermore, geochemical source control practices can reduce water resources used, wastewater generated and treatment requirements to mitigate pollutants in hydrological systems (see Section 4.3).

31 Mining3 (2017) In Place Mining – A transformational shift in metal extraction. <https://www.mining3.com/place-mining-transformational-shift-metal-extraction/> (accessed 29 August 2023)

32 ICMM (2022) Tailings Reduction Roadmap <https://www.icmm.com/en-gb/guidance/innovation/2022/tailings-reduction-roadmap>

33 ICMM (2022)

34 Novamera (n.d.) Technology – Smart Precision Drilling <https://novamerainc.com/smd-technology/> (accessed 07 September 2023)

Table 4: Mining technologies enabling waste reduction

TECHNOLOGY	DESCRIPTION[35]	MATURITY
In-situ recovery	Dissolves valuable metals from ore into a chemical or biochemical solution (lixiviant) to allow the surrounding rock to remain in place. In contrast, the solution is pumped through the ore, dissolving the mineral, and then to the surface for further processing. Challenges remain in lixiviant control.	• Commercially mature for Uranium mining[36] • EnviroCopper is undertaking pilot-scale projects for copper extraction from legacy copper mine sites in Kapunda, South Australia [37]
In-mine recovery	Where selective rock breakage (and/or pre-conditioning) is combined with leaching of materials in place with no bulk material movement.	• CSIRO undertook lab-scale feasibility studies through strategic resource-constrained planning models[38]
In-line recovery	Combining precision mining, material preparation and processing stages (beneficiation, pre-concentration or leaching) adjacent to the mining face.	• Lab scale at the conceptual level[39]
Modular mining	Utilising equipment and infrastructure designed for quick deployment, activation, and decommissioning. This technology allows lesser excavation of material through mining smaller ore bodies and less non-mineral waste as the equipment is designed is for adaptability and reuse.	• Pilot studies in Europe have demonstrated small-scale mining using modular and mobile plants to extract high-grade lead[40]

35 CSIRO (2017) Mining Equipment, Technology and Services A Roadmap for unlocking future growth opportunities for Australia, CSIRO, Canberra; Vella H (2019) Switch on switch off: rethinking how smaller deposits are mined. Mining Technology. <https://www.mining-technology.com/features/switch-on-switch-off-rethinking-how-smaller-deposits-are-mined/?cf-view>

36 World Nuclear Association (2020) In Situ Leach Mining of Uranium. <https://world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/in-situ-leach-mining-of-uranium.aspx> (accessed 29 August 2023)

37 Environmental Copper Recovery SA Pty Ltd. (2021) The Kapunda Copper & Gold ISR Project. <https://www.envirocopper.com.au/kapunda-isr-project> (accessed 29 August 2023)

38 Mousavi A, Sellers, E (2019). Optimisation of production planning for an innovative hybrid underground mining method. Resources Policy, 62, pp.184-192.

39 Mining3 (2017)

40 Beylot A, Muller S, Segura-Salazar J, Brito-Parada P, Paneri A, Yan X, Lai F, Roethe R, Thomas G, Goettmann F, Braun, M (2021). Switch on-switch off small-scale mining: Environmental performance in a life cycle perspective. Journal of Cleaner Production, 312, p.127647.

3.2 Repurposing mineral waste

Solutions that repurpose mined waste stockpiles for use on mine sites or in other industries can reduce waste volume that must be managed during mine closure. Opportunities include:

- Waste-derived materials and products

Transportation, treatment, storage, and disposal of mineral waste can create significant costs and liabilities for miners during closure activities. Waste rock represents 10–20% of the annual waste from the mining industry.[41] Waste rock formed during excavation is commonly left as large stockpiles, which can incur additional costs during rehabilitation.[42] Management of waste rock stockpiles and other mineral waste storage facilities is essential for long-term safety and stability as they can present structural and geochemical risks, including acidic and metalliferous drainage (AMD).

- Mineral waste left over in waste stockpiles, tailings and the various processing streams can find further use through repurposing. Identifying beneficial uses of mineral waste can unlock a commercial opportunity and reduce closure costs.

Opportunities

Waste-derived materials and products

Repurposing mineral waste may reduce the burden of waste management and generate cost-effective products. Converted waste products can support mine rehabilitation processes. For example, a common practice of waste repurposing is the co-disposal of tailings and waste rock to create physically stable mixtures to backfill mining voids.[43]

Converted waste products can also support other industries, such as agriculture, construction, and manufacturing (see Table 5: Mineral waste repurposing examples). Technical solutions can convert mineral waste into neutral and stable products depending on mineralogy. Ideally, solutions will align with circular economy principles and generate waste-derived products to meet local demand such as the production of construction materials for local infrastructure.

MCS providers will need to ensure they address any risks and environmental uncertainties as well as waste and licensing regulations related to the products derived from materials recovered from mine waste. Stakeholders noted that regulatory barriers around waste-derived products may hinder repurposing activities. These activities include repurposing benign waste rock, which may be treated as a quarrying activity that may not be allowable under a mine's existing agreements. Similarly, some stakeholders needed clarification on whether royalties would be applied to waste rock. Western Australia recognised the importance of clarity for waste repurposing and consulted on a proposed legislative framework for waste-derived materials in 2020.[44] Potentially hazardous waste would require adequate assessment and treatment before repurposing to reduce community and environment safety risks.

41 Vuillier C, Ingwersen M (2022) Making repurposed mine waste a reality. AusIMM Bulletin. <https://www.ausimm.com/bulletin/bulletin-articles/making-repurposed-mine-waste-a-reality/> (accessed 31 August 2023)

42 Shengo LM (2021). Review of practices in the managements of mineral wastes: The case of waste rocks and mine tailings. Water, Air, & Soil Pollution, 232(7), p.273.

43 Shengo, LM (2021)

44 Department of Water and Environmental Regulation (2020) Waste not, want not: Valuing waste as a resource. Government of Western Australia. <https://www.wa.gov.au/service/environment/environment-information-services/waste-not-want-not-valuing-waste-resource>

Table 5: Mineral waste repurposing examples

INDUSTRY	REPURPOSING EXAMPLES
Mining	Cementitious tailings and metallurgical processing waste such as fly ash and slag can be used to create paste products to stabilise backfill.[45]
Agriculture	Mineral rich waste from tailings can produce solid and liquid fertiliser containing high levels of key nutrients such as potassium, magnesium and silicon.[46]
Construction	Aluminosilicate minerals found in waste can be synthesised into polymer materials through repolymerisation for use as construction materials such as cement.[47] For example: • Laboratory and field trials facilitated by Murdoch University has resulted in low emissions geopolymer concrete 'Colliecrete' derived from fly ash and other industrial by products.[48] • Amira has partnered with CSIRO to research the repurposing of coal industry tailings into geopolymer concrete.[49] Waste rocks supplemented with mineral carbonation techniques can offset carbon emissions by capturing $CO_{2,}$ locking away carbon in carbonate materials.[50] For example: • MCi (Australia) is developing a carbonation process that can produce construction materials from mine waste and carbon dioxide.[51]
Manufacturing	Production of silica-sand products from mine waste can be utilised in construction and in the creation of products such as ceramics and glass. For example: • The Sustainable Minerals Institute at University of Queensland are undertaking research to develop processes to capture 'Ore-sand' to meet the growing sand sustainability challenges.[52]

45 Behera SK, Mishra DP, Singh P, Mishra K, Mandal SK, Ghosh CN, Kumar R, Mandal, P.K (2021) Utilization of mill tailings, fly ash and slag as mine paste backfill material: Review and future perspective. Construction and Building Materials, 309, p.125120.

46 Crusciol CA, de Campos M, Momesso L, Bossolani JW, Moretti LG, Portugal JR, de Melo CV, Calonego JC, (2022) Nickel Ore Mining Waste as a Promising Source of Magnesium and Silicon for a Smart-Agricultural Management. Frontiers in Environmental Science, 10, p.880613.; Yong MT, Babla M, Karan S, Katwal U, Jahandari S, Matta P, Chen ZH, Tao, Z (2022) Coal tailings as a soil conditioner: evaluation of tailing properties and effect on tomato plants. Plant Growth Regulation, 98(3), pp.439-450.

47 Mabroum S, Moukannaa S, El Machi A, Taha Y, Benzaazoua M, Hakkou R (2020) Mine wastes based geopolymers: A critical review. Cleaner Engineering and Technology, 1, p.100014.

48 Murdoch University (2022) Environmentally focused and sustainable concrete set to shake up building industry. <https://www.murdoch.edu.au/news/articles/new-environmentally-focused-and-sustainable-concrete-set-to-shake-up-building-industry>

49 Amira Global (n.d.) Geopolymer concrete from tailings and other mine wastes. https://amira.global/2021/06/geopolymer-concrete-from-tailings-and-other-mine-wastes/ (accessed 31 August 2023); CSIRO (2022) Tailings, an emerging market opportunity. https://www.csiro.au/en/work-with-us/industries/mining-resources/resourceful-magazine/issue-26/tailings (accessed 31 August 2023)

50 Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A, (2021) CO2 Utilisation Roadmap. CSIRO, Canberra.

51 MCi Carbon (2023) Mineral Carbonation. https://www.mineralcarbonation.com/mineral-carbonation (accessed 31 August 2023)

52 Sustainable Minerals Institute (2023) Ore-sand: A circular economy solution to reduce mineral wastes and improve global sand sustainability. The University of Queensland. https://smi.uq.edu.au/project/ore-sand-circular-economy-solution-improve-global-sand-sustainability (accessed 31 August 2023)

3.3 Mineral resource recovery

Solutions that enable the cost-effective recovery of secondary minerals from mining waste can unlock valuable critical and strategic mineral resources and may offset the costs of mine rehabilitation activities. Opportunities include:

- Technologies to characterise and recover minerals from waste

Many legacy TSFs and waste stockpiles contain critical or strategic minerals that may present economic opportunities for recovery.[53] It is estimated that tailings hold over US$3.4 trillion of precious, critical and strategic minerals globally.[54] Geospatial satellite imagery analysis has identified over 1,000 TSFs across six states in Australia.[55] Recognising the potential value of these assets, Geoscience Australia recently launched an online Atlas of Mine Waste to provide information about mine tailings, waste rock, and other mining waste stockpiles in Australia.[56]

Secondary mineral recovery may also allow companies to rehabilitate legacy and abandoned assets, reducing the long-term safety and environmental risks that TSFs pose.[57] This rehabilitation may also support mining transitions and additional social and economic benefits if it can enable the relinquishment and repurposing of land that would otherwise be tied up due to the risk associated with TSFs. This may benefit from a shift of TSF design and management to include optimisation of value within the asset alongside managing residual risk, allowing greater characterisation and extraction of minerals.

Secondary mineral recovery is an emerging practice, with mining consultations noting the need for a clear policy and framework to support these activities. The *Global Industry Standard on Tailings Management* (GISTM) provides guidelines for defining the safe closure of tailings dams. However, there is limited global guidance on reprocessing tailings.[58] The Sustainable Minerals Institute identified institutional bottlenecks that limit the circular economy transition and tailings valorisation potential. These include limitations associated with environmental permitting, land use and leasing regulations, waste disposal and reagent restrictions, stigma around contaminated land and inconsistent regulations in the local and global market.[59] Stakeholders suggested that valuable mineral recovery from waste streams would benefit from harmonised local and global guidelines. The European Union's Circular Economy Action Plan contains an alignment of waste directives in member states to allow a well-functioning market for secondary raw minerals.[60]

53 Sarker SK, Haque N, Bhuiyan M, Bruckard W, Pramanik BK (2022) Recovery of strategically important critical minerals from mine tailings. Journal of Environmental Chemical Engineering. 10(3) p 107622.

54 Minerals Research Institute of Western Australia (2023) Alternative Use of Tailings and Waste. Government of Western Australia <https://www.mriwa.wa.gov.au/minerals-research-advancing-western-australia/focus-areas/alternative-use-of-tailings-and-waste/> (accessed 29 August 2023)

55 Sarker SK, Haque N, Bruckard W, Bhuiyan M, Pramanik, BK (2022) Development of a geospatial database of tailing storage facilities in Australia using satellite images. Chemosphere, 303, p.135139.

56 Geoscience Australia (2021) Atlas of Australian Mine Waste. <https://portal.ga.gov.au/persona/minewaste> (accessed 29 August 2023)

57 Kinnunen P, Karhu M, Yli-Rantala E, Kivikytö-Reponen P, Mäkinen J (2022) A review of circular economy strategies for mine tailings. Cleaner Engineering and Technology, 8, p.100499.

58 Global Tailings Review (2020) GLOBAL INDUSTRY STANDARD ON TAILINGS MANAGEMENT <https://globaltailingsreview.org/global-industry-standard/>

59 Kinnunen PHM, Kaksonen AH (2019) Towards circular economy in mining: Opportunities and bottlenecks for tailings valorization. Journal of Cleaner Production, 228, pp.153-160.

60 European Commission (2020) Communication from the Commission to the European Parliament, The Council, The European Economic and Social Committee and The Committee of the Region: A new Circular Economy Action Plan. Brussels.

Opportunities

Technologies to characterise and recover minerals from waste

Cost-effective solutions that support secondary mineral extraction from waste streams such as tailings, wastewater, and waste rock stockpiles present an opportunity to improve closure outcomes. Consultations have noted that economic recovery opportunities are present in legacy sites where less efficient extractive processes have left high concentrations of target minerals in waste. Reprocessing waste may also enable miners to implement strategic rehabilitation activities while a site is still in a positive cash flow. MCS providers and secondary mineral recovery businesses can improve processes by implementing innovative, cost-effective practices and reducing waste volume and long-term liabilities from tailings creation and storage.

Emerging local and existing international projects demonstrate the viability of tailings retreatment in some contexts. Australia now has multiple operational secondary mineral recovery projects extracting metalliferous materials including tin, zinc, gold, silver and copper (see Table 6).

In some cases, mineral resource recovery projects may be able to generate cash flow to offset the costs of remediating historic and ongoing liabilities. For example, Regeneration (US) is a social enterprise that seeks to convert mine waste from legacy sites into responsible minerals and use their profits for mine rehabilitation and habitat restoration.[61]

Table 6: Identified Australian secondary mineral recovery projects

PROJECT	COMPANY	DETAILS
Ardlethan Tin, New South Wales	Australia Tin Resources Pty Ltd	Rehabilitation and tailings reprocessing of the Ardlethan tin mine.[62] A pilot plant has been established, and commercial operations are planned to formally commence for recovery of tin concentrates.[63]
Century Mine, Queensland	New Century Resources (Silbayne Stilwater)	Commercial recovery of zinc concentrate from historic zinc, lead and silver mine tailings through hydraulic mining techniques.[64]
Mt Carbine, Queensland	EQ Resources	Tailings materials are processed alongside operational mines through a gravity plant to recover tungsten minerals.[65]
Hellyer Tailings Reprocessing, Tasmania (in development)	EnviroGold	Full scale pilot program for metal recovery of gold, silver, zinc, lead, and copper contained within the tailings is in development.[66]
Mt Morgan, Queensland (in development)	Heritage Minerals	Concurrent tailings reprocessing and rehabilitation of the abandoned historical Mt Morgan gold mine to recover gold and copper.[67]
Rentails project (proposed), Tasmania	Metals X	Proposed recovery project of tin and copper from historical tailings at the Renison tin mine.[68]

61 Resolve (n.d.) Regeneration Begin Again. <https://www.resolve.ngo/regeneration.htm> (accessed 29 August 2023)

62 Department of Enterprise, Investment and Trade (2023) Tin in NSW. NSW Government. <https://www.business.nsw.gov.au/industry-sectors/industry-opportunities/mining-and-resources/base-metals/tin-in-nsw> (accessed 29 August 2023)

63 Australian Tin Resources Pty Ltd (2023) Ardlethan Tin Mine <http://atresources.com.au/> (accessed 29 August 2023)

64 Sibanye-Stillwater (2023) New Century Resources. <https://www.sibanyestillwater.com/business/new-century-resources-australia/> (accessed 29 August 2023)

65 EQ Resources (2023) Mt Carbine Tungsten Project <https://www.eqresources.com.au/site/what-we-do/mt-carbine-project> (accessed 29 August 2023)

66 EnviroGold Global (2023) EnviroGold Announces Positive Pilot Plant Results Confirming Efficacy of Metals Recovery Technology. <https://envirogoldglobal.com/envirogold-announces-positive-pilot-plant-results-confirming-efficacy-of-metals-recovery-technology/> (Accessed 14 September 2023);

67 Heritage Minerals (2023) Mt Morgan. <https://heritageminerals.com.au/> (accessed 29 August 2023)

68 Metals X Limited (2023)

Developing non-invasive solutions for characterising minerals in legacy TSFs will further support this opportunity. Established and historic TSFs have been designed to minimise the risk of seepage and structural failures, not for easy access and reprocessing. Consultations noted that current tailings characterisation methods are complex as they require invasive drilling and sampling of sealed TSFs. As a result, accessing and sampling historic and sealed TSFs is limited, expensive and potentially risky if landforms are disturbed. Safe and cost-effective characterisation of tailings and waste at operational and abandoned mine sites is necessary to identify opportunities for secondary value recovery.

Sustainable and scalable mineral recovery technologies are critical to enabling the full social and environmental benefits of remining. Recovery of secondary minerals must overcome technical challenges, including managing low mineral concentrations and high concentrations of gangue material, and developing methods with lower environmental footprints.[69] Many secondary extraction methods utilise toxic processing agents that can present environmental and safety risks if not managed correctly.[70] Demonstration of non-toxic and non-polluting recovery technologies (see Table 7) at commercial scale can reduce the risk associated with secondary mineral recovery from TSFs, wastewater and waste rock stockpiles. Some of these technologies also have applications in remediating contaminated land and water bodies (see Section 4.3)

Table 7: Low-impact technologies for mineral recovery from waste

TECHNOLOGY	DESCRIPTION
Biomining	Bioleaching utilises the metabolic activity of microorganisms to extract minerals from ores and wastes into solution, and bioprecipitation enables the recovery of valuable elements from leach liquors. Moreover, biobeneficiation through bioflotation may enable the separation of minerals of interest from waste rock. In partnership with industry and academia, CSIRO is developing biotechnical processes to extract and recover mineral commodities.[71]
Phytomining	Hyperaccumulator plants can uptake and accumulate metals from the surrounding soil/wastes and can be harvested to produce 'bio-ore'. The University of Queensland is developing phytomining to value recovery metals (e.g., nickel, zinc, selenium) from technology to be implemented on low grade ore bodies or mine tailings.[72]
Membrane technologies	Innovative membrane and separation technologies can filter substances within solutions such as wastewater. The membranes filter materials with high specificity based on the minerals physical and chemical properties. They could be used to filter extracted secondary minerals from tailings.[73]
Geochemical approaches	Naturally absorbent minerals can be used to capture critical minerals and other chemical species within solutions. CSIRO is developing technology for the treatment wastewater as well as value recovery of critical minerals and radioisotopes from contaminated uranium mine wastewater.[74]

69 Sarker et al. (2022)

70 Nkuna R, Ijoma GN, Matambo TS, Chimwani N (2022). Accessing Metals from Low-Grade Ores and the Environmental Impact Considerations: A Review of the Perspectives of Conventional versus Bioleaching Strategies. Minerals, 12(5), p.506.

71 Kaksonen AH, Deng X, Bohu T, Zea L, Khaleque HN, Gumulya, Y, Boxall NJ, Morris C, Cheng KY (2020) Prospective directions for biohydrometallurgy. Hydrometallurgy, 195, p.105376.

72 Sustainable Minerals Institute. (2021) Plants that absorb metal could help provide a sustainable future for mining. The University of Queensland. <https://smi.uq.edu.au/article/2021/08/plants-absorb-metal-could-help-provide-sustainable-future-mining> (accessed 29 August 2023)

73 Panayotova M, Panayotov, V, (2021) Application of membrane processes in mining and mineral processing. In E3S Web of Conferences (Vol. 280, p. 08016). EDP Sciences.

74 Douglas, G (2023) Radioactive waste isn't going away. We've found a new way to trap it in minerals for long-term storage. <https://www.csiro.au/en/news/all/articles/2023/february/radioactive-waste> (accessed 08 September 2023)

3.4 Recycling non-mineral waste

Solutions that enable recycling of non-mineral by-products such as mining equipment and infrastructure. Opportunities include:

- Cost-effective and responsible recycling services for mining equipment and infrastructure

In addition to mineral waste, mining activities generate diverse waste streams from their operations and equipment decommissioning, including tyres, belts, textiles, electronic waste, polyethylene piping and scrap metal.[75] Depending on the economics of the mine location and the volume of these materials, they may be disposed of in a landfill or buried onsite, posing risks for mine closure and relinquishment as abandoned waste present safety and environmental liabilities. For example, the Australian mining industry disposed of 63.3 thousand tonnes of used off-the-road (OTR) tyres onsite in 2019, with a large proportion approved to be disposed of onsite due to the regional nature of the mine.[76]

Recycling of non-mineral waste streams presents an opportunity to recover resources and divert waste from disposal. While the economics of recycling can be challenging, stakeholders noted an increase in the technological capability to cost-effectively recycle waste equipment. However, these emerging solutions are yet to see wide commercial uptake within the mining industry.

There are growing markets and providers for recycling tyres and belts using innovative technology (see Table 8). Consultations identified gaps in the market for recycling equipment such as polyethylene piping, network cabling, carbon fibre infrastructure and proprietary technologies. Increasing waste volume and demand from the mining sector may support a commercial marketplace for recycling vendors and innovative solutions.

Table 8: Australia mining tyre and belt recycling companies

COMPANY	SOLUTION
CTS Tyre Recycling	Establishing a tyre recycling centre in Neerabup, WA, with support from the state and federal government to process at initial stages 30,000 tonnes of tyres annually.[77] The facility will be Australia's largest OTR/mining tyre recycling facility.
Novum Energy Australia	Utilising Thermo Vacuum Recovery (Green Carbon TVR) to convert the variable carbon feedstock from the tyres.[78]
Tytec	Facilitating the breakdown OTR tyres using their single step destructive distillation reactors to convert tyres.[79]
RubberGem	Recycling tyres and belts using proprietary technology, using the rubber to manufacture various products including road base, concrete and recreational surfacing.[80]

75 Peel W (2021) Reconsidering waste in mining. Stantech. <https://www.stantec.com/en/ideas/topic/stantec-era/reconsidering-waste-in-mining> (accessed 29 August 2023)

76 Randell P, Brock B (2020) Mining Industry Off The Road Used Tyre Analysis. Tyre Stewardship Australia. <https://www.tyrestewardship.org.au/reports-facts-figures/mining-industry-off-the-road-otr-used-tyre-analysis/>

77 Smith S (2022) New recycling plant to help mining industry deal with one of its lesser known environmental problems. The Western Australian. <https://thewest.com.au/business/mining/new-tyre-recycling-plant-aims-to-help-mining-industry-deal-one-of-its-lesser-known-environmental-problems-c-7844423>

78 Novum Energy Australia Pty Ltd (2023) Technology. <https://novumenergy.com.au/technology> (accessed 29 August 2023

79 Tytec Recycling Pty Ltd (2023) OTR Tyre Recycling Procedure <http://www.tytecrecycling.com.au/process.html?> (accessed 29 August 2023)

80 RubberGem (2023) Technology <https://www.rubbergem.com.au/technology/> (accessed 29 August 2023)

Opportunities

Cost-effective and responsible recycling services for mining equipment and infrastructure

There is an opportunity for MCS providers to implement cost-effective recycling solutions that bring together and process the high volume of equipment waste held on remote mine sites. Many recycling opportunities are limited in commercial viability due to the high cost associated with establishing processing plants and transporting materials from remote mines. Inconsistent markets for recycled products may also impact their profitability. The recycling industry has a commercial opportunity to develop sustainable business models that can aggregate recyclable materials and build economies of scale. Consultations noted that hub and spoke models may aid in waste aggregation, similar to the aggregation of extracted ores in regional Canada.[81]

Increasing the mobility and modularity of processing equipment to cater to remote regions can improve recycling technology solutions. There is an increased demand for onsite processing that can also mitigate the capital intensity of waste transport. For example, REVYRE is deploying modular, scalable, and mobile tyre recycling equipment in Australia and New Zealand to process stockpiles of mining OTR tyres into rubber goods and feedstock for tyre manufacturing and additives into paving.[82] Similarly, Ecotyre (Germany) have developed modular and containerised mine tyre recycling equipment.[83]

Australian equipment manufacturers can maintain market appeal by aligning with industry sustainability trends and generating social, environmental and economic value for the sector. Stakeholders reported that sustainability trends will drive demand for responsible equipment recycling, such as decommissioning the obsolete diesel-powered fleet due to the transition to renewables. Furthermore, manufacturers undertaking product stewardship processes developing new equipment will hold a competitive advantage. This stewardship involves designing, manufacturing and selling products with low-impact end-of-life recycling processes.[84]

81 Calibre Mining Corp. (n.d.) UTILIZING A "HUB & SPOKE" OPERATING STRATEGY IN NICARAGUA <https://www.calibremining.com/assets/hub-spoke-strategy/> (accessed 29 August 2023)

82 Gleeson D (2020) REVYRE recycling JV looks to tackle mining tyre problem in Australia, New Zealand. International Mining. <https://im-mining.com/2020/05/27/revyre-recycling-jv-looks-tackle-mining-tyre-problem-australia-new-zealand/>

83 EcoTyre (2019) About EcoTyre <http://ecotyrelab.com/#rec127472685> (accessed 29 August 2023)

84 Product Stewardship Centre of Excellence (2023) What is product stewardship <https://stewardshipexcellence.com.au/product-stewardship/#what-is> (accessed 29 August 2023)

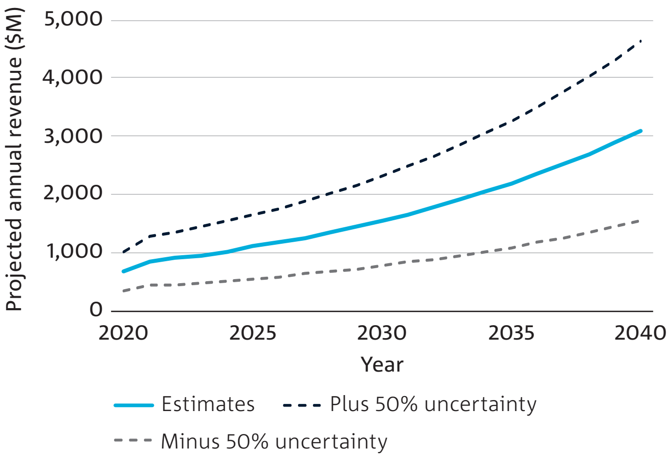
4 Mine rehabilitation

Rehabilitation of mined land is critical to prepare for land relinquishment or reclamation of the site for future uses (see Section 4.4). Rehabilitation objectives vary between sites but typically ensure that the mined land is safe, stable, and non-polluting to support agreed land use. Specific rehabilitation criteria are established in agreement with regulatory bodies. Completing these criteria will allow the relinquishment of the mining tenure and return of government-held mining tenement bonds or equivalent.[85] Rehabilitation is also critical to meeting stakeholder expectations for community safety and well-being, and to restoring and protecting environmental systems. Common rehabilitation activities include engineering landforms for long-term stability, managing hydrological systems, remediating hazardous pollutants, restoring biodiversity, and decommissioning equipment and infrastructure.[86]

Leading practice now encourages progressive rehabilitation and routine progress monitoring throughout operations.[87] Many jurisdictions now mandate progressive rehabilitation. As such, MCS providers must consider how to implement their solutions throughout the mine operations and how to integrate monitoring into their offerings.

This report estimates that the Australian market for environmental remediation technologies and services for mining (a subset of all mine rehabilitation solutions) was worth $800 million in annual revenue in 2020. It could grow to $3 billion annually by 2040 (see Figure 4 and Appendix B). This projection illustrates the potential value of mine rehabilitation solutions that could be captured by Australian businesses.

Figure 4: Projected annual revenue for Australia's mining environmental remediation market[88]



Consulted mining stakeholders identified four mine rehabilitation challenges that could benefit from mine closure solutions provided by Australian businesses (see Table 9).

85 Tiemann CD, McDonald MC, Middle G, Dixon, KW, (2019) Mine relinquishment policy in Australia. In Mine Closure 2019: Proceedings of the 13th International Conference on Mine Closure (pp. 1451-1460). Australian Centre for Geomechanics.; Department of, Energy, Environment and Climate Action (2023) Rehabilitation bonds – minerals exploration mines and quarries. State Government of Victoria <https://earthresources.vic.gov.au/legislation-and-regulations/guidelines-and-codes-of-practice/rehabilitation-bonds> (accessed 29 August 2023)

86 Department of Industry, Science, Energy and Resources (2016a)

87 ICMM (2019) Integrated Mine Closure Good Practice Guide, 2nd Edition. <https://www.icmm.com/en-gb/guidance/environmental-stewardship/2019/integrated-mine-closure>

88 CSIRO Futures calculation.

ABS 2022, Australian industry, Table 1 Key data by industry subdivision, https://www.abs.gov.au/statistics/industry/industry-overview/australian-industry/2020-21.

BCC Research 2021, Global markets for environmental remediation technologies.

IBISWorld 2022, Contract mining services in Australia industry report.

IBISWorld 2022, Contract mining services in New Zealand industry report.

Reserve Bank of Australia 2023, Historical data, Exchange rates – Monthly – January 2010 to latest complete month of current year, https://www.rba.gov.au/statistics/historical-data.html#exchange-rates.

Table 9: Summary of mine rehabilitation related challenges and opportunities

Challenges	Opportunities
Physical stability	• Enhanced data collection with remote technology for landform design and monitoring • Resilient landform construction products and engineering solutions • Thickening and dewatering technologies to stabilise tailings • Technology solutions to optimise the movement of excavated materials
Hydrological systems	• Engineered solutions for hydrological system restoration, stabilisation and water quality management • Technology to monitor and model the long-term impacts of mining on surface and groundwater systems
Pollutant management	• Prevention and monitoring technologies to mitigate hazardous pollutants • Improved pollutant remediation technologies
Revegetation and biodiversity	• Modelling and monitoring technologies to measure biodiversity impacts • Cost-effective treatment technologies to enhance the quality of disturbed topsoil • Sustainable native seed collection services for revegetation • Weed removal systems to reduce labour intensity and prevent potential hazards

4.1 Physical stability

Solutions that optimise the creation of stable landforms and engineered structures can reduce costs and mitigate the risks associated with structural failures. Opportunities include:

- Enhanced data collection with remote technology for landform design and monitoring
- Resilient landform construction products and engineering solutions
- Thickening and dewatering technologies to stabilise tailings
- Technology solutions to optimise the movement of excavated materials

Mined and engineered landforms, including TSFs, can present significant risks that require mitigation. These landforms can be susceptible to structural deterioration caused by ongoing geochemical processes, complex and unfavourable geotechnical conditions, poor long-term engineering design, surface and subsurface water flows, or climate and other environmental factors. Structural damage and degradation can result in environmental impacts, including increased erosion, soil degradation, ecological destruction, and adverse effects on the surrounding region.[89] Failures pose considerable safety risks to communities and may also damage infrastructure or heritage sites.[90]

Improving the geotechnical design, execution, and monitoring of landforms is essential to mitigating risks while controlling associated costs. International catastrophic TSF failures[91] and other events of subsidence and landform collapse have prompted the industry to reassess landform construction methods, emphasising residual risks and commitments to more significant standards of operation.[92] Consulted stakeholders suggested that earthworks can account for up to 40–50% of total direct mine rehabilitation costs and evolving standards are driving increased expenditure on stabilisation activities. MCS providers can develop and deploy innovative solutions that support the design, construction and monitoring of complex landforms. These solutions can reduce costs, mitigate risks and enable optimal outcomes for this critical mine closure challenge.

Opportunities

Enhanced data collection with remote technology for landform design and monitoring

Customised remote surveying equipment and technology can enable high-resolution, real-time data collection. This can enable landform design and stability monitoring activities. Traditional methods of site surveying and land mass movement are labour-intensive and expensive. They may present safety risks associated with working in potentially hazardous areas. MCS providers can utilise modern remote and multimodal sensing technologies to help mitigate the inefficiency and safety risks associated with manual surveying.[93] The data collected can be incorporated into dynamic geotechnical modelling systems or machine learning algorithms to provide insights into landform design and long-term stability to plan effective rehabilitation.[94]

The industry may benefit from greater use of sensing technologies, including drones and satellites to inform mine closure activities and enable greater prediction of landform stability over time. Drones and satellites are commercially mature technologies within adjacent markets (such as civil construction and agriculture) and offer high potential for peripheral customisation to meet mining requirements.

89 Joann, M., & Allan, J. (2021). Geomorphic Perspectives on Mining Landscapes, Hazards, and Sustainability. In Treatise on Geomorphology, (Eds. JJ Clague.) 106-143. Academic Press, Omaha.

90 Williams DJ (2023) A systematic and systemic review of mined landform stability and its impact on transitioning for regional benefits. CRC TiME Limited, Perth.

91 Most notably the failure of a tailings dam in Brumadinho, Brazil, in 2019 which resulted in at least 270 fatalities and impacted on downstream communities up to 120km away. As noted in: Rotta LHS, Alcântara E, Park E., Negri RG, Lin YN, Bernardo N, Mendes TSG. Souza Filho CR, (2020). The 2019 Brumadinho tailings dam collapse: Possible cause and impacts of the worst human and environmental disaster in Brazil. International Journal of Applied Earth Observation and Geoinformation, 90, p.102119.

92 Piciullo L., Storrøsten E.B, Liu Z, Nadim F, Lacasse, S, (2022) A new look at the statistics of tailings dam failures. Engineering Geology, 303, p.106657.; Global Tailings Review (2020)

93 Chen W. Li X. Wang L (2022) Multimodal Remote Sensing Science and Technology. In Remote Sensing Intelligent Interpretation for Mine Geological Environment: From Land Use and Land Cover Perspective. pp. 7-32. Singapore: Springer Nature Singapore.

94 Bai S, Zhao J (2023). A New Strategy to Fuse Remote Sensing Data and Geochemical Data with Different Machine Learning Methods. Remote Sensing, 15(4), p.930.

Drones can be equipped with integrated 3D imaging and LiDAR technology for site surveying with greater mobility and efficiency.[95] Satellites with multispectral and multitemporal cameras can support effective above-ground and underground surveying on a larger scale where drone deployment isn't practical. Satellites equipped with Interferometric Synthetic Aperture Radar (InSAR) are increasingly being used to monitor the structural stability of TSF. High-resolution data is captured and processed over extended time periods to identify early warning signs of catastrophic failures.[96]

The mining sector has previously used these technologies for mineral exploration, and there is a recent increase in their use to support landform design and monitoring (see Table 10 for examples).[97] These technologies can also be utilised to support environmental monitoring and revegetation activities (see Section 4.4)

Table 10: Remote sensing companies supporting rehabilitation activities

COMPANY	SOLUTION
RocketDNA (formerly Rocketmine)	A multinational company operating in Australia and Africa providing mine inspection and survey services. Uses aerial survey drones equipped with multispectral cameras and LiDAR sensors to capture and map data across the mining life. Data from TSF inspections, surface stability monitoring, and pit and stockpile surveys can be used to create 3D maps of the mine.[98]
Geoimage	An Australian business utilising low Earth orbit satellites mounted with hyperspectral, optical and radar sensors. Data can be used to generate large-scale geospatial images and models that can enable long-term regional monitoring of landforms and vegetation affected by rehabilitation.[99]

Satellite imagery of Handlebar Hill Mine in Queensland, displaying mine rehabilitation progress between 2016 (left) and 2023 (right). Supplied by Geoimage Pty Ltd. © Airbus DS (2016) / © Airbus DS (2023).

95 Shahmoradi J, Talebi E, Roghanchi P, Hassanalian M, (2020) A comprehensive review of applications of drone technology in the mining industry. Drones, 4(3), p.34.

96 Carlà T, Intrieri E, Raspini F, Bardi F, Farina P, Ferretti A, Colombo D, Novali F, Casagli N (2019) Perspectives on the prediction of catastrophic slope failures from satellite InSAR. Scientific reports, 9(1), p.14137.

97 McKenna, PB, Lechner, AM, Phinn, S, Erskine PD (2020) Remote sensing of mine site rehabilitation for ecological outcomes: a global systematic review. Remote Sensing, 12(21), p.3535.

98 Rocketmine (2023) Drone Surveying & Mapping Services <https://www.rocketmine.com/our-solutions/survey-mapping/> (accessed 29 August 2023)

99 Geoimage (2023) Mining & Exploration. <https://www.geoimage.com.au/mining-exploration/#industry-solution-section> (accessed 29 August 2023)

Resilient landform construction products and engineering solutions

Using resilient materials for landform construction can reduce environmental and safety risks such as structural instability and geochemical seepage. Stakeholders noted that cost-effective solutions are required to optimise the structure of stable landforms. Many available engineering solutions are capital-intensive and have limited longevity. Optimal materials and products should be sustainable, maintain structural integrity and be non-reactive to the environment. Geotechnical and geochemical characteristics of landforms will determine the suitability of solutions. Backfilling with waste rock is also used to stabilise mine voids (see Section 3.3).

Sustainable and durable methods to line and cover TSFs are required to increase confidence in the long-term containment of tailings. TSF liners and cover systems provide a physical separative barrier between mine tailings and the surrounding landmass to prevent leaching into the environment. Conventional lining products may result a risk of long-term deterioration or potential ripping during installation, which exposes the TSF to contamination risks.[100] Australian company Geofabrics manufactures sustainable geosynthetic products from recycled plastics that can be used for the lining and covering of tailings.[101] Improved cover system solutions are also being developed for industry, including biological covers, new reinforcement materials, and optimised placement strategies for tailings covers.[102]

Thickening and dewatering technologies to stabilise tailings

Water removal or viscosity-increasing technology can reduce the burden of managing liquid tailings slurries, improve safety outcomes, reduce the volume of tailings deposited, and increase water recovery. MCS providers can design tailings stabilising technologies to enable safe TSF construction that meets global safety standards and reduces ongoing risks. These processes require high-energy mechanical pump systems to transport and reduce the risk of water impacting structural integrity that could cause TSF failure.[103] The primary barrier to the uptake of dewatering technologies is its cost; however, there is evidence that dewatering technology can be financially superior to business-as-usual tailings management when the potential financial impact of a failure is considered.[104]

Several technologies can be utilised to increase tailings slurry stability, with selection dependent on site feasibility and prospective economic outcomes of deployment. Options include but are not limited to:

- Thickening tailings using thickening agents to create a greater solid content and make a paste. Many mining operations currently use this technology, with expectations for broader deployment.[105]
- Dry stacking using solid-liquid separation technologies (e.g., centrifugation and filtration) to create a pseudo-solid product that is stackable and transportable by truck. Creating dry stack tailings is widely considered the most sustainable long-term treatment option. It has seen more applications in recent years.[106]

100 Tuomela A, Ronkanen AK, Rossi PM, Rauhala A, Haapasalo H, Kujala K (2021) Using geomembrane liners to reduce seepage through the base of tailings ponds—A review and a framework for design guidelines. Geosciences, 11(2), p.93.

101 Geofabrics Australiasia Pty Ltd (n.d) Tailings and Waste. <https://www.geofabricsmining.com.au/mining-solutions/tailings-and-waste> (accessed 30 August 2023)

102 Rodin S, Champagne P, Mann V (2023) Pilot-scale feasibility study for the stabilization of coal tailings via microbially induced calcite precipitation. Environmental Science and Pollution Research, 30(4), pp.8868-8882; ATC Williams Pty. Ltd (2020) The Groundwork Capping and Rehabilitation of Coal Tailings Storages <https://atcwilliams.com/capping-and-rehabilitation-of-coal-tailings-storages/> (accessed 30 August 2023).

103 Department of Industry, Science, Energy and Resources (2016b) Tailings Management – Leading Practice Sustainable Development Program for the Mining Industry. Australian Government. <https://www.industry.gov.au/sites/default/files/2019-04/lpsdp-tailings-management-handbook-english.pdf>.

104 Armstrong M, Langrené N, Petter R, Chen W, Petter C (2019) Accounting for tailings dam failures in the valuation of mining projects. Resources Policy, 63, p.101461.

105 Department of Industry Science, Energy and Resources (2016b)

106 Avery Q and Wilson K (2013) Red mud pressure filtration for the alumina refinery's bauxite residue tailings disposal. 16th International Seminar on Paste and Thickened Tailings 225–238. <https://papers.acg.uwa.edu.au/p/1363_17_Avery/>.

Technology solutions to optimise the movement of excavated materials

Optimising solid material movement and placement during earthwork rehabilitation can reduce costs and decrease environmental impact. Stakeholders reported that primary earthworks account for a significant proportion of closure expenses. They are also a significant source of emissions. Optimising material and heavy vehicle movement can also save costs through reduced fuel consumption (and associated carbon emissions) and lower maintenance requirements.

Emerging solutions, including digital diagnostics, strategic site designs, and vehicle automation systems can increase the efficiency of waste movement and fleet operations efficiency. For example, on-board vehicle diagnostics that monitor vehicle performance data (such as engine performance, health, and fuel consumption) can improve the rehabilitation fleet's operational efficiency. Using data, performance and efficiency can be optimised through strategic route planning and site design. Australian business Maxmine has developed a data platform to optimise the load and haul system on a mine site and has been reported to reduce carbon emissions by 20%.[107]

Autonomous vehicle systems can reduce inefficiency and costs through optimised vehicle performance, longevity of vehicle health, reduced idle times and reduced hazardous conditions for onsite workers. As many of the vehicles involved in rehabilitation are also used in the operational mining fleet, equipment manufacturers and other METS businesses with existing solutions can potentially expand their offerings into closure activities where appropriate. This includes ensuring that electric vehicle technologies developed for the operations fleet are also supplied for rehabilitation-specific vehicles, as the mining sector strives to meet its decarbonisation objectives.

107 Resolution Systems Pty Ltd (2023) MaxMine Carbon <https://maxmine.com.au/maxmine-carbon> (accessed 30 August 2023)

4.2 Hydrological systems

Solutions that aid in restoring, monitoring, and modelling surface and groundwater systems can protect long-term water quality and quantity and mitigate environmental and safety risks. Opportunities include:

- Engineered solutions for hydrological system restoration, stabilisation and water quality management
- Technology to monitor and model the long-term impacts of mining on surface and groundwater systems

Mining activities including excavation and mine dewatering, affect hydrological systems above and below the water table. They may alter water quality, quantity and movement, potentially impacting downstream systems.[108] Hydrological systems connect the mining lease to the greater surrounding region. As such, poorly managed water systems may lead to geotechnical (e.g., erosion and landform instability) and environment risks (e.g., ecological disruption and compromised water chemistry) that can extend well beyond the mine site.

Hydrological systems management presents a complex challenge as miners need to manage onsite systems that may have social, cultural, environmental, and economic impacts on the surrounding regions. For example, waterways can hold significant cultural importance to Aboriginal and Torres Strait Islander peoples, and social and economic value to local communities.[109] The technical management of hydrological systems also provides significant challenges as they are dynamic systems that can require ongoing monitoring. Mine closure practitioners must also ensure that post-closure hydrological systems such as pit lakes are designed to meet local climate pressures and mitigate the risks associated with drought or flooding events.

Opportunities

Engineered solutions for hydrological system restoration, stabilisation and water quality management

There is demand for MCS providers to develop engineered solutions to aid in restoring surface and groundwater systems and reduce mine dewatering impacts. Dewatering of mines below the water table can adversely influence surface and groundwater systems. Impacts on regional aquifer systems can cause unstable groundwater levels and compromise water quality, potentially extending to surrounding communities and ecosystems. Recharging dewatered groundwater systems and filling pit lakes can require investment in new infrastructure for water supply, which can increase costs. Water quality requirements and water licensing legislation can compound by restricting access to available water sources.[110]

Water restoration solutions are required to restore the water systems in dewatered mining areas and manage quality and levels in new water systems in open pit mines. Emerging approaches for water system restoration are explored in the CRC TiME report *Hydrological and geochemical processes and closure options, for below water table open pit mines*. These include engineered barriers to reduce water drawdown and pumped aquifer recharge to resupply extracted water into the subsurface aquifers during mining. Pit lake water quality can be improved through prevention of hazardous geochemistry by selection

108 Meißner S (2021) The impact of metal mining on global water stress and regional carrying capacities—a GIS-based water impact assessment. Resources, 10(12), p.120.

109 Department of Industry, Science and Resources (2016c) Working with Indigenous Communities - Leading Practice Sustainable Development Program for the Mining Industry. Australian Government. <https://www.industry.gov.au/publications/leading-practice-handbooks-sustainable-mining/working-indigenous-communities>

110 Productivity Commission (2021) National Water Reform 2020, Inquiry Report no. 96, Commonwealth of Australia, Canberra.

of neutral pit backfill materials, amendment of reactive materials or through innovative treatment options such as bioremediation.[111] Furthermore, on site water retreatment may alleviate some of the restoration challenges as water of suitable quality is fed back into the mine site or regional waterways. Water system restoration may also help to enable post-closure opportunities such as agriculture, recreation, or pumped-hydro energy storage opportunities. Australia's well-developed wastewater treatment industry and high-water stewardship standards are an area of comparative advantage and may present an export opportunity for Australian business.[112]

Technology to monitor and model the long-term impacts of mining on surface and groundwater systems

The long-term impacts of mining on hydrological and hydrogeological systems are challenging to accurately predict. Mining companies now have a greater responsibility to monitor and manage their impact of regional surface and groundwater systems during operations and closure. In the context of closure, this includes modelling water flows and groundwater interactions post-closure, considering the potential impact regional water systems, biophysical interactions of water systems, predicting and mitigating the impact of extreme weather and managing the recovery of dewatered groundwater systems.

Improved data collection and modelling tools can inform strategic planning and optimise water management decisions for the long-term sustainability of post-closure water systems. Hydrological and hydrogeological modelling tools and consulting services are relatively mature. However, hydrogeological systems have great complexity and uncertainty that can be challenging and expensive to model accurately. Solutions that enable cost-effective and reliable continuous monitoring of surface and groundwater systems and their interactions can improve certainty and optimise risk management. Groundwater assessments are informed by point-based measurement using monitoring wells, satellite-based monitoring for regional storage,[113] and numerical modelling approaches. Optimising the joint use of these approaches may help to assess and model groundwater resources more efficiently.[114]

111 Cook PG, Black S, Cote C, Kahe MS, Linge K, Oldham C, Ordens C, McIntyre N, Simmons C, Wallis I (2021). Hydrological and geochemical processes and closure options for below water table open pit mines. CRC TiME Limited, Perth.

112 Australian Trade and Investment Commission (2017) Water in Mining. <https://www.austrade.gov.au/international/buy/australian-industry-capabilities/mining>

113 Particularly GRACE satellite data. National Drought Mitigation Center (2023) Groundwater and Soil Moisture Conditions from GRACE-FO Data Assimilation for the Contiguous U.S. and Global Land. <https://nasagrace.unl.edu/>

114 Masood A, Tariq MAUR, Hashmi MZUR, Waseem M, Sarwar MK, Ali W, Farooq R, Almazroui M, Ng AW (2022) An overview of groundwater monitoring through point-to satellite-based techniques. Water, 14(4), p.565.

4.3 Pollutant management

Solutions that prevent, treat and monitor mining-related pollutants can mitigate safety and environmental risks and long-term mining liabilities. Opportunities include:

- Prevention and monitoring technologies to mitigate hazardous pollutants
- Improved pollutant remediation technologies

Pollutants that are exposed or introduced during mining activities can cause long-lasting safety and environmental impacts. Mining results in the exposure of sealed minerals, which may react and contaminate the surrounding environment. If pollutants are not effectively controlled, they may diffuse into surrounding regional systems posing risks to communities and ecosystems.[115]

Pollutant management is required throughout the life-of-mine. However, pollutant control may encounter unique challenges during and after closure activities. For example, previously unidentified bio-geochemical reactions may occur in natural settings, unidentified pollutants may be overlooked in remediation strategies, and diffusion of pollutants can be difficult to detect. Pollutant containment and treatment methods may incur high costs. For example, some active pollutant remediation solutions require large energy requirements and extended treatment times.[116]

Common pollutants that must be managed include AMD,[117] toxic heavy metals,[118] mineral processing reagents or dangerous by-products (such as radioactive species). The opportunities presented are framed to address AMD, however the diversity of pollutants generated throughout the mining cycle needs to be managed, presenting opportunities for MCS providers to develop innovative solutions. CRC TiME is aiming to improve AMD management through exploring the links between prediction, scale-up and residual risk to bridge the gap between lab-scale methodologies and mine site implementation.[119]

Opportunities

Prevention and monitoring technologies to mitigate hazardous pollutants

There is an ongoing need for effective management tools to predict, monitor and control the formation of AMD. AMD is caused by the oxidation of sulphide minerals in mined waste and land. This process can result in a typically acidic solution that may also contain elevated concentrations of major ions or dissolved metals that can contaminate surface and groundwater systems. This may lead to ecological damage, and human and animal health impacts. The Australian Government released a handbook noting leading practices for the prevention and management acid and metalliferous drainage.[120]

The development of proactive prevention and monitoring solutions is necessary to limit the oxidisation of sulphidic ores and reduce the risk of AMD.[121] Suitable preventative solutions may need to be tailored to different AMD-causing minerals. Potential solutions to inhibit oxidation include non-reactive oxygen barriers, microencapsulation technologies, chemical barriers, or novel electrochemical strategies.[122] Soil and waterway

115 Okereafor U, Makhatha M, Mekuto L, Uche-Okereafor N, Sebola T, Mavumengwana V (2020) Toxic metal implications on agricultural soils, plants, animals, aquatic life and human health. International journal of environmental research and public health, 17(7), p.2204.

116 Karaca O, Cameselle C, Reddy KR (2018). Mine tailing disposal sites: contamination problems, remedial options and phytocaps for sustainable remediation. Reviews in Environmental Science and Bio/Technology, 17, pp.205-228.

117 Department of Industry, Science and Resources (2016d) Preventing Acid and Metalliferous Drainage – Leading Practice Sustainable Development Program for the Mining Industry. Australian Government <https://www.industry.gov.au/publications/leading-practice-handbooks-sustainable-mining/preventing-acid-and-metalliferous-drainage>

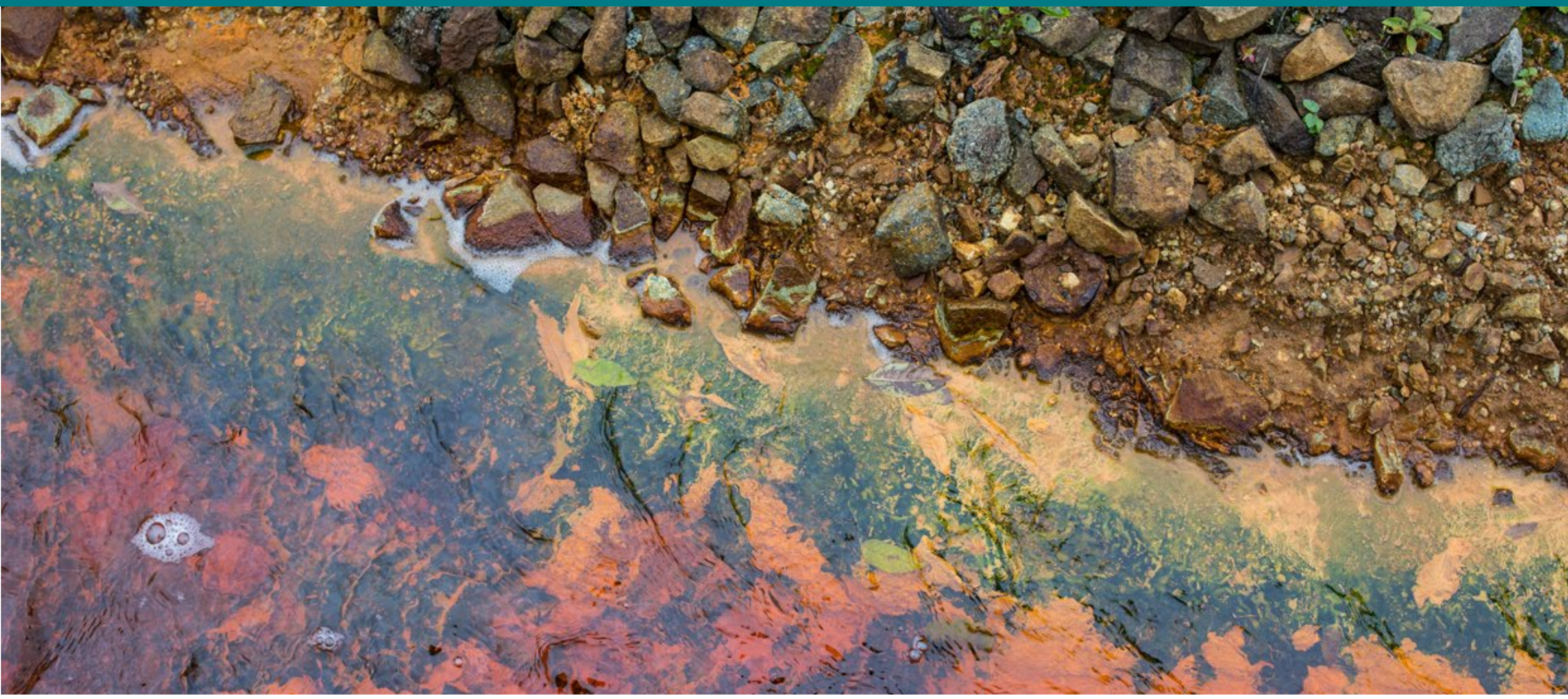
118 Karn R, Ojha N, Abbas S, Bhugra S (2021) A review on heavy metal contamination at mining sites and remedial techniques. In IOP Conference Series: Earth and Environmental Science (Vol. 796, No. 1, p. 012013). IOP Publishing.

119 CRC TiME Limited (2023) Improved prediction, remediation and closure of AMD/NMD sites by examination of mine waste behaviour at the meso-scale <https://crctime.com.au/research/projects/project-3-10/> (accessed 30 August 2023)

120 Department of Industry, Science and Resources (2016d)

121 Park I, Tabelin CB, Jeon S, Li X, Seno K, Ito M, Hiroyoshi N (2019) A review of recent strategies for acid mine drainage prevention and mine tailings recycling. Chemosphere, 219, pp.588-606.

122 Park I et al. (2019); Singh A, Bourgault C, Kanse L, Oldham C (2022) Developing the business case for responsible acid and metalliferous drainage (AMD) management. CRC TiME Limited, Perth.



monitoring tools will be required prior to and following interventions to evidence the prevention of AMD formation. Prevention systems have shown positive results in feasibility studies but have yet to be widely adopted commercially.[123] Source control practices such as strategic waste rock stockpile design may also mitigate the risks associated with pollutant discharge.[124]

Improved pollutant remediation technologies

There is an opportunity to develop more effective, affordable, scalable pollutant remediation solutions. Current treatments often require the heavy use of eco-toxic chemicals, high energy inputs and sizeable equipment costs.[125] As such, there is also an ongoing cultural shift to utilise more sustainable and environmentally friendly treatment systems such as passive treatment approaches.[126] Stakeholders noted that current active treatment methods would benefit from substituting hazardous chemicals with non-toxic reagents.

Innovative passive treatment technologies such as permeable reactive barriers, small-scale bioreactors, and ecological systems (e.g., wetlands) are all at variable levels of technological development and are not yet widely adopted.[127] Passive treatments currently require improvements to overcome scalability and cost challenges.[128] Internationally, some passive and semi-passive treatments have been demonstrated. An example of this is the use of saturated rock fill in Canada,[129] which was enabled by Canadian regulators publishing guidelines for the evaluation and use of emerging water treatment technologies in mines.[130] Active and passive technologies can potentially be implemented together to offset the challenges present with both solutions.

Pollution remediation technologies can also be integrated into post-closure land use to help support environmental outcomes through ecological restoration. For example, construction of wetlands can address AMD while supporting ecosystem development. In Australia, Evolution Mining, in collaboration with CSIRO and Australian Wetlands Consulting, has demonstrated the use of wetlands to treat sulphidic wastewater at Mt Rawdon mine in Queensland.[131]

123 Singh et al. (2022)

124 The International Network for Acid Prevention (2020) Rock Placement Strategies to Enhance Operational and Closure Performance of Mine Rock Stockpiles. <https://www.inap.com.au/research/>

125 Skousen JG, Ziemkiewicz PF, McDonald LM (2019) Acid mine drainage formation, control and treatment: Approaches and strategies. The Extractive Industries and Society, 6(1), pp.241-249.

126 Moodley I, Sheridan CM, Kappelmeyer U, Akcil A (2018) Environmentally sustainable acid mine drainage remediation: Research developments with a focus on waste/by-products. Minerals Engineering, 126, pp.207-220.

127 Shabalala A, Masindi V (2022) Insights into mechanisms governing the passive removal of inorganic contaminants from acid mine drainage using permeable reactive barrier. Journal of Environmental Management, 321, p.115866.

128 Masindi V, Foteinis S, Renforth P, Ndiritu J, Maree JP, Tekere M, Chatzisymeon E (2022) Challenges and avenues for acid mine drainage treatment, beneficiation, and valorisation in circular economy: A review. Ecological engineering, 183, p.106740.

129 International Mining (2019) Teck sees big future for saturated rock fill water treatment technology <https://im-mining.com/2019/02/13/teck-sees-big-future-saturated-rock-fill-water-treatment-technology/> (accessed 30 August 2023)

130 Ministry of Energy, Mines and Low Carbon Innovation (2022) Technology Readiness Assessment – Interim Technical Guidance, Province of British Columbia. https://www2.gov.bc.ca/gov/content/environment/waste-management/industrial-waste/mining-smelting/guidance-documents

131 CSIRO (2021) Natures cleaners. Resourceful. <https://www.csiro.au/en/work-with-us/industries/mining-resources/resourceful-magazine/issue-16/natures-cleaners> (accessed 11 September 2023)

4.4 Revegetation and biodiversity

Solutions that optimise revegetation, weed removal, and biodiversity management can reduce associated costs and improve outcomes for local and regional environments. Opportunities include:

- Modelling and monitoring technologies to measure biodiversity impacts
- Cost-effective treatment technologies to enhance the quality of disturbed topsoil
- Sustainable native seed collection services for revegetation
- Weed removal systems to reduce labour intensity and prevent potential hazards

Revegetation of mined land is critical to the success of mine rehabilitation, biodiversity restoration and long-term stability. Mining activities suppress the natural ecosystems and vegetation that play an important role in maintaining the stability and function of the surrounding biophysical environment. This increases the risk of adverse effects such as erosion and can expose miners and local communities to greater liabilities, risks, and costs.

This section focuses on the challenges and opportunities related to the restoration and biodiversity of flora. The impact of mining on native fauna is a broader issue that is not primarily manageable through mine closure solutions. Consulted mining stakeholders identified the following key challenges to revegetation:

- Many mines face extensive topsoil deficits that increase the cost of revegetation activities. Access to quality topsoil at the appropriate stage in closure timelines is necessary to enable revegetation. The original topsoil is displaced during extraction and may be combined with other mine waste stockpiles, reducing its suitability for revegetation. Remote mines with topsoil deficits will face great costs and delays to revegetation due to the high transport costs of importing topsoil.
- There are supply bottlenecks for native seeds in Australia including appropriate flora species needed to sustainably revegetate a mine site and restore biodiversity.[132] Seed selection and collection requires specialist knowledge and skills to sustainably manage native populations that are resilient enough to thrive in unique environmental conditions and the changing climate.
- Invasive weed species cause detrimental impacts on local ecosystems and may jeopardise mine rehabilitation outcomes. Invasive weeds are often better suited to survive harsher environments, compete with native flora, spread beyond the mine site and can increase risks of fire and erosion.[133]

Stakeholders suggested that it is essential to draw upon Indigenous ecological knowledge and co-design with Indigenous stakeholders to achieve the best environmental and cultural outcomes from revegetation. The recently launched Australian Research Council Training Centre for Healing Country is focused on supporting the development of Indigenous-led ecological restoration businesses. This research and training initiative aims to provide training and credentials for environmental restoration utilising Indigenous knowledge.[134]

Mine closure practitioners must ensure that they are adequately addressing revegetation challenges to meet environmental regulations and closure completion criteria for relinquishment. MCS providers have opportunities to develop technologies and services that help enable and monitor the success of revegetation activities and meet closure requirements.

132 Hancock N, Gibson-Roy P, Driver M, Broadhurst L (2020) The Australian Native Seed Sector Survey Report. Australian Network for Plant Conservation, Canberra.

133 Department of Environment, Parks and Water Security (n.d.) Preventing weed spread is everybody's business. Northern Territory Government of Australia <https://depws.nt.gov.au/rangelands/publications2/weed-management-publications> (accessed 30 August 2023)

134 ARC Training Centre for Healing Country (2023) Healing Country Official Launch. Curtin University <https://archealingcountry.com.au/healing-country-official-launch/> (accessed 11 September 2023)

Opportunities

Modelling and monitoring technologies to measure biodiversity impacts

Innovative systems that quickly and cost-effectively identify biodiversity concerns and model their potential impacts can be used to reduce revegetation costs. Traditional surveying and identification methods are labour and resource intensive. Emerging monitoring technology can track plant growth, assess threat levels of weed species, and inform integrated management with great precision and efficiency.[135] Modelling long-term biodiversity impacts can also be used to develop solutions and identify the scale of the revegetation challenge prior to the implementation of a mine closure plan.

Remote sensing technologies can be used to monitor both mining impacts and revegetation success, providing baseline and ongoing data**.** For example, innovative monitoring systems combined with advanced remote detection methods, such as camera-mounted drones or low Earth orbit satellites and image processing algorithms, can detect invasive weeds over large-scale regions. For example, Australian business Dendra uses automated drones to capture high-resolution imagery and apply machine learning algorithms specifically trained in ecology to monitor plant species, vegetation health, weed incursions, and the presence of pest and native fauna.[136] These modes of remote monitoring solutions can be used to inform strategies that enable successful revegetation and the restoration of biodiverse ecosystems in large mine closure projects. These technologies may also be used to monitor long-term landform stability (see Section 4.1).

135 Song W, Song W, Gu H, Li F (2020) Progress in the remote sensing monitoring of the ecological environment in mining areas. International Journal of Environmental Research and Public Health, 17(6), p.1846. ; Department of Primacy Industries (n.d.) Integrated weed management. State of New South Wales. <https://www.dpi.nsw.gov.au/biosecurity/weeds/weed-control/general-management/integrated-weed-management> (accessed 30 August 2023)

136 Dendra Systems (2022) Ecosystem Analysis At Scale With Dendra RestorationOS. <https://dendra.io/solutions/ecosystem-analysis/> (accessed 30 August 2023>

Cost-effective treatment technologies to enhance the quality of disturbed topsoil

Mine closure practitioners highlighted the high cost of sourcing quality fertile topsoils as a key challenge in revegetation. Cost-effective solutions that can maintain the quality of excavated topsoil during mine operations or upgrade the quality of other soils onsite are required to meet the topsoil demand during rehabilitation.

Mines can operate for decades, and the quality of any topsoil that is stored for this duration is likely to decline significantly. Maintaining topsoil over this period faces cost and technical challenges, such as acidity, low organic matter, and low porosity.[137] To address this, there is a demand for specialist consultancies that can develop and implement evidence-based strategies to reduce the rate of soil deterioration. These may include design of stockpile facilities (e.g., drainage systems, erosion control measures, vegetation covers, windbreaks),[138] logistical arrangements (e.g., volume and height of stored soil),[139] and procedures (e.g., soil testing and amendments).

Developing cost-effective and time-efficient solutions to improve the physical, chemical, and biological properties of stored or disturbed soil onsite can also reduce the costs associated with importing fertile topsoil.

Current approaches to upgrading soils to topsoil quality are time-intensive, requiring long treatment periods and access to large volumes of water. Research in this space is exploring ways to efficiently increase the availability of nitrogen for plant growth in waste rock, tailings and stockpiled soils.[140] Solutions that improve soil properties in short durations are likely to have a competitive advantage compared to traditional upgrading approaches. Australian company, SoilCyclers provides an example of treatment opportunities through their soil amelioration expertise which was successfully deployed at the Ensham coal mine in Queensland (see Case Study below).

Sustainable native seed collection services for revegetation

The growing demand for seed supply presents an economic opportunity for Australian businesses, particularly those that are Indigenous-owned, with experience in managing native plant populations and sourcing diverse plant species. Demand from mining and other heavy industry for native seeds continues to grow as stakeholder expectations and regulatory requirements increase. Nurseries with seed propagation capabilities will be required to address the growing concern that wild plant populations may not be able to sustainably meet demand for native species.

Case Study: Creating pasture from overburden material and bioremediated pit water at Ensham Mine

Rehabilitation of the Ensham Mine in Queensland faced multiple challenges including a topsoil deficit, erosion issues and water contamination. A collaborative project involving Cammel Consulting, Innovate Enviro and SoilCyclers demonstrated both the upcycling of overburden material to topsoil and the bioremediation of saline pit water. SoilCyclers soil alteration solutions were deployed to facilitate topsoil amelioration, geotechnical soil amendments, and acid sulphate soil remediation to generated topsoil from overburden material. Innovate Enviro's expertise in bioremediation was used to demonstrate the treatment of mine water to create a water source suitable to growing pasture. This project was enabled by funding from Ensham Resources, Idemitsu and METS Ignited.[141]


Image: SoilCyclers

137 Guedes RS, Ramos SJ, Gastauer M, Júnior CFC, Martins GC, da Rocha Nascimento Júnior W, de Souza-Filho PWM, Siqueira, JO (2021) Challenges and potential approaches for soil recovery in iron open pit mines and waste piles. Environmental Earth Sciences, 80(18), p.640.

138 Dai S, Ma Y, Zhang K (2022) Land Degradation Caused by Construction Activity: Investigation, Cause and Control Measures. International Journal of Environmental Research and Public Health, 19(23), p.16046.

139 Fischer AM, Van Hamme JD, Gardner WC, Fraser LH (2022) Impacts from Topsoil Stockpile Height on Soil Geochemical Properties in Two Mining Operations in British Columbia: Implications for Restoration Practices. Mining, 2(2), pp.315-329.

140 CRC TiME Limited. (2023) Increasing bio-available plant nutrients in mineral waste <https://crctime.com.au/research/projects/project-3-8/> (accessed 30 August 2023)

141 SoilCyclers (2022) Ensham Mine Case Study (video). <https://soilcyclers.com.au/sectors/> (accessed 18 August 2023)

However, there is evidence that the costs associated with this development may increase the cost of revegetation.[142]

Aboriginal and Torres Strait Islander peoples and enterprises have a critical role to play in this emerging industry, capturing economic gains through industry development while facilitating the rehabilitation and restoration of Australia's landscapes. There are already successful examples of Indigenous businesses operating in seed supply for mining revegetation, including:

- The Gelganyem Seed Project, established in 2019, assembled a local Indigenous team to coordinate a community seed collection program and provide Traditional Owners near the Argyle mine in the Kimberley region (WA) with the opportunity to supply native seeds.[143]
- A collaboration of multiple organisations within the Midwest Employment and Economic Development Aboriginal Corporation (MEEDAC) which resulted in the founding of the first Indigenous-owned and managed native seed farm for mining land restoration in regional WA.[144]
- Kakadu Native Plants has partnered with Energy Resources of Australia (ERA) to propagate local seeds from the mine lease to rehabilitate the Ranger project area in Kakadu National Park.[145]
- Various local Indigenous collection groups supply seeds for over 60 native plant species to the Rio Tinto Weipa bauxite mine in Cape York (QLD). The program has been running between the Aurukun, Napranum, and Mapoon communities for many years.[146]

The native seed sector is currently small and faces some barriers to its growth. The Australian native seed sector is comprised predominately of siloed sole traders and small operators. The sector has also noted that market pricing does not always cover the cost of seed collection and propagation. This is further compounded by inconsistency and unpredictability of demand as well as natural climatic conditions limiting sourcing activities.[147] Better management and support from the mining industry and other sectors will help to enable the growth and maturity of this sector.

Weed removal systems to reduce labour intensity and prevent potential hazards

Australian businesses offering novel technologies that reduce the need for manual weed removal and avoid the use of potentially toxic herbicides can improve revegetation outcomes. Current technologies for weed removal rely on manual processes, chemical herbicides, controlled burns, introduction of biological agents or large-scale mechanical disruption. These methods can be labour or resource-intensive and may pose hazards to the environment or local communities.[148]

Beyond traditional removal technologies, several novel systems are emerging that could offer improved safety and efficiency outcomes in large-scale weed removal. Rapid developments and convergence in robotics, automation, machine learning and artificial intelligence technologies are enabling the development of novel weed detection and management systems.[149] New approaches for targeted and integrated weed management are also being explored, including lasers, novel chemicals, and biological treatments (e.g., RNA interference[150]).

142 Gibson-Roy P, Hancock N, Broadhurst L, Driver M, (2021) Australian native seed sector characteristics and perceptions indicate low capacity for upscaled ecological restoration: insights from the Australian Native Seed Report. Restoration Ecology, 29(7), p.e13428.

143 Urzedo D, Pedrini S, Hearps C, Dixon K, van Leeuwen S (2022) Indigenous environmental justice through coproduction of mining restoration supply chains in Australia. Restoration Ecology, 30, p.e13748.

144 Urzedo et al. (2022)

145 Energy Resources of Australia (2019) A journey with Kakadu native Plants to mine rehabilitation <https://www.energyres.com.au/ranger-rehabilitation/stories/a-journey-with-kakadu-native-plants-to-mine-rehabilitation/> (accessed 30 August 2023)

146 Barnes R, Holcombe S, Parmenter J (2020) Indigenous groups, land rehabilitation and mine closure: exploring the Australian terrain. University of Queensland, Brisbane, Australia

147 Gibson-Roy et al. (2021)

148 Department of Environment, Parks and Water Security (2021) Weed Management Handbook, Northern Territory Government. <https://nt.gov.au/environment/weeds/how-to-manage-weeds/weed-management-handbook>

149 Westwood JH, Charudattan R, Duke SO, Fennimore SA, Marrone P, Slaughter DC, Swanton C, Zollinger R (2018) Weed management in 2050: Perspectives on the future of weed science. Weed science, 66(3), pp.275-285.

150 Zabala-Pardo D, Gaines T, Lamego FP, Avila LA (2022) RNAi as a tool for weed management: challenges and opportunities. Advances in Weed Science, 40, p.e020220096.

5 Land use transitions

Transitioning a site beyond mining provides an opportunity to generate lasting social, environmental or economic value and reduce potential adverse impacts of closure. The variety of potential post-closure land uses presents an opportunity to cultivate innovative, sustainable businesses and communities that leverage a mine site's infrastructure and final landform. Examples of post-closure land use include recreation and tourism, waste management and recycling, and energy generation and storage.[151]

Creating sustainable business models and associated land uses that meet community and cultural interests requires the identification of opportunities that deliver social, environmental and economic approach to value generation. The optimal outcome of mine closure is for the site to transition to a use that creates value for and is supported by local communities.

Working with communities to determine a land use transition plan can help build trust and support the social performance of mining companies. Local and regional communities, including Indigenous communities, will be best placed to determine suitable opportunities. However, opportunities will vary from region to region and between stakeholders. Sound engagement strategies (see Section 2) will be necessary to ensure that the views of each stakeholder are considered.

Establishing post-closure land uses may also enable the mining industry to recoup closure costs, offset the costs of managing any ongoing liabilities, and improve social performance. For example, utilisation of existing infrastructure (e.g., electricity networks) can reduce costs associated with new projects and decommissioning. Communities can also benefit from repurposing mine features, such as the conversion of underground mines for cold store food storage.[152]

Reports have documented 15 examples of post-closure land use in Australia.[153] Figure 5 highlights five established and emerging examples that showcase the diverse uses of mined land. Further case studies on emerging land use can be found in CRC TiME's *Post-mining land uses* report.[154]

Consultations suggested the identification and development of post-closure land uses as a challenge that offers opportunities for Australian businesses (see Table 11).

Table 11: Summary of land use transitions challenges and opportunities

Challenges	Opportunities
Post-closure land use	• Businesses specialising in identifying, assessing, enabling and developing of post-closure land uses

151 Beer A, Haslam-McKenzie F, Weller S, Davies A, Cote C, Ziemski M, Homles K, Keenan J (2022) Post-mining land uses. CRC TiME Limited, Perth, Australia.

152 Galgaro, Antonio & Dalla Santa, Giorgia & Cola, Prof. phD. Eng. Simonetta & Cultrera, Matteo & De Carli, Michele & Conforti, Fabrizio & Scotton, Paolo & Viesi, Diego & Fauri, Maurizio. (2020). Underground warehouses for food storage in the Dolomites (Eastern alps – Italy) and energy efficiency. Tunnelling and Underground Space Technology. 102. 103411. 10.1016/j.tust.2020.103411.

153 Keenan J, Holcombe S (2021).

154 Beer A et al. (2022)

Figure 5: Examples of innovative uses of mined land in Australia

Hannans North Tourist Mine
Kalgoorlie, WA

Historic gold mine converted into a visitor attraction and educational site.

Clean energy hub
Kidston, QLD

Gold mine under transition to develop renewable energy generation and storage site with solar, wind and pumped hydro technologies.

Image: Genex Power

Woodlawn Eco-Precinct
Tarago, NSW

Open-cut mine pit converted into a bio-reactor landfill creating bio-gas to fuel a power generator. Site also holds aquaculture facilities, solar and wind farm.

Image: Veolia

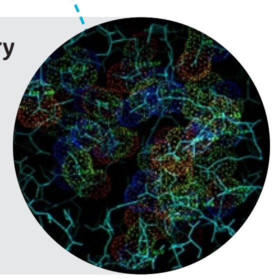
Lake Kepwari
Collie, WA

Recreational lake that was created from conversion of a coal mining pit via local river diversion.

Image: CRC TiME

SUPL: Stawell Underground Physics Laboratory
Stawell, VIC

Laboratory located in an operational gold mine 1km underground, where conditions are optimal for research into dark matter, neutrinos and geoscience.



Eden Project (UK) is a botanical garden and visitor attraction established on a reclaimed clay mine.

5.1 Post-closure land use

Solutions that address challenges preventing the establishment of post-closure land uses on mined land can generate lasting economic, social, or environmental value and offset the costs of managing ongoing liabilities. Opportunities include:

- Businesses specialising in identifying, assessing, enabling and developing post-closure land uses

Post-closure land use opportunities have traditionally been limited to revegetating land. However, novel opportunities or repurposing of existing infrastructure are emerging. Stakeholders noted that regulatory preferences for revegetation have limited alternative post-closure land use on mining tenements in some jurisdictions. Alternatives to revegetation include novel post-closure land uses, including economic development opportunities or repurposing existing infrastructure for community use.

Determining and enabling optimal post-closure land uses remains a challenge for the mining industry. The optimal use of a mine site varies significantly based on its location, final landforms, infrastructure, community values and expectations, regulatory requirements, local skillsets, and residual risks.[155] The operational status of a mine site will also impact this, including whether the site is being managed in perpetuity by a mining company, abandoned, government-managed, returned to a landowner or divested to a different entity. Historically, reuse of mined land has been driven by mining companies and government with limited success, indicating that other actors are likely to take on a leading role in mine transitions.[156]

Working with key stakeholders to inform and guide land use decisions is essential to successful implementation. Encouraging a productive dialogue on mine transitions can support the management of complex stakeholder relationships and train closure practitioners in local community concerns (see Section 2). Repurposing of infrastructure can require extensive and regular community engagement to ensure asset life and management does not negate these opportunities.

Closure plans may be developed decades before closure activities, which unless revisited regularly and updated with appropriate engagement, can create a potential disconnect between community expectations and available opportunities for post-closure land use at the time of closure. Integrated closure planning, while necessary, faces several challenges. Regulatory processes may limit the activities undertaken on mined land as the presence of residual risks and ongoing liabilities can create hurdles in obtaining approvals and transitioning the mining leases.[157] This may reduce opportunities for mine closure planning to integrate post-closure infrastructure and land use.

Mining companies focus on optimising extraction processes, and therefore there may be a limited appetite to invest in planning capability focused on post-closure land use. Partnerships are needed to enable post-closure land use and infrastructure repurposing. Expertise from non-mining industries is often required as the mining industry is primarily focused on resource extraction. Partnerships increase the complexity for mining companies seeking to explore post-closure land use and infrastructure reuse opportunities. Examples of industry-specific expertise required include energy generation and storage, tourism, and agriculture. The need to partner across industries can create additional complexity and risk of the unknown for mine site operators.

155 Beer A et al. (2022)

156 Keenan J, Holcombe S (2021)

157 Ashurst (2018) Mining rights in Australia. <https://www.lexology.com/library/detail.aspx?g=6ea86c96-ce2a-44aa-9efc-708727eb1966> (accessed 30 August 2023)

Opportunities

Businesses specialising in identifying, assessing, enabling and developing post-closure land uses

Businesses that can provide solutions that facilitate the development of high-value post-closure land and asset use opportunities will be critical in enabling mine transitions and allowing miners to focus on mining.

While mining companies' practitioners may lead closure planning and implementation, specialised consultancy services can support the integration of opportunities into closure planning and increase awareness of emerging transition options. The opportunity for these consultants exists beyond the period of detailed planning for closure, as preliminary consideration of potential post-closure land use may be undertaken early in the mine life.

Services offered may include identification and assessment of potential viable market and community opportunities, post-closure business planning, project management, community engagement and partnership development, and supply chain assessment.[158] BeyondLOM is one example of an emerging Australian business that seeks to support miners to develop integrated post-mining and post-closure land use solutions. BeyondLOM has developed strategic partnerships with other specialist companies to expand the breadth of opportunities they can explore for their clients.[159]

Project developers and experts from other industries have a critical role in identifying emerging opportunities for post-closure land use and attracting capital for investment. Many post-closure land uses require industry-specific expertise, such as energy generation and storage, and agriculture, as well as knowledge of mined land capabilities and limitations. There are emerging companies that specialise in acquiring post-mining assets and developing new projects that make use of the unique characteristics of mined land. For example, Green Gravity is a company that is focused on developing renewable energy projects on abandoned or closing mines, making use of the energy storage potential produced by changes in elevation in mine shafts.

Companies that facilitate the transition of site ownership and liabilities between the mining industry and post-closure project developers can play a role in enabling emerging post-closure opportunities. Consultancies that develop commercial transition models can de-risk investment and facilitate partnerships across industries. Legal services that navigate the complex planning and regulatory processes for emerging post-closure land use options can support partnerships between mine operators and downstream industries. Stakeholders noted the existence of companies in other jurisdictions that assume or transfer environmental liabilities.[160] There may also be opportunities for the development of Australian businesses that specialise in mine closure and transitions and assume liabilities for mining companies for a fixed price.

158 Brock D (2020) Consultants and the future of mine closure. AusIMM Bulletin. <https://www.ausimm.com/bulletin/bulletin-articles/consultants-and-the-future-of-mine-closure/> (accessed 30 August 2023)

159 BeyondLOM (2022) Opportunities Beyond Mining – Repurposing Liabilities into Assets <https://www.beyondlom.com.au/> (accessed 30 August 2023)

160 Environmental Liability Transfer in the United States (2023) ELT Services <https://eltransfer.com/services/> (accessed 30 August 2023)

6 Enabling industry growth

As a major mining nation, Australia has the potential to leverage domestic mine closure challenges to become a leading supplier of solutions that improve outcomes and reduce the costs of mine closure and transitions. To enable this opportunity, government and industry stakeholders can take coordinated and targeted actions to address key barriers that will limit sustainable growth of the MCS industry.

In the sections below, a series of enabling actions that can address barriers to the growth of a sustainable and productive ecosystem of MCS providers are discussed. These were identified through a workshop, stakeholder consultations, and desktop research. Figure 6 summarises the actions identified for the consideration of government and industry stakeholders. Most of the identified actions require a degree of collaboration and a subset has been identified that will require coordinated action from multiple stakeholders (Section 6.1).

The success of MCS providers is closely tied to the value that miners and governments place on improving mine closure and transition outcomes. Some companies and jurisdictions are showing leadership, but many consulted stakeholders shared concern that mine closure teams and activities may continue to be undervalued by mining companies that focus primarily on operational productivity and reducing costs to increase their competitiveness. To address this, stakeholders noted that broader reforms and industry actions to drive successful mine rehabilitation, closure, relinquishment, and post-closure land use will also be critical to enabling these opportunities.

Figure 6: Government and industry stakeholder actions to enable growth of Australia's MCS industry

Multi-stakeholder actions

1. Increase visibility of mine closure challenges and opportunities to support partnerships and innovation with MCS providers.
2. Develop and implement methods that value the social and environmental outcomes of mine closure and transitions.
3. Encourage collaborative research and support demonstration of innovative mine closure solutions.

MCS industry actions

4. Develop a coherent MCS industry identity and aligned strategy.
5. Broaden customer base through adaptability, interoperability and export.
6. Align solutions with evolving stakeholder expectations and miner requirements.
7. Strengthen commercialisation and business development skills of emerging providers.

Mining industry actions

8. Embed performance indicators that increase the focus on mine closure and transitions within mining companies and drive uptake of effective solutions.
9. Ensure that procurement policies allow new market entrants and small companies to provide innovative mine closure solutions.

Government actions

10. Review regulatory barriers to novel mine closure and transition solutions.
11. Support MCS industry capability development and export opportunities.

6.1 Multi-stakeholder actions

Action 1: Increase visibility of mine closure challenges and opportunities to support partnerships and innovation with MCS providers

Workshop participants suggested that there is limited transparency and awareness of challenges and opportunities presented in mine closure. Low levels of engagement with non-mining industries (e.g., agriculture, tourism, energy) have resulted in poor knowledge transfer and hindered development of innovative solutions. Improving the visibility of mine closure challenges and opportunities could encourage emerging MCS providers (including Indigenous, regional, and non-mining businesses) to provide their diverse expertise to support mine closure and transitions.

Industry, government and research organisations can play a key role in promoting cross-sector collaboration, improving transparency and fostering partnerships related to mine closure. This could help to attract businesses to address mine closure and transition challenges. Specific examples include:

- Industry-led public innovation challenges like the BHP and Rio Tinto Tailings Technologies Open Call[161] and Austmine's mineinnovate platform.[162] These initiatives attract new perspectives and approaches to solving mine closure and transition challenges by publicly promoting them to potential solutions providers.
- Government-led information sharing platforms that allow businesses and developers to engage with mine closure and transition opportunities. Geoscience Australia has developed an Atlas of Australian Mine Waste that supports identification of potential resource recovery projects by providing an online mapping tool for mine tailings, waste rock, smelter residue and other mine waste materials (see Section 3).[163] Similar platforms could be used to share data on expected mined land characteristics and encourage post-closure land use.
- Research-led initiatives that explore and promote mine closure challenges and opportunities. For example, researchers have demonstrated the development of a country-wide database of inactive hard rock mine sites to aid in identifying mine closure and transition challenges and opportunities.[164]

Indigenous-led MCS business development could be specifically encouraged through active industry and government engagement with accessing existing initiatives that promote Indigenous businesses, including Aboriginal Enterprises in Mining, Energy and Exploration Ltd (AEMEE) and the members of the National Indigenous Business Chambers Alliance.

This report itself attempts to increase the visibility of mine closure challenges and to illustrate the scale of related opportunities by quantifying the potential expenditure on mine closure activities in Australia (see Appendix B). To support better targeting of solutions development, more granular and detailed economic analysis could be undertaken to identify the mine closure and transition cost drivers for mines of different scales, commodities and processes.

Action 2: Develop and implement methods that value the social and environmental outcomes of mine closure and transitions

The social and environmental aspects of mine closure are often undervalued. Beyond accurately valuing economic impacts, translating the social, environmental and economic impacts and benefits of mine closure and transitions into economic terms can improve the value proposition for investing in innovative closure solutions. This will require the use of models and frameworks that prescribe value to environmental and social outcomes. For example, CRC TiME's partners are developing natural capital accounting methods. These methods are aimed at supporting miners in meeting their disclosure expectations and encourage greater investment into solutions that improve biodiversity and conservation outcomes.[165]

161 BHP (2023) BHP and Rio Tinto invite collaboration on new tailings technologies. <https://www.bhp.com/news/media-centre/releases/2023/05/bhp-and-rio-tinto-invite-collaboration-on-new-tailings-technologies> (accessed 30 August 2023)

162 Austmine (2022) mineinnovate <https://mineinnovate.com.au/> (accessed 30 August 2023)

163 Geoscience Australia (2021)

164 Werner et al. (2020)

165 CRC TiME Limited. (2023) Natural capital accounting in the mining sector. <https://crctime.com.au/research/projects/project-2-7/> (accessed 30 August 2023)

Frameworks that improve the way the industry evaluates both social and economic performance can support the value proposition for closure solutions that are harder to quantify. The updated perspective of value can support miner uptake and regulatory sign off on innovative solutions where positive social and environmental impacts offset financial risk. Design and implementation of these frameworks will require collaboration amongst all stakeholders and robust community consultation to ensure values are aligned. Miners can play a role in leading adoption of these new value frameworks, with government incentivising their use by incorporating them into regulatory processes. These models may also support the business case for progressive closure or concurrent reclamation activities during operational phases.

Action 3: Encourage collaborative research and support demonstration of innovative mine closure solutions

Low levels of funding and limited access to test sites for mine closure solutions constrain the opportunities for researchers and businesses to generate data on real-world performance and demonstrate the value of their solutions. Consulted stakeholders noted that risk aversion is limiting investment and commercialisation of novel solutions. Mining stakeholders reported reluctance to invest in closure solutions that have not already proven their ability to reduce liabilities. Similarly, some government stakeholders reported reservations in approving closure plans that include solutions that have not already been demonstrated at scale.

To address these challenges, government and industry can support research, development and demonstration to reduce risk, improve commercialisation and encourage market uptake of innovative solutions. Stakeholders suggested collaborative actions to support the demonstration and commercialisation of mine closure solutions could include:

- Collaborative investment to develop solutions that can be used to address common challenges. This can be in the form of government grant initiatives and funding pools that can be accessed by industry to supplement research and development activities. Collaborative research funding models can help ensure that research is aligned with industry closure requirements and limiting risks to individual parties.
- Development of pilot testing sites at abandoned mines to demonstrate emerging closure and transition solutions. Governments can foster pre-competitive collaboration by incentivising collaborative testing models and reducing the accessibility barriers on abandoned sites.[166] Using abandoned sites for technology demonstration could help to address Australia's abandoned mine legacy while supporting businesses to prove the effectiveness of their solutions. The Queensland Resources Industry Development Plan has identified the opportunity of re-commercialising Queensland's abandoned mines to retrieve valuable resources from mine waste and is supporting pilot studies.[167]

166 Salmi EF, Bekele EB, Schmid S (2022). Towards an inventory of abandoned mines in Australia: risk, prioritisation, and opportunities. CRC TiME Limited, Perth, Australia

167 Department of Resources, Queensland (2022) Queensland resources industry development plan <https://www.resources.qld.gov.au/qridp>

6.2 MCS industry actions

Action 4: Develop a coherent MCS industry identity and aligned strategy

MCS providers may be associated with the METS industry or a range of other diverse industries including environmental, planning, engineering, and consulting services. This leads to a poorly defined industry identity, siloing of skills and low levels of industry collaboration. The establishment of professional communities and initiatives could bring MCS providers together to collaboratively develop the industry, nurture productive collaborations, network with mine closure practitioners, and discuss emerging mine closure challenges. These initiatives can help to strengthen the industry's brand and drive greater global interest in using Australian businesses to support mine closure and transitions. It may also support the development of best practices and collaborative solutions to address the industry's challenges. This may also support the development of Indigenous and regional businesses through professional networking and training opportunities.

EnviroMETS Qld is an example of an industry-led, not-for-profit company that promotes METS solutions and businesses to improve the sustainability and value of post-closure outcomes in Queensland. At the national level, the Closure Planning Practitioners Association, METS Ignited, and Austmine exist to support Australia's mine closure planning and METS industries, but no national initiative exists specifically for MCS providers and as such their importance is often overlooked.

Action 5: Broaden customer base through adaptability, interoperability and export

The cyclical nature of the mining industry can lead to intermittent demand for many mine closure solutions. Providers that offer highly specific or niche solutions will face natural barriers to their business growth due to their constrained addressable market. To enable sustainable industry growth in the long term, MCS providers will be well placed to develop solutions that are compatible with different commodities and mining processes, and to target export opportunities.

Solutions providers that demonstrate high performance and adaptability across various sites with different commodities, mine characteristics, social contexts, and regional factors such as regulation and climate will have a significant advantage. Similarly, designing solutions to be compatible and interoperable with conventional mining practices and systems will facilitate easier implementation of solutions on mine sites. This can reduce integration barriers to solution deployment and strengthen the value proposition for mining customers.

To further broaden their customer base, MCS providers can seek to export their solutions to target international markets. Australia's relatively high standards of environmental regulation and performance mean that Australian providers will be well placed to enhance mine closure outcomes in international markets. Alongside Australia, analysis suggests that China, Canada, the US, South Africa and Mexico are expecting the highest number of mine closures between 2021–2040.[168] Some MCS providers may also benefit from targeting non-mining markets to maintain cashflow between mine closure related activities.

Action 6: Align solutions with evolving stakeholder expectations and miner requirements

Increasing community and shareholder expectations for positive social and environmental outcomes are driving miners' decision-making, government regulatory requirements and industry best practices. Stakeholders noted that this is now directly influencing the selection and procurement of solutions. To maintain competitiveness, MCS providers need to be aware of where their business can align with community values, and solutions can help miners meet the evolving expectations. Active engagement with industry stakeholders can identify evolving expectations and future priorities to inform the development of solutions.

168 CSIRO Futures calculation; S&P Global Market Intelligence 2023, S&P Capital IQ Pro, Asset Data, Metals & Mining Properties.

MCS providers can increase their competitiveness by designing solutions that align with the mining industry's growing need to demonstrate strong environmental, social and governance performance. Solutions should be designed to operate within sites and jurisdictions that which uphold best practice. High degrees of transparency on issues such as ethical supply chains, embodied emissions, and safety outcomes can increase the potential value proposition and provide a point of difference from competitors. For example:

- The mining sector's target to achieve net-zero emissions by 2050 will increase demand for zero-emissions mine closure solutions. For example, it is expected that the diesel-powered rehabilitation fleets and equipment will need to be replaced with zero-emission alternatives such as electric vehicles.[169]
- MCS providers may improve market appeal by adopting responsible product stewardship approaches for their products and materials.[170]

Action 7: Strengthen commercialisation and business development skills of emerging providers

Historically, the mining sector has had an inconsistent track record for technology translation,[171] and the METS industry has identified a requirement to further develop its research translation and commercialisation capabilities.[172] It will be critical for MCS providers to continue to strengthen their commercialisation and business development skills to encourage adoption from miners and secure clients.

Robust communication of the alignment with customer values and drivers can improve the value proposition of MCS providers. Stakeholders highlighted the importance of providers tailoring their pitches to demonstrate the suitability and value of their solutions.

The benefit of solutions must be demonstrated to customers at the enterprise and operational levels. Validation of cost-effectiveness and performance will be critical to assuring clients that new solutions can meet closure standards without increasing cost and risk, and ensure that the value is clearly communicated to key decision-makers with customer organisations. This can be showcased by presenting capabilities and performance through case studies, commercial advocates and previous projects across other industries.

MCS providers could align themselves with early commercial development strategies and insights attained from the growth of the broader Australian METS industry. This can be facilitated through programs that assist researchers in developing their commercialisation skills such as Austmine's Innovation Mentoring program[173] or CSIRO's ON Prime program.[174] Greater commercialisation and business development skills can build industry reputation, positioning the Australian mine closure and transition solutions industry for greater competitiveness in local and export markets.

MCS providers may benefit from undertaking courses developed for mine closure practitioners to better understand how their solutions can target key issues of mine closure. For example, the Australasian Institute of Mining and Metallurgy (AusIMM) is launching an Integrated Mine Closure course and professional certification in October 2023. This may provide a platform for MCS providers and other resource professionals to gain knowledge from industry leaders to develop capabilities in risk assessment generating the business case for integrated closure.[175]

169 Constable T (2022) Media Release - Mining industry continues progress with emissions reduction. Minerals Council of Australia. <https://minerals.org.au/resources/mining-industry-continues-progress-with-emissions-reduction/> (accessed 30 August 2023)

170 Department of Climate Change, Energy, the Environment and Water (2023) Product stewardship accreditation. <https://www.dcceew.gov.au/environment/protection/waste/product-stewardship/product-schemes/voluntary-product-stewardship> (accessed 30 August 2023)

171 CSIRO (2017)

172 METS Ignited (2020) Mining Equipment Technology Services – Sector Competitiveness Plan 2020 Update. Department of Industry, Science, Energy and Resources, Australian Government. <https://metsignited.org/wp-content/uploads/2020/06/METS-Ignited-Sector-Competitiveness-Plan-2020-Update-Web.pdf>

173 Austmine (2023) Austmine Innovation Mentoring Program. <https://austmine.com.au/Public/Public/Programs/IMP.aspx> (accessed 30 August 2023)

174 CSIRO (2023) ON Prime. <https://www.csiro.au/en/work-with-us/funding-programs/innovation-programs/on-prime> (accessed 30 August 2023)

175 AusIMM (2023) Professional Certificate - Integrated Mine Closure https://www.ausimm.com/courses/professional-certificates/integrated-mine-closure/ (accessed 12 September 2022)

6.3 Mining industry actions

Action 8: Embed performance indicators that increase the focus on mine closure and transitions within mining companies and drive uptake of effective solutions

Stakeholders reported that inconsistent uptake of mine closure performance indicators reflects and reinforces the low prioritisation of closure and transitional activities within mining companies. This can have adverse effects on collaboration and create knowledge silos that make the transdisciplinary practice of mine closure more challenging. Consideration of closure and transitions throughout the entire mining life cycle may help shift the appetite for innovation and create opportunities for the deployment of innovative mine closure solutions. Mining companies can encourage this by including closure in corporate and operational objectives.

Consulted stakeholders supported the embedding of closure and transition-related KPIs into existing organisational frameworks to establish a culture that favours sustainable outcomes. KPIs for senior decision-makers could include closure and residual risk management objectives, with value metrics considering social, environmental and economic outcomes. Measurement of performance matched with incentives can drive a top-down cultural shift throughout organisations. By encouraging a culture of closure from the outset, knowledge transfer within mining companies can be strengthened, ensuring effective use of insights and expertise.

The ICMM has developed a Key Performance Indicator Tool, which outlines a set of Key Performance Areas aligned with context-dependent closure objectives to support responsible closure.[176] This tool is to be used in alignment with the ICMM Integrated Mine Closure: Good Practice Guide and implemented throughout the closure process.

Action 9: Ensure that procurement policies allow new market entrants and small companies to provide innovative mine closure solutions

Stakeholders indicated that mining companies often have procurement policies that can be barriers to engaging with innovative MCS providers. Procurement barriers include strict vendor lists, complex procurement processes with long lead times, inconsistent procurement policies, mining experience requriements, meeting strict health and safety requirements for operating on a mine site and establishing relationships with top-tier mining companies. Meeting mining companies high procurement policies can be a high-cost and time-intensive practice for solution providers and may make the mining sector an unappealing market for small and medium-sized enterprises as well as cross-vertical businesses who may turn to other industries with lower barriers to entry.

Ensuring that procurement policies are effective and balanced will enable small businesses and market entrants from other sectors to participate in a competitive market for innovative mine closure solutions. Possible strategies include flexible qualification criteria to measure vendor capability and expanded market access to allow businesses who have proven technology use outside of a mining context but in similar environments, such as revegetation specialists operating in agricultural or energy generation industries.

6.4 Government actions

Action 10: Review regulatory barriers to novel mine closure and transition solutions

Stakeholders noted that a variety of regulatory and policy barriers are limiting the implementation of existing solutions and deterring entrepreneurship within the closure space. These insights are supported by previous studies that describe departments and regulatory frameworks that govern many closure activities as ineffective,[177] siloed and potentially hindering the deployment of innovative solutions.[178]

176 ICMM (2020) Key Performance Indicators: Tool for Closure. https://www.icmm.com/en-gb/guidance/environmental-stewardship/2020/kpi-tool-for-closure (accessed 30 August 2023)

177 Unger et al. (2020)

178 Beer et al. (2022)

Government stakeholders could explore how current regulatory framework and policies can be aligned to encourage the uptake of closure solutions and opportunities for optimised social, environmental and economic outcomes. Stakeholders and past reports have identified various legislative barriers that are limiting the uptake of novel closure solutions. These include administrative complexity, risk adversity and varying requirements between jurisdictions.[179] Stakeholders suggested that Australia's regulatory environments could better incentivise proactive and progressive closure activities. This would encourage the uptake of innovative solutions and support the growth of MCS providers. These include exploring where frameworks can support circular economy initiatives such as waste recovery and resource management, as well as mine closure planning that incorporates suitable post-closure land use. Stakeholders also suggested that this could be encouraged by reducing environmental bonds (where applicable) or providing other incentives when early interventions and progressive rehabilitation practices are successfully implemented.

Achieving post-closure land use transitions was identified as a particularly complex challenge that is hindered by unclear regulatory pathways for miners to achieve relinquishment and transference of mining. Regulatory barriers to the economic transformation of mine-affected land may be explored in more detail in an EnviroMETS-led CRC TiME project, *Navigating the Regulatory Framework Impacting the Economic Transformation of Mine Affected Land,* commenced in August 2023.[180]

Government can continue to strengthen the capability of regulatory departments through skills development and knowledge sharing between jurisdictions. Stakeholders reported limitations in regulatory experience in closure and siloing of knowledge, which can lead to unclear closure criteria and inefficiencies in the approval process. Consulted stakeholders advocated for continuing the development of regulatory departments through increasing the closure experience of regulatory staff, enhancing knowledge sharing between jurisdictions, and greater collaboration with appropriate environmental, planning and development departments. Strengthening regulatory capability can allow regulators to operate beyond the business-as-usual, which may enable governments to explore how they can facilitate improved closure and transition outcomes.

Action 11: Support MCS industry capability development and export opportunities

Skills and training, professional development and export support initiatives can enhance MCS provider capability development and growth. Government can play a role in programs focused on the development of closure competencies among closure practitioners and MCS providers through funding, incentives and alignment with regulatory requirements and global standards. Government can support the delivery of these programs and ensure adequate training to Indigenous and regional community businesses, who may otherwise be limited due to location and local resources. This can also extend to commercialisation skills to ensure providers are equipped to navigate commercial and regulatory barriers and enable long-term business sustainability of MCS providers.

MCS providers would benefit from government and government-backed industry association skills and training programs. For example, the Australian Government-supported industry growth centre, METS Ignited, has previously run accelerator courses and masterclass programs to develop innovation cultures, business models, and commercial skills for METS businesses. [181]

Government organisations can also support export opportunities for mine closure solutions by working with the MCS industry to develop export strategies, including targeting export markets and potential trade partners. Stakeholders noted that the Australian Government may have the ability to nurture export opportunities by encouraging other nations to raise their mine closure standards and by leveraging existing productive international relations. Austrade promotes the METS industry internationally and could expand this support to include MCS providers. As noted above, countries that are expected to have large numbers of mine closures in the coming years (including China, Canada, USA, South Africa and Mexico) could be suitable targets for mine closure solutions-focused trade missions and promotion.

179 Hamblin L, Gardner A, Haigh Y (2022) Mapping the Regulatory Framework of Mine Closure. CRC TiME limited, Perth, Australia.

180 CRC TiME Limited (2023) New collaborative project with enviroMETS kicks off. <https://crctime.com.au/blog/new-collaborative-project-with-enviromets-kicks-off/> (accessed 30 August 2023)

181 METS Ignited (n.d.) METS Ignited Accelerator Programs <https://metsignited.org/accelerators/> (accessed 30 August 2023); METS Ignited (n.d.) METS Ignited Masterclass Programs <https://metsignited.org/masterclasses/> (accessed 30 August 2023)

Appendices

Appendix A: Glossary

This report's glossary has been compiled with the aid of multiple sources, including:

- Department of Industry, Science, Energy and Resources (2016a) Mine Closure: Leading Practice Sustainable Development Program for the Mining Industry. Australian Government. [182]
- ICMM (2019) Integrated Mine Closure Good Practice Guide, 2nd Edition[183]
- ISO 20305:2020 Mine closure and reclamation — Vocabulary[184]

TERM/ACRONYM	DEFINITION
Abandoned mine or site	An abandoned site describes a mine where mining leases or titles no longer exist, and responsibility for rehabilitation cannot be allocated to any individual, company or organisation responsible for the original mining activities.
Acid and metalliferous drainage (AMD)	Traditionally referred to as 'acid mine drainage' or 'acid rock drainage'; includes both acidic and near-neutral but metalliferous drainage. Acidic drainage results from the oxidation of sulphides such as pyrite in mine wastes.
Backfilling	Refilling of an excavation or void.
Care and maintenance	Phase following a temporary cessation of operations, when infrastructure, plant and equipment remain intact and are maintained in anticipation of production recommencing. May also be referred to as 'temporary closure'; such a site may be referred to as 'inactive'.
Closure planning	A process that extends over the mine life cycle and that typically culminates in tenement relinquishment. This includes decommissioning and rehabilitation. The term 'closure' alone is sometimes used to indicate the point at which operations cease, infrastructure is removed, and management of the site is largely limited to monitoring.
Community	In mining industry terms, the inhabitants of immediate and surrounding areas who are affected by a mining operation's activities. 'Local community' usually indicates the community in which operations are located and may include Indigenous and non-Indigenous people.
Completion criteria	Agreed standards or levels of performance that indicate the success of rehabilitation and enable an operator to determine when its liability for an area ceases.
Decommissioning	Begins with the cessation of production, when infrastructure, plant and equipment are isolated from services such as power and water. Commonly includes the removal (deconstruction or demolition) of unwanted plant and equipment. Individual facilities may be decommissioned and removed if no longer required, while mining and processing operations continue.
Dewatering	Tailings dewatering: removal of water from tailings or slurry by either passive or active treatment such as thickening, filtration or centrifuging. Mine dewatering: Removal of groundwater or surface water from a mine site.
Groundwater	Water beneath the earth's surface that fills pores between porous media—such as soil, rock, coal and sand—usually forming aquifers. In some jurisdictions the depth below the soil surface is also used to define groundwater (although different states use different depths).
Leaching	Chemical or biological processes that dissolve minerals or metals out of ore.
Landholder	The owner of freehold land, the holder of leasehold land, or any person or body that occupies or has accrued rights in freehold or leasehold land.
METS	Mining Equipment, Technology and Services (industry/business)

182 Department of Industry, Science, Energy and Resources (2016a)

183 ICMM (2019)

184 International Organisation for Standardisation (2020) ISO 20305:2020 Mine closure and reclamation — Vocabulary <https://www.iso.org/obp/ui/en/#iso:std:iso:20305:ed-1:v1:en>

TERM/ACRONYM	DEFINITION
Mine closure and transitions	There are varying interpretations of the term mine closure. It is often used interchangeably with mine rehabilitation or to indicate the point at which operations cease, infrastructure is removed, and management of the site is largely limited to monitoring. In this report, the term *mine closure and transitions* is used to describe strategies and activities related to the completion of mining activities, rehabilitation of mined land, and the establishment of post-closure land uses. This includes not only mine rehabilitation, but also engagement and partnerships, waste reduction and resource recovery, and transitioning mined land.
Mine closure solutions	Equipment, technology or services that support and enable mine closure and transitions.
Mine closure solutions (MCS) providers	Businesses that provide mine closure solutions to mining companies or other parties responsible for mine closure. In this report this includes both METS and non-METS businesses.
Post-closure land use	Refers to the use of mined lands after the completion of extractive mining, closure activities and relinquishment of the land.
Post-mining land use	A land use that occurs after the cessation of mining operations.
Post-mining landform	A constructed topographic feature for which rehabilitation has been completed to support long-term stability.
Progressive rehabilitation	Proactive rehabilitation activities that take place during operations to reduce the rehabilitation burden at the end of mining operations.
Reclamation	Treatment of previously degraded and often contaminated land to achieve a useful purpose. Often used outside Australia instead of 'rehabilitation'.
Rehabilitation	Mine rehabilitation describes the biophysical repair of a mined landscape to render it safe, stable, and non-polluting, taking into account beneficial uses of the site and surrounding land.
Relinquishment	The end of site ownership by the mining company and of their responsibility for the site, with transition of ownership and residual liability to the jurisdictional authority or a third party.
Remediation	Cleaning up or mitigating contaminated soil or water.
Residual risk	The risk that a rehabilitated area (or closed mine), in the foreseeable future, fails to perform as predicted and the consequence of the failure will result in the need for repair, replacement or maintenance works, and thus associated costs
Tailings	A combination of the fine-grained solid material remaining after the recoverable metals and minerals have been extracted from crushed and ground mined ore, and any process water remaining.
Tailings management	Managing tailings over their life cycle, including their production, transport, placement and storage, and the closure and rehabilitation of the TSF.
Tailings storage facility (TSF)	An area used to contain tailings; its prime function is to achieve solids sedimentation, consolidation and desiccation, and to facilitate water recovery or removal without affecting the environment. Refers to the overall facility and may include one or more tailings storages.
Thickened tailings	Tailings thickened to a high density, which beach at a steeper slope and segregate less than tailings slurry, producing far less supernatant water.
Waste rock	Uneconomic rock extracted from the ground during a mining operation to gain access to the ore.
Water table	The underground boundary between the aerated zone (above) and saturated zone (below). The saturated zone sits below the water table, where groundwater fills the space between soil and rock, underground aquifers are present below the water table. The aerated zone sits above the water table, where both oxygen and water fill the spaces between soil and rocks, surface water systems are present above the water table.

Appendix B: Economic analysis

This report undertook an economic analysis of projected expenditure on mine closure activities to assess the commercial opportunity for Australia's mine closure market by 2040. This Appendix summarises the parameters, methodology and results, developed in consultation with stakeholders and used to produce the estimates presented in this report.

This report developed two approaches to showcase the economic opportunity of mine closure. The first approach explores the opportunity of mine closure broadly from a top-down approach. In contrast, the second approach explores the specific opportunity for environmental remediation.

Results of both approaches should be interpreted as indicative, given limitations arising from data quality and uncertainties implicit in projecting forward multiple decades. As this economic analysis is the first for Australia, further research building on this analysis is encouraged.

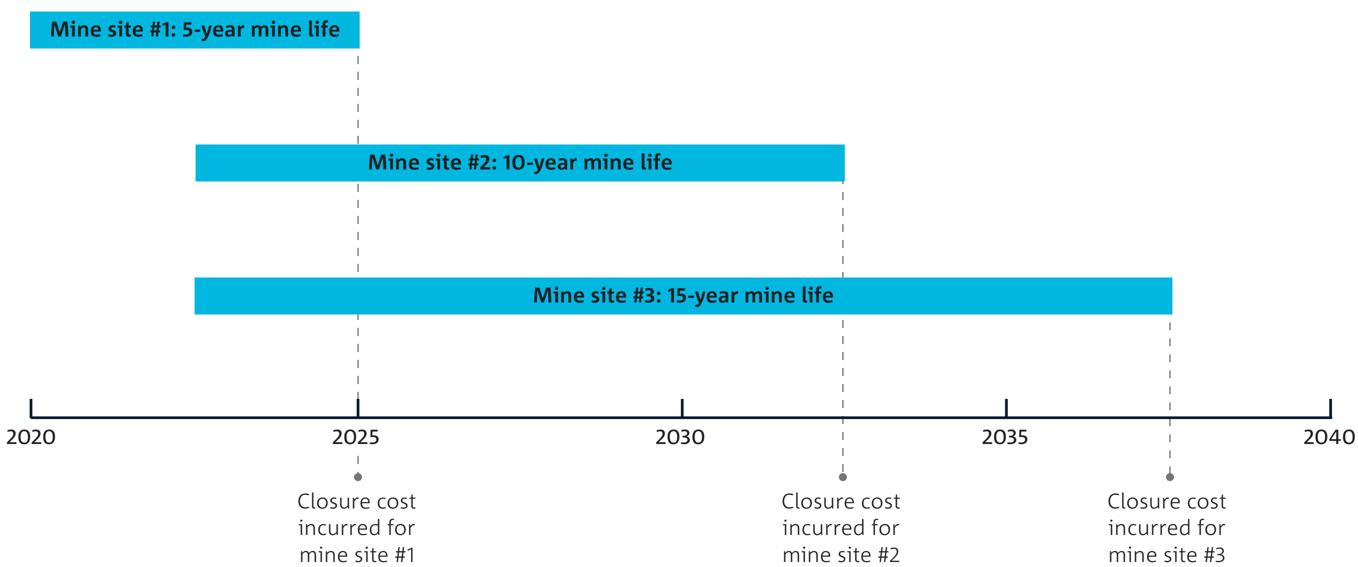
For simplicity, inflation has not been incorporated, so the estimates should be interpreted in 2023 Australian dollars.

Projected expenditure on mine closure activities

Approach

Publicly available data on historical expenditure on mine closure activities is limited. An assumed cost of each mine's closure based on mine claim area was applied to its expected closure year to estimate projected expenditure on mine closure activities to 2040. This data showcases a ready-to-go opportunity for Australia over the coming decades, including for activities such as decommissioning infrastructure, stabilising landforms and waterways, and managing contaminants and pollutants.

Figure 7: Visualisation of projected mine closure expenditure approach



Parameters

The parameters used in this report's economic analysis to estimate Australia's projected mine closure expenditure are summarised in Table 12.

Table 12: Parameters for estimating projected mine closure expenditure

PARAMETER		DEFINITION	DATA SOURCE
A	Mine start-up year	Actual or projected mine start-up year up to 2040 for all Australian mine sites where data is available and has been publicly reported.	S&P Global Market Intelligence[185]
B	Mine closure year	Actual or projected mine closure year up to 2040 for all Australian mine sites where data is available and has been publicly reported. Assumes that mines become permanently closed in the given year.	S&P Global Market Intelligence[186]
C	Average mine life	Estimated average mine life for Australian mine sites based on mine start-up year and mine closure year.	CSIRO Futures calculation
D	Average mine closure cost	Assumed conservative average mine closure cost for Australian mines held constant from 2021 to 2040, varying based on mine claim area.	Conservative assumption informed by consultations with mine closure practitioners and validated by desktop research. Actual mine closure costs will vary significantly between commodities, locations, practices, and outcomes.

The S&P Capital IQ Pro dataset reports the latest available publicly available information on mine properties. As such, it should be noted that this information is not holistic for Australia and may be outdated, missing or inaccurate in some cases. This dataset also is unable to account for future unexpected mine closures.

As of 7 July 2023, S&P Capital IQ Pro reported 5,317 Australian mine properties. Of those, 558 mines had available and valid data for both start-up year and closure year, whereby start-up year was reported in the same or prior year to closure year.[187] Of those, 249 mines had closure years from 2021 to 2040. 12 mines were excluded as they did not have area data, leaving a total of 237 mines for analysis.

185 S&P Global Market Intelligence 2023, S&P Capital IQ Pro, Asset Data, Metals & Mining Properties, Australia.

186 S&P Global Market Intelligence 2023, S&P Capital IQ Pro, Asset Data, Metals & Mining Properties, Australia.

187 In the S&P Capital IQ Pro dataset, closure year may be reported prior to start-up year if a mine property has closed and re-opened, as only the latest published start-up year and latest published closure year is reported. In these cases, this report investigated and took the earliest start-up year and latest closure year reported to resolve where possible.

Descriptive statistics of the sample of 237 mines expected to close from 2021 to 2040 are summarised below.

Table 13: Mine life of Australian mines closing from 2021 to 2040[188]

STATISTIC	MINE START-UP YEAR	MINE CLOSURE YEAR	MINE LIFE (YEARS)
Minimum	1898	2021	0
Q1	1995	2026	11
Median	2010	2030	20
Q3	2019	2034	36
Maximum	2026	2040	136

Table 14: Location of Australian mines closing from 2021 to 2040[189]

STATE OR TERRITORY	COUNT
New South Wales	33
Northern Territory	16
Queensland	53
South Australia	8
Tasmania	9
Victoria	3
Western Australia	115

Table 15: Primary commodity of Australian mines closing from 2021 to 2040[190]

COMMODITY	COUNT
Coal	44
Iron ore	27
Base metal	54
Precious metal	79
Bulk commodity	9
Specialty commodity	24

Table 16: Primary mine type of Australian mines closing from 2021 to 2040[191]

MINE TYPE	COUNT
Open pit	161
Underground	65
Other	9

Table 17: Claim area of Australian mines closing from 2021 to 2040[192]

CLAIM AREA	COUNT
Under 5,000ha	59
5,000 to 15,000ha	56
15,000 to 55,000ha	62
Over 55,000ha	60

188 CSIRO Futures calculation; S&P Global Market Intelligence 2023, S&P Capital IQ Pro, Asset Data, Metals & Mining Properties, Australia.

189 CSIRO Futures calculation; S&P Global Market Intelligence 2023, S&P Capital IQ Pro, Asset Data, Metals & Mining Properties, Australia.

190 CSIRO Futures calculation; S&P Global Market Intelligence 2023, S&P Capital IQ Pro, Asset Data, Metals & Mining Properties, Australia.
Base metal includes cobalt, copper, lead, molybdenum, nickel, tin, zinc.
Precious metal includes gold, platinum, silver.
Bulk commodity includes bauxite, manganese, phosphate, potash.
Speciality commodity includes diamonds, graphite, heavy mineral sands, ilmenite, lanthanides, lithium, scandium, tungsten, uranium, vanadium.

191 CSIRO Futures calculation; S&P Global Market Intelligence 2023, S&P Capital IQ Pro, Asset Data, Metals & Mining Properties, Australia.
Other includes brine, dredging, in-situ leach, stock pile, tailings.

192 CSIRO Futures calculation; S&P Global Market Intelligence 2023, S&P Capital IQ Pro, Asset Data, Metals & Mining Properties, Australia.
Thresholds rounded from quartiles of sample dataset.

Assumptions of average mine closure costs for Parameter D are summarised below. Closure costs are defined by area quartiles for the sample of mines closing from 2021 to 2040 to distinguish between small and large mines, noting that mines may have multiple claims associated with a single mine property. This report has elected to keep closure costs static over time due to market and price uncertainty. Post-closure monitoring costs and unknown risks and uncertainties are also not included in this analysis.[193]

It is recognised that in reality, mine closure costs will vary significantly between commodities, locations, practices, outcomes, and other factors. However, these assumptions are plausibly benchmarked against publicly available historic Australian industry statistics and should be interpreted as indicative.[194] Furthermore, projections of mine closure years may be inaccurate if mines close later than expected or if expenditure on closure is spread over a longer timeframe than assumed. Results are also reported as a 5-year moving average to address this.

Table 18: Average mine closure cost assumptions by area for Australian mines closing from 2021 to 2040[195]

CLAIM AREA	ASSUMED MINE CLOSURE COST (A$M)
Under 5,000ha	50
5,000 to 15,000ha	250
15,000 to 55,000ha	500
Over 55,000ha	1,000

Methodology

This report's methodology used to estimate Australia's projected mine closure expenditure using the parameters defined above is summarised here.

The results are calculated by applying an assumed cost of each mine's closure (Parameter D, Table 18) to its expected closure year (Parameter B). The methodology steps are outlined below.

1. Calculate mine life for all reported Australian mine sites where mine start-up year and mine closure year are available.
2. Calculate the average mine life where mine start-up year and mine closure year are available for mine sites.
3. Sum mine closures from 2021 to 2040 for all Australian mine sites estimated to close each year.
4. Calculate the total mine closure cost for each year from 2021 to 2040.

193 For further discussion on unknown risks and uncertainties in mine closure cost estimation, see:

Maybee B, Lilford E and Hitch M 2023, Environmental, social and governance (ESG) risk, uncertainty, and the mining life cycle, The Extractive Industries and Society, vol. 14, https://www.sciencedirect.com/science/article/pii/S2214790X23000357?dgcid=coauthor

194 Commonwealth of Australia 2019, Rehabilitation of mining and resources projects and power station ash dams as it relates to Commonwealth responsibilities, https://www.aph.gov.au/Parliamentary_Business/Committees/Senate/Environment_and_Communications/MiningandResources/Report

Fletcher D, Hutton A and Dick C 2011, The "smoking gun" of detailed mine closure cost over-run – a review using case studies of the real costs associated with the demolition and removal of infrastructure in mine closure, in AB Fourie, M Tibbett & A Beersing (eds), Mine Closure 2011: Proceedings of the Sixth International Conference on Mine Closure, Australian Centre for Geomechanics, Perth, pp. 97-106.

ICMM 2019, Integrated mine closure: good practice guide, 2nd edition, https://www.icmm.com/website/publications/pdfs/environmental-stewardship/2019/guidance_integrated-mine-closure.pdf?cb=56219

Lock the Gate 2016, Mine rehabilitation and closure cost: a hidden business risk, https://www.lockthegate.org.au/mine_rehabilitation_and_closure.

Nehring M & Cheng X 2016, An investigation into the impact of mine closure and its associated cost on life of mine planning and resource recovery, Journal of Cleaner Production, vol. 127, pp. 228–239.

Northern Territory Government 2023, Securities held for mining sites, https://nt.gov.au/industry/mining/decisions/securities-held

Parshley JV, Bauman W and Blaxland D 2009, An evolution of the methods for and purposes of mine closure cost estimation, in AB Fourie & M Tibbett (eds), Mine Closure 2009: Proceedings of the Fourth International Conference on Mine Closure, Australian Centre for Geomechanics, Perth, pp. 187-200.

The Australia Institute 2017, Dark side of the boom, https://australiainstitute.org.au/report/dark-side-of-the-boom/

195 This was developed in consultation with mining industry, METS and economic stakeholders and is supported by high-level desktop research.

CSIRO Futures assumption; S&P Global Market Intelligence 2023, S&P Capital IQ Pro, Asset Data, Metals & Mining Properties, Australia.

Results

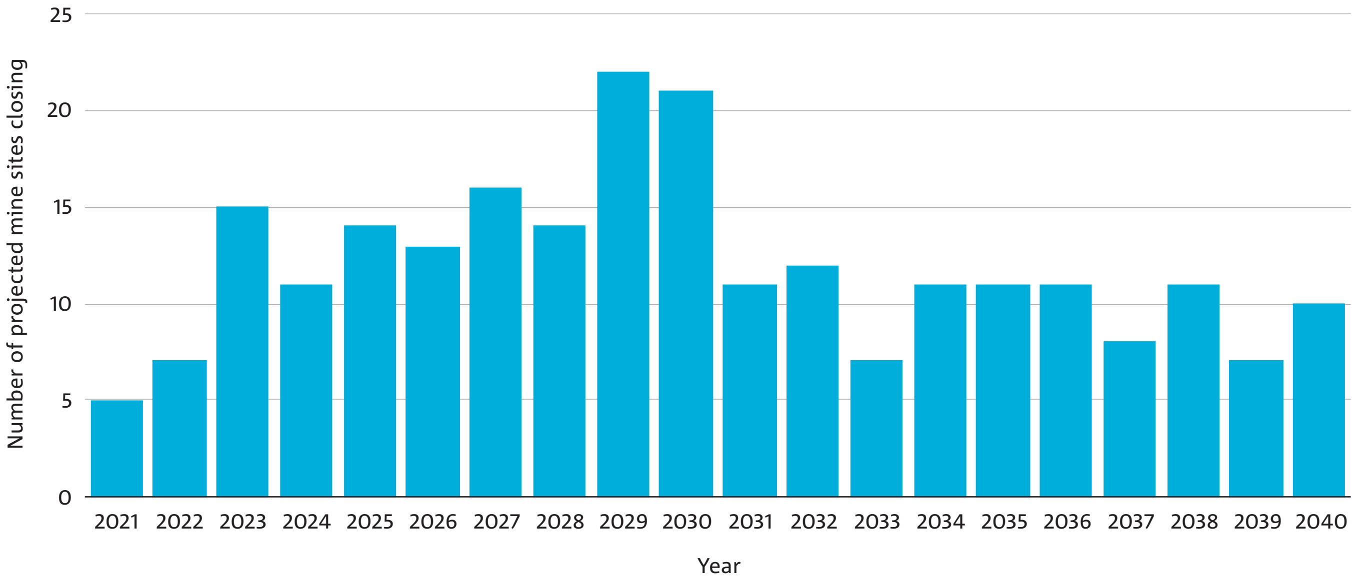
The results of this report's economic analysis of Australia's projected mine closure expenditure are summarised here. Expenditure graph displays a 5-year moving average trendline to account for year-to-year variation in annual projections that are expected to occur, as well as closure expenditure spent over multiple years.

The results show that expenditure on mine closure is expected to grow in the coming decades as an estimated 240 Australian mines reach the end of their economically productive life between 2021 and 2040. It is projected that total expenditure on mine closure activities could range from $4–8 billion on average annually between 2021 and 2040. This expenditure is projected to be highest in 2030 due to both the number and size of mines closing.

Table 19: Projected number of known mine closures for Australia (2021–2040)[196]

PERIOD	PROJECTED NUMBER OF MINE CLOSURES
2021	5
2022	7
2023	15
2024	11
2025	14
2026	13
2027	16
2028	14
2029	22
2030	21
2031	11
2032	12
2033	7
2034	11
2035	11
2036	11
2037	8
2038	11
2039	7
2040	10

Figure 8: Known Australian mine sites projected to close (2021–2040)[197]



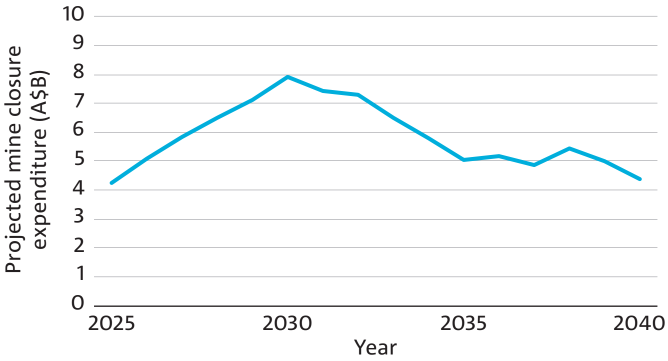
196 CSIRO Futures calculation; S&P Global Market Intelligence 2023, S&P Capital IQ Pro, Asset Data, Metals & Mining Properties, Australia.

197 CSIRO Futures calculation; S&P Global Market Intelligence 2023, S&P Capital IQ Pro, Asset Data, Metals & Mining Properties, Australia.

Table 20: Projected expenditure on mine closure activities for known Australian mine sites closing (2021–2040)[198]

PERIOD	PROJECTED EXPENDITURE (A$B)	5-YEAR MOVING AVERAGE (A$B)
2021	1.8	
2022	3.1	
2023	3.9	
2024	5.1	
2025	7.4	4.3
2026	6.0	5.1
2027	6.8	5.8
2028	7.2	6.5
2029	8.2	7.1
2030	11.4	7.9
2031	3.7	7.4
2032	6.2	7.3
2033	3.1	6.5
2034	4.7	5.8
2035	7.8	5.1
2036	4.3	5.2
2037	4.6	4.9
2038	6.1	5.5
2039	2.4	5.0
2040	4.6	4.4

Figure 9: Projected expenditure on mine closure activities for known Australian mine sites closing (2025–2040)[199]



198 CSIRO Futures calculation; S&P Global Market Intelligence 2023, S&P Capital IQ Pro, Asset Data, Metals & Mining Properties, Australia.

199 CSIRO Futures calculation; S&P Global Market Intelligence 2023, S&P Capital IQ Pro, Asset Data, Metals & Mining Properties, Australia.
Graph displays a 5-year moving average trendline, so 2021–2024 data points are omitted. 2025 data point is interpreted as average expenditure from 2021–2025 and so on.

Environmental remediation for mining market sizing

Approach

There was limited publicly available data to support this analysis. As such, data on the global environmental remediation market was used to assess this opportunity. As Australia's mine closure solutions industry will provide further opportunities than just environmental remediation, it should be recognised that this analysis quantifies only a portion of this emerging MCS industry.

Parameters and methodology

As seen in Table 21 and Table 22 below, BCC Research reports historical data and projections for the environmental remediation market, subdivided geographically and by application.

Figure 10: Visualisation of market sizing approach

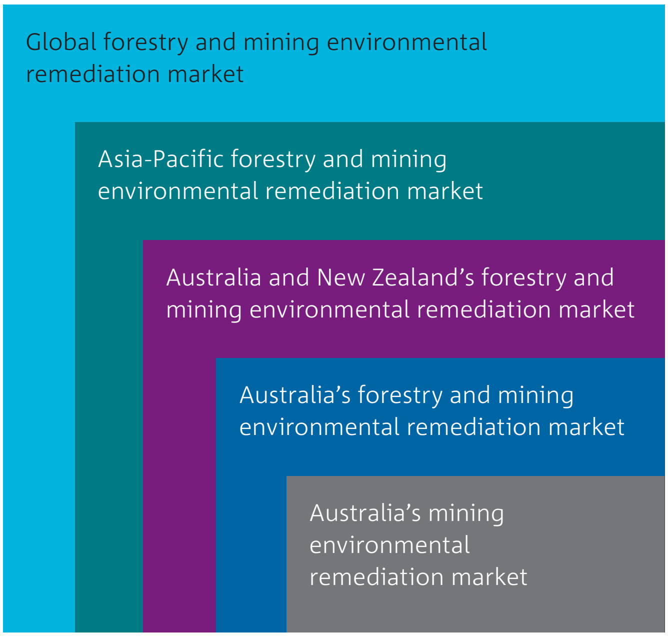


Table 21: Market for environmental remediation technologies by geographic region[200]

	2019	2020	2021	2022	2027
Australia and New Zealand market (US$M)	4,340	3,685	4,635	4,915	6,940
Total Asia-Pacific market (US$M)	25,650	21,535	27,365	29,275	41,290
Total global market (US$M)	117,900	99,040	125,790	134,780	189,100

Table 22: Market for environmental remediation technologies for forestry and mining applications[201]

	2019	2020	2021	2022	2027
Asia-Pacific market for forestry and mining applications (US$M)	4,115	3,455	4,390	4,690	6,605
Global market for forestry and mining applications (US$M)	18,910	15,885	20,175	21,585	30,275

200 BCC Research 2021, Global markets for environmental remediation technologies.

201 BCC Research 2021, Global markets for environmental remediation technologies.

Since no data is directly available for Australia for environmental remediation technologies for mining applications, analysis portioned this out utilising data from Tables 21 and 22. This report developed a four-step approach to do this:

1. Portion out Australia and New Zealand from the Asia-Pacific market for environmental remediation technologies for forestry and mining applications.
2. Portion out Australia from the combined Australian and New Zealand market.
3. Portion Australia's mining environmental remediation from its environmental remediation market for forestry and mining applications.
4. Apply a growth rate out to 2040 and apply relevant conversions.

For Step 1, the Australia and New Zealand market is divided by the total Asia-Pacific market to obtain a percentage share. This share is then multiplied by the Asia-Pacific market for forestry and mining applications to obtain estimates of the Australian and New Zealand markets for forestry and mining applications.

Similarly, estimates of this market are obtained by dividing the Australian and New Zealand market by the total global market and multiplying this share by the worldwide market for forestry and mining applications. These estimates were averaged to consider both approaches, summarised in Table 23.

For Step 2, to portion out the Australian market from the Australian and New Zealand market, data from a similar market was used; IBISWorld reports historical data and projections for the contract mining services industry for both Australia and New Zealand. The average Australian percentage share is obtained by adding annual revenue for both countries for the same years as the BCC Research data.[203] This share was then multiplied by the data on the Australian and New Zealand market for forestry and mining applications. As such, the Australian market for environmental remediation technologies for forestry and mining applications was obtained.

For Step 3, the Australian industry data portioned out only mining applications from forestry and mining applications. The ABS reports historical data on the forestry and logging industry and the total mining industry. The average mining percentage share is obtained by adding annual sales and services income for both industries.[204] This share was then multiplied by the data on the Australian market for forestry and mining applications, obtaining the Australian mining environmental remediation market.

Table 23: Estimated market for environmental remediation technologies by region and application[202]

	2019	2020	2021	2022	2027
Australia and New Zealand market for forestry and mining applications (US$M)	696	591	743	787	1,111

202 BCC Research 2021, Global markets for environmental remediation technologies.

203 IBISWorld 2022, Contract mining services in Australia industry report.

IBISWorld 2022, Contract mining services in New Zealand industry report.

Calculated average Australian share of contract mining services revenue in Australia and New Zealand from 2019 to 2027 as 97%. This was assumed to be an appropriate proxy as forestry data was unavailable to portion out.

204 ABS 2022, Australian industry, Table 1 Key data by industry subdivision, https://www.abs.gov.au/statistics/industry/industry-overview/australian-industry/2020-21

Calculated average share of total mining as portion of total mining plus forestry and logging sales and services income from 2010-11 to 2020-21 as 98%.

For Step 4, to estimate the missing years from 2022 to 2027 and forecast out to 2040, the compound annual growth rate (CAGR) from 2022 to 2027 was calculated, as seen in Equation 1 below.

$$CAGR = \left(\frac{final\ value}{start\ value}\right)^{\frac{1}{t}} - 1 = \left(\frac{1{,}111}{787}\right)^{\frac{1}{2027-2022}} - 1 = 7.12$$

where t = time in years

This CAGR was then applied to Table 23 data to obtain annual revenue from 2019 to 2040 via Equation 2 below.

$$(t + 1) = t * \left(1 + \left(\frac{CAGR}{100}\right)\right)$$

where t = time in years and $CAGR$ = 7.12

These 2019 to 2040 estimates were converted from USD to AUD using the 10-year historical exchange rate to obtain the final results.[205]

It should be noted that this analysis relies on revenue data reported by market research reports and portioning relevant shares based on conversion ratios, both of which may be subject to data inaccuracies and outdated information.

Results

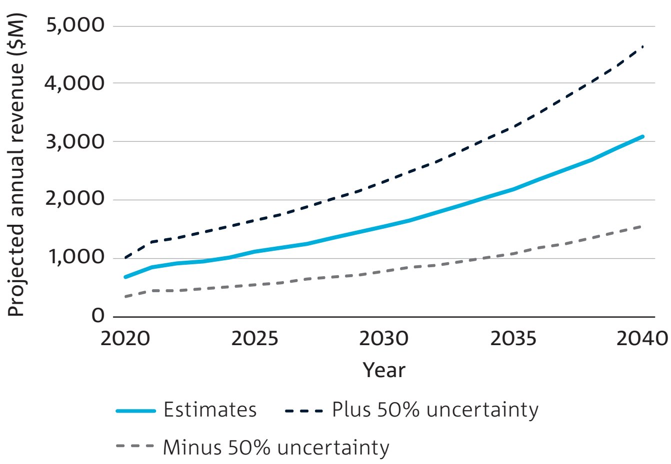
The summary of this report's market sizing is shown in Table 24. As seen in Figure 11, estimates are also shown with plus or minus 50% accuracy, a standard industry percentage that stakeholders typically use to account for uncertainty associated with closure projections.

The results show that the Australian market for environmental remediation technologies and services for mining (a subset of mine rehabilitation solutions) was estimated at $800 million in 2020 and could grow to $3 billion per annum by 2040. This illustrates the potential value of mine rehabilitation solutions more broadly.

Table 24: Projected annual revenue for Australia's mining environmental remediation market

YEAR	PROJECTED ANNUAL REVENUE (A$M)
2020	789
2025	1,097
2030	1,547
2035	2,183
2040	3,079

Figure 11: Projected annual revenue for Australia's mining environmental remediation market



205 Reserve Bank of Australia 2023, Historical data, Exchange rates – Monthly – January 2010 to latest complete month of current year, https://www.rba.gov.au/statistics/historical-data.html#exchange-rates

Calculated average exchange rate from January 2010 to December 2020 as US$1=A$1.19.

Appendix C: Project participants

The report was developed with input from **114** individuals from **62** organisations. This includes input from the project steering committee, advisory group, and a broad range of engagement with industry, research and government stakeholders.

Steering Committee

ORGANISATION	REPRESENTATIVE
CRC TiME	Dr Agnes Samper
CSIRO	Dr Ewan Sellers
CSIRO and CRC TiME	Dr Jason Kirby
Fortescue Metals Group	Dr Kirsty Beckett
GHD	Dave Clark
Intract Australia and CRC TiME First Nations Advisory Team	John Briggs
Minerals Research Institute of Western Australia	Dr Laura Machuca Suarez

Advisory Group

ORGANISATION	REPRESENTATIVE
enviroMETS	Allan Morton
K2Fly	Sean Helm
METS ignited	Dr Adrian Beer
Okane Consultants	Miriam Clark
Queensland Department of State Development, Infrastructure, Local Government and Planning	Stephen Bird
University of Queensland	Dr Anna Littleboy

Project participants

Alfa Laval

Anglo American

Austrade

BCC Research

BHP

Cammel Consulting / Beyond LOM

Charles Darwin University

Circular Mine Consortium

CRC TiME

CSIRO

CTS Tyre Recycling

Curtin University

Dendra

Department of Industry, Science and Resources

Department of Regional New South Wales

Ecocene

Energy Australia

EnviroCopper

enviroMETS

Erizon

Federation University

FMG

Geofabrics Australia

Geoimage

Geoscience Australia

GHD

Hanson Australia

Hatch

Indigenous Business Australia

Institute of Environmental Management and Assessment (IEMA)

Intract

K2fly

Landloch

METS Ignited

Mine Land Rehabilitation Authority

Minerals Council of Australia

Minerals Research Institute of Western Australia

Mining and Energy Related Councils New South Wales

MMG Limited

National Indigenous Australian Agency (NIAA)

New Century Resources (Silbane-Stilwater)

Newmont

North Australian Resource and Commodity Consultant Services

Okane Consultants

Pershke Consulting

Pilbara Development Commission

Planning 4 Sustainable Development

Queensland Dept. of State Development, Infrastructure, Local Government and Planning

Queensland Mine Rehabilitation Commissioner

Regeneration

Revyre

Rio Tinto

RPMGlobal

Rum Jungle Mine Rehabilitation

S&P Global

Shire of Murray

Soil Cyclers Pty Ltd

South 32

University of Queensland

Resources Victoria, Department of Energy, Environment and Climate Action

Western Australia Department of Mines, Industry Regulations and Safety

WSP

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Contact us
1300 363 400
csiro.au/contact
csiro.au

For further information
CRC TiME
hello@crctime.com.au
crctime.com

B&M | 23-00511