PERTH, AUSTRALIA
21 - 23 NOVEMBER 2023

CRITICAL MINERALS CONFERENCE 2023

Conference Proceedings

CRITICAL MINERALS CONFERENCE 2023

21–23 NOVEMBER 2023
PERTH, AUSTRALIA

The Australasian Institute of Mining and Metallurgy
Publication Series No 07/2023

Published by:
The Australasian Institute of Mining and Metallurgy
Ground Floor, 204 Lygon Street, Carlton Victoria 3053, Australia

All papers published in this volume were peer reviewed before publication.

ORGANISING COMMITTEE AND REVIEWERS

Dr Stephen Grocott
FAusIMM
Conference Organising Committee Chair

Dr Keith Barnard

Prof Ismet Canbulat
FAusIMM

Dr Chris Du Plessis

Clare Eilbeck

Dr Lynette Molyneaux

A/Prof Gamini Senanayake
MAusIMM

Leigh Slomp
FAusIMM(CP)

Tony Tang
FAusIMM(CP)

Chris Tiemann
MAusIMM

John Warner

AUSIMM

Julie Allen
Head of Events

Joelle Glenister
Manager, Events

Vicki Melhuish
Conference Program Manager

FOREWORD

On behalf of the Conference Organising Committee, I'm pleased to welcome you to AusIMM's first ever Critical Minerals Conference.

With the world's accelerating energy transition, coupled with supply chain insecurity, it is important to discuss the mining and processing of critical minerals. These materials are essential components of clean energy production and for many other advanced technologies. Over the three-day conference program, we will explore topics that will shape the future of this growth area of the resources sector.

The Organising Committee has assembled an impressive program. There will be over 60 presentations by speakers from nine countries, eight keynote speakers, and four probing, interactive panel discussions. The program covers the entire critical minerals value chain, including exploration, downstream processing, project funding, new technology, ESG and the role of Governments and more.

This wide range of content in the conference has attracted professionals from all disciplines across industry, consulting, government and non-government organisations, and academic and research organisations. This diverse audience will help to create discussions that offer new perspectives from every corner of our industries. This will benefit all of us in our businesses and professions.

I would like to thank our speakers, authors and reviewers for helping bring the program to life and for sharing their expertise for the benefit of our entire community. I would also like to thank:

- Major Mining Partner Rio Tinto
- Gold Sponsors Allkem and IGO
- Silver Sponsors CSIRO and GHD
- Automation Sponsor Honeywell
- and all of our many other sponsors and exhibitors for supporting this new event.

Congratulations to the Organising Committee for making this inaugural conference a reality. I am extremely grateful for your time, advice and commitment. It has also been a pleasure to work closely with the extremely capable AusIMM team to ensure a successful and engaging conference.

We wish you an enjoyable and rewarding experience at the 2023 Critical Minerals Conference.

Yours faithfully,

Dr Stephen Grocott *FAusIMM*

Critical Minerals Conference Organising Committee Chair

SPONSORS

Major Mining Partner

RioTinto

Gold Sponsors

Allkem
Together we go further

igo

Silver Sponsors

CSIRO

GHD

Automation Sponsor

Honeywell

Welcome Reception Sponsor

Powered by Epiroc

Networking Function Sponsor

MURRAY ENGINEERING

Coffee Cart and Break Sponsor

DrM

Premier Content Sponsor

DevelopmentWA

Name Badge and Lanyard Sponsor

SGS

Critical Conversations Sponsor

AUSTRALIAN critical minerals RESEARCH & DEVELOPMENT HUB

Technical Session Sponsors

ASM Australian Strategic Materials

Ausenco

emesent

ERM Sustainability is our business

VERACIO

wood.

Lunch Sponsor

معادن MAADEN

Destination Partner

BUSINESS EVENTS PERTH

Association Partner

AUSTMINE Smart Mining

CONTENTS

Abstracts

Abstracts

ESG implications of high critical minerals demand for the clean energy transition

A Bonis[1], C Tinari[2], R Asamoah[3] and R Ruan[4]

1. MSc Researcher, University of South Australia, Adelaide SA 5000.
   Email: konay027@mymail.unisa.edu.au
2. Masters Student, University of South Australia, Adelaide SA 5095.
   Email: tincy017@mymail.unisa.edu.au
3. Research Fellow, University of South Australia, Adelaide SA 5000.
   Email: richmond.asamoah@unisa.edu.au
4. Student, University of South Australia, Adelaide SA 5074.
   Email: ruasy006@mymail.unisa.edu.au

ABSTRACT

This study presents a comprehensive analysis of the environmental, social and governance (ESG) aspects associated with the production of critical metals. The investigated metals, copper (Cu), nickel (Ni), neodymium (Nd) and dysprosium (Dy), are evaluated in terms of their usage in renewable energy technologies (solar photovoltaics and wind turbines) and battery energy storage systems (BESS). The global overview was conducted across six geographical areas, quantifying the total volume of metals embedded in the low-carbon energy technologies (LCET) that are currently deployed. Increasing deployments trends of LCET, globally, confirm the future surge in critical metal demand.

The environmental assessment conducted in the study investigates the extraction and processing techniques employed for the production of the metals, evaluating their associated gross energy requirement (GER) and global warming potential (GWP). The analysis found that, to produce the four critical minerals embedded in the installed LCET of interest, 30.9 PJ of energy were required and 2.1 Mt of CO_2 were released, annually. The environmental performance of mineral production was found to be influenced heavily by the mineralogy of the ore and the energy source of the operations, while the type of mining and processing techniques were secondary factors. For this reason, shifting energy reliance from fossil fuels to renewable sources in the mining industry itself has been identified as a key initiative for the sustainable development of mineral production. Due to decrease ore grades associated with the depletion of the minerals the process type that is expected to be dominant in the clean energy transition is hydrometallurgy due to higher efficiency in processing low ore grades compared to pyrometallurgy.

The study addresses the social issues arising from mining practices, issues such as resource use, pollution and tailing failures were highlighted. Finally, the role of governance in promoting responsible mining practices was explored, determined by the law enforcement strategies adopted by different countries. To address the variance between regions, tools such as international agreements, corporate responsibility and social licences to operate, were found to be effective in promoting responsible practices. Overall, this study outlines the interplay between the clean energy transition and critical metal production within the context of sustainable development.

26 at a time – uncovering the potential of critical minerals in South Australia

A Caruso[1], C Krapf[2] and A Fabris[3]

1. Project Geologist, Geological Survey of South Australia, Adelaide SA 5000. Email: alicia.caruso@sa.gov.au
2. Principal Geologist, A/Manager Resources and Commodities, Geological Survey of South Australia, Adelaide SA 5000. Email: carmen.krapf@sa.gov.au
3. Principal Geologist, Geological Survey of South Australia, Adelaide SA 5000. Email: adrian.fabris@sa.gov.au

ABSTRACT

South Australia has a rich endowment of critical minerals including zircon, graphite, REE and manganese amongst others. However, with emerging demand for a variety of other critical minerals that have historically not been explored for or mined in South Australia, the Geological Survey of South Australia's 'Critical Minerals' project focuses on expanding the understanding of South Australia's critical mineral potential – and by doing so, advancing knowledge to support critical minerals discovery and exploration in the state.

Whilst global critical mineral demand is growing, the occurrence of critical minerals in South Australia, ranging from cobalt to nickel, REE, magnesite and platinum group elements, are not uniformly understood. Many projects have not holistically assessed the potential for these elements within mineral deposits as part of traditional metallic exploration programs. This poses a key gap in the State's robust understanding of the potential for economic critical mineral deposits and a significant gap in existing public geoscience data. To address these knowledge and data gaps we undertook a stocktake of mineralisation styles that produce economic grades of key critical minerals via a detailed review and compilation of mineralisation styles for all 26 elements listed on the Australian Critical Minerals list using South Australia's extensive Mineral Deposit database (MinDep), as well as historic records that had previously not been captured.

This resulted in the compilation of new precompetitive critical mineral geoscience data and information that aims to drive interest and future investment in the state. This will be facilitated by the compilation of prospectivity maps for each critical mineral derived and expanded from the known mineral occurrences assisting to unlock new critical minerals deposits across South Australia.

Criticality of raw materials – a clarification and redefinition of the term worldwide

A Castro-Sejin[1], A Mammadli[2] and G Barakos[3]

1. Master of Professional Engineering Mining Engineering candidate, Western Australian School of Mines, Minerals, Energy and Chemical Engineering, Curtin University, Kalgoorlie WA 6430. Email: a.castrosejin@postgrad.curtin.edu.au
2. PhD candidate, Western Australian School of Mines, Minerals, Energy and Chemical Engineering, Curtin University, Kalgoorlie WA 6430. Email: anvar.mammadli@curtin.edu.au
3. Lecturer, Western Australian School of Mines, Minerals, Energy and Chemical Engineering, Curtin University, Kalgoorlie WA 6430. Email: george.barakos@curtin.edu.au

ABSTRACT

Though not new in the literature, the term criticality of raw materials has become prevalent in recent years, referring to the importance and vulnerability of resources in various industries and technological advancements. However, criticality is perceived differently worldwide and is influenced by many more parameters than the supply disruption risk. This work comprehensively analyses the definition and determination of criticality for minerals and metals worldwide. The review examines the parameters used to assess criticality, considering factors such as supply and demand dynamics, geopolitical risks, market fluctuations, national security, environmental, and social and cultural considerations. The aim is to offer an in-depth understanding of the diverse conditions and perceptions surrounding criticality through a detailed review of research articles, technical reports, and industrial and governmental publications. The authors explore how different regions, countries and stakeholders define and prioritise critical raw materials based on their specific economic, political, environmental, social, and cultural contexts. By synthesizing the findings, this study aims to establish a more complete and broad understanding of the multifaceted nature of criticality assessment. It highlights the importance of simultaneously considering various parameters and factors when evaluating the criticality of raw materials. The culmination of these discussions will aid in developing a unified global term for raw materials criticality. The outcomes of this research will improve informed decision-making, resource management strategies, and the development of sustainable practices in the critical minerals and metals industry.

INTRODUCTION

The global economy strongly depends on minerals and metals, essential for manufacturing various goods, such as electronics, automobiles and clean energy technology (Nansai *et al*, 2014). Especially as the demand for renewable energy continues to grow, the demand for minerals and metals will rise exponentially in the following years. The supply of critical commodities necessary for this transition must pick up sharply over the coming decades to meet the global net zero emissions goals. The aforementioned is one of the many parameters determining specific minerals and metals critical in several countries worldwide.

It is understood that commodities like rare earth elements, lithium, nickel, cobalt and others have not always been critical, nor will they be forever. The increasing demand for specific minerals and metals at certain periods of time inspires nations and organisations to inspect their criticality situation, aiming to ensure supply security in the foreseeable future (Eheliyagoda, Zeng and Li, 2020). However, since governments, industries and organisations view criticality from different lenses, defining a singular term is challenging.

Criticality generally refers to the current value of minerals and metals to the economy and the potential risks associated with their supply chains (Girtan *et al*, 2021). The definition and determination of raw materials criticality are not agreed upon, leading to varying assessments across different countries and regions (Blengini *et al*, 2017; Eheliyagoda, Zeng and Li, 2020). As a result of the lack of standardisation, the process of comparing and prioritising critical minerals and metals can be complicated and unclear, which may adversely affect the supply chains.

In the literature, we can find several parameters that determine criticality. Geological scarcity is one of the most significant factors, along with geopolitical instability, prices of the commodities and their applications that depend on market trends and technological advances. Nonetheless, there are several gaps in evaluating mineral and metal criticality. These gaps include (Daw, 2017):

- Inconsistency in the number of parameters and conditions used to evaluate commodities' criticality.
- Insufficient description of criticality assessment methodologies and evaluation frameworks.
- Analyses of criticality assessments in different countries and regions are limited.
- Critical minerals and metals are not always adequately understood in terms of the supply chain and other risks associated with them.

These gaps need to be addressed for several reasons. Firstly, filling these gaps can contribute to developing a globally stable and secure supply of minerals and metals (Hayes and McCullough, 2018). As a second benefit, it can assist in mitigating supply chain risks and reduce supply disruptions' economic impact (Schrijvers *et al*, 2020). As well as developing sustainable mining practices and promoting more circular economic performance, it can contribute to the development of a sustainable mining sector (Vidal *et al*, 2022). In mining projects, especially in polymetallic deposits, a mineral or metal's status as either the primary product or a byproduct can substantially influence its criticality status (Mammadli *et al*, 2022). Understanding the interaction of these factors is vital for conducting more robust criticality evaluations.

The concept of criticality is becoming more popular, though further research is needed to establish a standard definition and methodology for assessing criticality (Jin, Kim and Guillaume, 2016). It is also necessary to evaluate criticality assessments across countries and regions, and better understand supply chain risks associated with critical minerals and metals (Achzet and Helbig, 2013).

Hence, this work provides a comprehensive overview of how criticality is defined and determined for minerals and metals worldwide. It is crucial to comprehend raw materials' strategic significance and vulnerabilities in today's linked world when the demand for many resources is rising. In the context of this study, criticality includes a thorough identification of metals and minerals considering their economic, environmental, geopolitical and technical implications. Consequently, strategies can be formulated concerning managing mineral resources and mitigating supply chain risks.

LITERATURE REVIEW

Given the dynamic nature and popularity of the topic, many researchers have been dealing with the criticality of raw materials. However, how researchers, organisations, governments and nations define criticality is discussed hereinafter. This work is based on the review of existing literature, so an initial review of criticality assessments is discussed in this section. A more detailed discussion of how criticality is determined by nations that are major stakeholders of the global critical raw materials industry is done as the central core of this paper.

Criticality assessments

Critical mineral and metal assessments constantly evolve as new research and technologies emerge. Criticality assessments are typically based on supply risk, currently the most widely used approach. A mineral or metal supply disruption is evaluated based on the likelihood and potential impacts (Farjana *et al*, 2019). Various indicators are considered to determine the criticality of a mineral or metal, such as production concentration, reserve distribution and political stability (Graedel *et al*, 2012).

Nevertheless, this approach is known to be limited, particularly for its narrow focus on economic and geopolitical aspects. It is, therefore, necessary to develop more comprehensive and integrated approaches that consider a wider range of factors, such as environmental and social implications (Eheliyagoda, Zeng and Li, 2020). Furthermore, the dynamic and complex nature of supply chains for several minerals and metals must be considered.

As a result, innovative approaches to criticality assessments have become increasingly popular. Stakeholder engagement and circular economy strategies are also incorporated into this process, as well as advanced data analytics and modelling techniques (Watari *et al*, 2019). Such approaches aim to provide more accurate and comprehensive criticality assessments and promote more sustainable and resilient supply chains. There has been a rapid advancement in critical minerals and metals assessment in recent years (Glöser *et al*, 2015). These critical resources face several complex and interrelated challenges.

It is possible to assess criticality using a variety of methodologies and frameworks found in many papers, articles and government publications. It should be noted that the definition of what constitutes critical material differs across these methodologies and frameworks. The necessity of criticality assessment of minerals has evolved due to various factors, including changes in global supply chains, increased demand for certain minerals driven by technological advances, and increasing concern over the risks associated with mineral extraction and processing, sustainability and environmental impacts (Eheliyagoda, Zeng and Li, 2020).

Definition of criticality

The vast majority of researchers worldwide have been working on defining which minerals and metals are considered critical based on each nation’s boundary conditions. Some others approach ‘criticality’ as a framework or a concept through which the minerals and metals can be classified as critical or not (Frenzel *et al*, 2017; Blengini *et al*, 2017; Eheliyagoda, Zeng and Li, 2020). There are sporadic descriptions and references of the definition of criticality in assessment reports, governmental publications and numerous research papers (Eheliyagoda, Zeng and Li, 2020). While some disagree on the definition of criticality, most agree that it refers to the economic significance of a mineral or metal. The term also refers to its vulnerability to disruptions in supply.

Nevertheless, few discussions and research outcomes are solely addressing the definition of the term. Such an event was held in June 2021 by the Critical Minerals Association in the UK (CMA, 2021). CMA organised a discussion on how a critical mineral can be defined and what determines the ‘criticality’ of a metal or mineral. Experts from governmental agencies, mining companies, consulting groups and other stakeholders attended this event.

Hence, this work analyses the term criticality in detail and aims to initiate a discussion that could end up with a global definition.

METHODOLOGY

Based on the research gaps identified, a multi-faceted and comprehensive literature review approach was utilised in this research project. The review included academic journals, technical reports, government publications and industry documents. The purpose of this methodological blend is to provide an overview of the criticality of minerals and metals worldwide. The vast number of publications and the diversity of sources led to a cross-comparison of data and consultancy from experts around the globe. The discussions with experts were not in an officially structured form (interviews or surveys), hence no references are made to specific people. The aim of these contacts and of the whole review is to uncover existing discussions on criticality, assessment parameters and the perspectives presented in global discourse.

It would be impossible to cover the globe and accumulate all opinions and definitions of criticality in one paper. Hence, this research focuses on eight main actors in the field of critical raw materials: Australia, Canada, China, the European Union, India, Japan, the United Kingdom and the United States of America. The selection of these countries and regions lies in the fact that these eight are significant suppliers and/or consumers of critical minerals and metals and rely heavily on them for their industries and technological advancement. At the same time, they face challenges related to the reliable and sustainable supply of these resources, as some are scarce or subject to market fluctuations and geopolitical risks. As a result, these countries and regions have a strategic interest in understanding the criticality of raw materials.

The influence of some of the players mentioned above in the criticality of raw materials may be more significant than others. However, it is not in the scope of this work to prioritise the suppliers or the consumers of critical minerals and metals. Hence, the status of the different countries and regions is discussed alphabetically.

The analysis continues with the evolution of the term ‘criticality of raw materials’ and an effort is made to narrow down the terminology and for the first time give a global definition.

DISCUSSION ON THE VARIOUS CRITICALITY APPROACHES

The diversity of conditions that govern the eight aforementioned major stakeholders of the critical raw materials sector leads to different approaches to criticality. For some countries, minerals and metals are critical due to lack of domestic production and their insecure supply. For some others, it is the opposite; the vast production of commodities in high demand elsewhere casts them as critical (or strategic) for the producers.

Australia

Australia is a resource-rich country with abundant critical raw materials such as lithium, nickel and rare earth elements (Barakos, Dyer and Hitch, 2022). Unlike other countries, Australia is not concerned about running out of these resources, as they have significant reserves and can continue to export them globally. Therefore, their focus on criticality is less about resource scarcity and more about the strategic value of these resources. A crucial turning point in the nation’s strategic planning for its mineral and metal resources was reached with the publication of the 2013 Australian government report on 33 critical commodities. This study was produced as part of Australia’s efforts to comprehend its contribution to supplying essential commodities required by several global sectors and technology (Skirrow *et al*, 2013).

In the 2019 Critical Minerals Strategy, the Australian Government created a blueprint for managing vital mineral resources sustainably. Consequently, the Critical Minerals Facilitation Office (CMFO) was established to advise and support the industry, particularly research, development and international collaborations on critical mineral matters (Department of Industry, Innovation and Science, 2019). Government-funded research projects, like those by the Cooperative Research Centre for Optimising Resource Extraction (CRC ORE), are innovating in critical minerals processing. Another notable initiative is the University of Queensland’s exploration of extracting these minerals from mine waste (Van der Ent, Parbhakar-Fox and Erskine, 2021).

Key publications include ‘The 2018 Critical Minerals in Australia’ report, which comprehensively analyses the status, challenges and opportunities tied to Australia’s critical minerals. It underscores their significance to the economy, innovation and sustainability. It advocates for joint efforts among industry, academia and government to tackle related challenges. The ‘2019 critical minerals strategy’ by the Australian Government, which outlines three primary actions to promote the sector: attracting investments, fostering innovation and focusing on infrastructure development. This strategy emphasises the importance of responsibly developing these resources to support Australia’s economic and strategic interests (Department of Industry, Innovation and Science, 2019). A 2022 report updates Australia’s approach to critical minerals, adding two minerals to their list due to their strategic importance (Department of Industry, Science, Energy and Resources, 2022). Key government actions involve de-risking projects, boosting R&D and strengthening international ties.

The most recent publication in 2023 by the Grattan Institute entitled: ‘Critical minerals: delivering Australia’s opportunity,’ discusses Australia’s potential as a significant global supplier of critical minerals (Wood, Reeve and Suckling, 2023). It stresses the importance of these minerals to modern tech and Australia’s economy while highlighting the associated challenges. The report recommends a strategy that promotes R&D, responsible mining practices and international collaboration. Finally, it is worth noting that the South Australian Government’s declaration of copper as a critical raw material in August 2023 was driven by economic and clean technology considerations (Government of South Australia, 2023).

Canada

Canada is another significant supplier of critical raw materials such as cobalt and lithium, but also a consumer of many others. The Canadian government recognises the strategic significance of these resources and is investing in research and development to enhance its domestic production and support emerging technologies development.

Minerals and other natural resources are not assessed for criticality according to a single standardised methodology in the country. However, as part of Canada's resource strategy and economic interests (NRCan, 2022), the government and various national research institutions have conducted studies that evaluate the criticality of raw materials. An example is the Natural Resources Canada (NRCan), the federal department responsible for the country's natural resources. NRCan has led reports and development activities about critical minerals in Canada. Minerals that are considered 'critical' in Canada must meet the following criteria (NRCan, 2022):

- it is essential to Canada's economic security and its supply is threatened
- specifically necessary for the nation's transition to a low-carbon economy
- a sustainable source of highly strategic critical minerals for their partners and allies.

According to these criteria, the Canadian government identified 31 minerals as being 'critical' in their most recent assessment (Maloney, 2021). The authors further express that 'as critical minerals are the foundation on which modern technology is built, the growing demand for them represents a generational opportunity for Canada' (NRCan, 2022).

China

For China, criticality may not be the correct expression as the nation is responsible for the production of several critical raw materials; it is more about strategic than critical like Australia. According to Andersson (2020), critical minerals and metals have been utilised as essential materials since the publication of the 13th five-year plan in China (2016–2020). In contrast to the US and the European Union, China does not view criticality as a primary concern, as they possess abundant critical raw materials resources and the know-how to process them. Instead, China approaches the issue of raw materials from a strategic perspective, recognising the importance of securing reliable access to key resources to support its economic growth and global influence.

The significance of raw materials to China stems from several factors, such as the production dominance where China is a leading producer and exporter of key commodities like rare earth elements and tungsten (Castillo and Purdy, 2022). This gives it a controlling position in global supply chains, influencing market dynamics and prices. As a result of Chinese firms investing in advanced processing technologies and manufacturing capabilities, China excels in downstream processing and value-added manufacturing of critical minerals and metals. China's trade policies and export controls on critical minerals and metals can adversely affect global supply chains and access to these resources.

Despite being a major producer, China's domestic supply is threatened by resource depletion, environmental concerns, regulatory shifts and geopolitical tensions. These challenges can affect global availability and pricing. Another factor is global consumption, as China's rapid economic expansion, urbanisation, industrialisation, and renewable energy goals have made it a significant consumer of critical minerals and metals, further elevating their importance in global supply chains.

China conducts its own evaluations to assess the criticality of minerals and metals for domestic needs and strategic objectives (Yan *et al*, 2021). Their three-dimensional system relies on three leading indices:

- Supply safety index: It characterises the risk associated with material supply, considering elements like sustainability, reliance and tolerance.
- Domestic economy index: It evaluates the material's importance to the national economy based on its value in each end-use.
- Environmental risk index: It considers environmental factors, categorising metals according to toxicity, waste produced during manufacturing and the impact of environmental protection measures.

The report identifies 24 metals as critical based on supply risk and economic fluctuations, with 18 metals exhibiting higher criticality when environmental risk is also considered (Yan *et al*, 2021). The methodology can be applied to evaluate critical materials in specific sectors like lithium batteries, aircraft engines, and energy storage devices, areas expected to draw global attention and competition in the future.

European Union

The European Union's lack of critical raw materials and reliance on external sources presents a significant concern regarding their supply chain stability. The EU's focus on criticality is determined by recognising the importance of securing access to key resources for their economy and technological advancement (Blengini *et al*, 2017). With the increasing demand for critical minerals to support emerging technologies such as electric vehicles and renewable energy, the EU's dependence on external suppliers poses a significant risk to their competitiveness in these industries (Grohol, Veeh and European Commission, 2023).

Europe evaluates critical raw materials (CRMs) to ensure sustainable economic, environmental, and social outcomes for its industries, fostering innovation, technological advancement and supply chain resilience (European Commission, 2023). The EU has established a methodology for identifying CRMs, considering economic importance and supply risk. Since 2011, the EU has released five CRM lists, increasing the number of identified CRMs in each subsequent assessment.

To determine the criticality of a material for the EU, the assessment considers its economic importance, contribution to the trade balance, end-use applications and value-added (Martins and Castro, 2020). The supply risk is evaluated by considering factors like production concentration, export stability and potential supply disruptions (Figure 1).

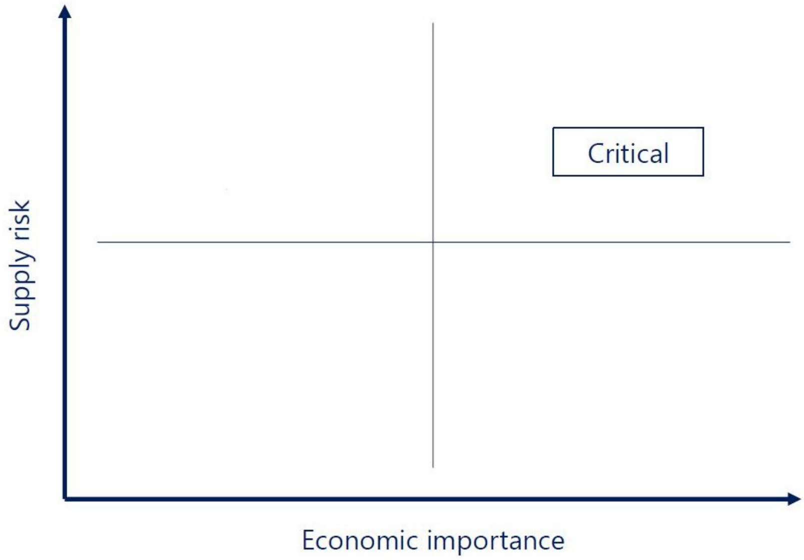

FIG 1 – A simplified chart showing the determination of criticality based on supply risk and economic importance (European Commission, 2023).

Recent key publications on the EU's approach include:

- The 2017 'EU methodology for critical raw materials assessment' critiques the existing approach and suggests incorporating environmental and social indicators, life cycle assessments and comprehensive CRM supply chain databases.
- Martins and Castro's (2020) article proposes a circular economy approach to tackle raw material depletion in the EU, emphasising reduced consumption, recycled materials and product reuse and repair.

- Godoy León and Dewulf's (2020) article introduces a framework for assessing data quality on CRMs, exemplified with cobalt. This framework aims to improve the accuracy and reliability of CRM information to aid sustainable policies and better decision-making.

The latest report by the European Union, 'Study on the critical raw materials for the EU 2023,' identifies 34 critical raw materials and examines their use, production and trade patterns. The two-step methodology considers economic significance, supply chain risks, environmental and social impacts and alternative materials. To ensure resilience and strategic autonomy in achieving green and digital transitions, access to CRMs is essential for the EU's political objectives, including the European Green Deal, REPowerEU Communication and Joint Communication on Defense Investment Gap Analysis and Way Forward.

India

Among other nations, India also recognises the importance of critical minerals and metals for its economic growth, technological advancements and national security (Chadha and Sivamani, 2022). Hence, the government has actively secured access to critical minerals and metals through various policies and strategies, by investing in research and development and by establishing partnerships with other nations. In 2016, the Centre for Social and Economic Progress (CSEP), a think tank based in India that conducts research and analysis on a wide range of social, economic and policy issues, evaluated the criticality of non-fuel minerals in this country. The updated CSEP study was based on the EU methodology (2017), while the previous study was built on the EU methodology in 2014 (Chadha and Sivamani, 2021). Two main factors determine criticality for India:

- Economic importance: A mineral that is no longer available in the supply chain has an impact on the national economy.
- Supply risk: Based on the concentration of mineral extraction in some countries and the quality of governance in these countries, the supply risk indicator of the criticality assessment attempts to assess the vulnerability of the global mineral supply chain.

It was determined that lithium, niobium and strontium have the highest economic importance, based on their substitutability potential, among 11 selected minerals. The authors also indicate that the study provides policy highlights on enhancing domestic mineral exploration and extraction, along with assurances of other sources, to ensure uninterrupted supplies of critical minerals. Nevertheless, the growth of clean technology has dependably been the primary goal in both formal government criticality assessments and informal evaluations conducted within India.

In a recent report by Isetani *et al* (2022), India and Japan collaborated on energy security and critical raw materials (CRM). The report highlights India's rapid growth in the e-waste sector and suggests that recycling CRM from e-waste could enhance CRM security instead of relying solely on mining minerals (Isetani *et al*, 2022). Furthermore, due to a lack of capacity for fostering technical innovations and research and development in utilising their abundant terrestrial resources, Japanese capital could help facilitate industrial development in India. This means the potential for collaboration on critical raw materials (CRM) supply chains between Japan and India is vast. Throughout official and non-official assessments of India, the target was clean technology.

Japan

Japan relies heavily on raw materials to sustain its highly advanced technology sector. The Japanese government has developed strategies to reduce its dependence on foreign sources, promote recycling and reusing critical materials and increase domestic production.

Given its limited domestic reserves, Japan's dependency on critical metals for its high-tech and renewable energy industries is a significant concern (Hatayama and Tahara, 2015). As such, Japan heavily relies on imports and has undertaken measures to ensure a stable supply. One such measure was the establishment of the National Evaluation and Development Organization (NEDO) in 2009, which conducted Japan's first official criticality assessment of metals used in advanced technologies and industries (NEDO, 2009).

NEDO's assessment categorised metals into five risk categories of 12 components. Though not explicitly using the term 'criticality', the assessment evaluated the critical metals for Japan, examining 39 minor metals. A single criticality score was calculated based on the results. NEDO identified 14 of 39 metals as essential minerals, assigning one to three points for each of the 12 components.

In 2015, Hatayama and Tahara assessed the criticality of Japan's 22 common metals, which the government deems strategic. Their assessment had a scale of 1 to 32, with minerals scoring 18 or higher considered necessary (Hatayama and Tahara, 2015). The same year, the Japan Oil, Gas and Metals National Corporation (JOGMEC) evaluated supply risk and economic importance of minerals, including recycling rates (Miyamoto, Kosai and Hashimoto, 2019).

In Japan, the most recent official assessment was conducted and released by the Ministry of Economic, Trade and Industry of Japan (METI) in 2020. The assessment identified 35 critical commodities with the help of 11 risk factors (METI, 2020).

United Kingdom

The United Kingdom's departure from the European Union has impacted its access to critical raw materials, as it can no longer rely on the EU's supply chain network. As a result, the UK has become increasingly interested in addressing criticality concerns to ensure the stability of its supply chain. In collaboration with other stakeholders, the British Geological Survey (BGS) published a 2021 report entitled 'UK Criticality Assessment of Technology Critical Minerals and Metals'. The report examines the criticality of various minerals and metals in developing and deploying advanced technology in the United Kingdom.

The report evaluates the criticality of technology-critical minerals and metals based on various factors, including their economic importance, supply risk, environmental and social impacts and future demand for emerging technologies (BGS, 2021). In addition, it provides insight into the availability, affordability and sustainability of the minerals and metals essential to the UK's technology-based industries.

Various high-tech applications require minerals and metals, such as rare earth elements, lithium, cobalt, platinum group metals, tungsten and tantalum. Materials such as these are used in various advanced technologies, including renewable energy, electric vehicles, aerospace, defence systems, electronics and other advanced technologies crucial to the UK's economic growth, innovation and societal well-being.

The report provides an exhaustive analysis of the supply chain risks, vulnerabilities and opportunities related to these critical minerals and metals, both globally and within the UK. In addition to recommendations for policy, regulatory, and strategic interventions to improve the resilience of the UK's supply chains for technology-critical minerals and metals, the report also contains recommendations for policy, regulatory and strategic interventions.

To underpin the dynamics of criticality and the long-term nature of their assessment strategy, BGS in collaboration with the Critical Minerals Intelligence Centre (CMIC) will evaluate the criticality of raw materials on an annual basis (Department for Business, Energy and Industrial Strategy, 2023). The assessment will be done through an impartial and evidence-based process and the establishment of a 'watchlist' of minerals and metals that are deemed to be increasing in criticality (Figure 2).

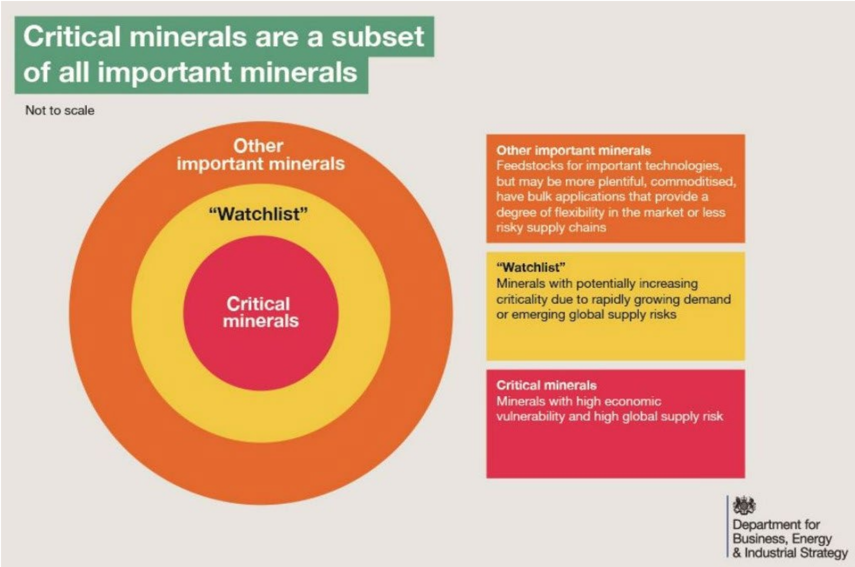

FIG 2 – Schematic of critical minerals, as a subset of all important minerals (Department for Business, Energy and Industrial Strategy, 2023).

United States of America

The United States' focus on criticality is driven by concerns regarding its defence system and national security. The US recognises that access to critical minerals and materials is essential for developing and deploying advanced defence technologies such as radar systems, missiles and aircraft (Hammond and Brady, 2022). The US also identifies that dependence on foreign sources for these materials poses a significant risk to national security and economic competitiveness (Gulley, Nassar and Xun, 2018).

The National Research Council (NRC) was established by the US National Academy of Sciences in 1916 to support its mission of advancing knowledge and advising the federal government by bringing together a wide range of scientists and technologists. The NRC, now the principal operating agency for the National Academy of Sciences and the National Academy of Engineering, provides services to the government, public and scientific and engineering communities (American Institute of Physics, 2023). It has developed a framework for criticality assessments, defining criticality as the importance of a mineral to the nation's economy and security, considering both supply risk and importance.

The methodology for criticality assessments includes quantitative, semi-quantitative and qualitative evaluations. It considers factors like geographical concentration, production, exports, political and regulatory factors and the importance of the mineral to various industries. The Department of Energy released a report in 2010 on critical minerals in emerging clean energy technologies, emphasising the need for collaboration and innovation to ensure responsible sourcing and management of critical minerals (Fortier *et al*, 2021).

In 2016, the Department of Science and Technology of the US developed its first assessment of critical minerals, using a consistent methodology and a scale from 0 to 1 to assess potential criticality. They calculated a geometric mean based on three key indicators: supply risk (R), production growth (G) and market dynamics (M). In 2019, the Congressional Research Service prepared a report on critical minerals, discussing policy tools the US government can use to promote the development of critical minerals.

The United States Geological Survey (USGS) published the 'USGS Critical Minerals Review' in 2021, providing an update on the global supply of critical minerals and identifying emerging trends and issues that could affect their supply and demand. In 2022, the USGS released the '2022 critical minerals' report, listing 50 critical minerals, including 15 new commodities (Mosley, 2022). The report outlines challenges and recommendations for improving the resilience and sustainability of the critical mineral supply chain in the US, such as expanding domestic mining and recycling, improving data collection and analysis and encouraging international cooperation. In the latest report (US DOE,

2023) two criticality matrices are included based on the supply risk and importance to energy (Figure 3); one for short-term (2020–2025) and one for long-term criticality (2025–2035).

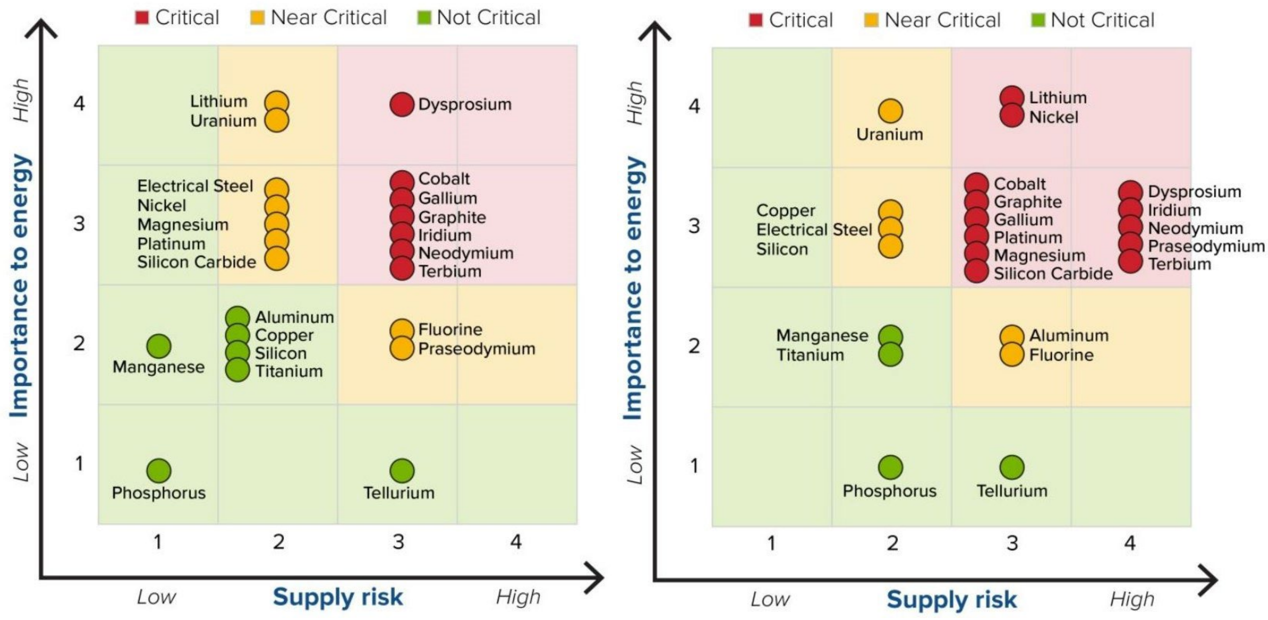

FIG 3 – (a) Short-term (2020–2025) and (b) Long-term (2025–2035) criticality matrices based on the most recent assessment in the US (US DOE, 2023).

EVOLUTION OF THE TERM CRITICALITY

As noted throughout the discussions, 'criticality' has transformed into a confusing term based on diverse conditions and parameters around the globe. Initially, the term was used to refer to the vulnerability of supply chains in various industries during periods of disruption or geopolitical tension (Eheliyagoda, Zeng and Li, 2020). In this case, it referred to the adverse effects of a shortage of particular minerals and metals on industrial sectors, technological advancement and economic stability.

The concept of criticality evolved to encompass broader dimensions as the global economy became more interconnected and dependent on intricate supply networks. Besides merely considering supply chain disruptions, it included geopolitical risks, environmental issues, social and cultural factors and national security considerations. The development of this emerging trend has been attributed to the growing complexity of global resource markets and the recognition of the interdependence between raw materials, sustainability and national interests.

The word 'criticality' has become even broader in recent years. There is a greater understanding that supply disruptions cannot be regarded as the sole determinant of mineral and metal criticality. As a result, it requires a holistic approach that considers the interrelationships among economic, environmental, societal and technological factors. As a result of this general viewpoint, it is acknowledged that their scarcity does not solely determine the criticality of certain minerals and metals but also by their strategic importance, the role they play in green technologies and their contribution to national and international prosperity (Martins and Castro, 2020).

According to certain countries' criticality concepts, their targets differed despite sharing similar meanings. Australia and China, for instance, target to secure their sources and demonstrate their strategic commodities under the criticality term. Demand highlights the criticality concept as resource-dependent countries such as EU and Japan scarcity (Andersson, 2020).

Criticality has demonstrated its significance beyond industry and economics as discourse on the topic has matured. Sustainable development, circular economy principles and international relations are all interconnected. In its evolution, criticality has shifted from an emphasis on immediate supply risks to a broader perspective that acknowledges the intricate web of factors contributing to the global importance of minerals and metals.

Additionally, as resource supply chains intertwine across economies everywhere, certain regions endowed with plentiful raw materials have adopted a distinctive perspective. These resource-rich regions have acquired a dual connotation when dealing with ‘criticality’. They acknowledge the inherent vulnerability of supply chains but also emphasise their strategic importance. There is a growing perception that mineral and metal resources are not merely at risk of disruption in supply but are also essential components in the drive for economic development and technological advancement.

There is a new meaning to the term ‘criticality’ in these strategic regions, indicating these resources’ significant role in strengthening national economies. In the context of industrial development, innovation and the advancement of key sectors, such resources are considered ‘strategic’. Consequently, the emphasis shifts from crisis-driven supply risk to an economic opportunity-driven focus. Considering the same set of resources from different perspectives based on regional circumstances demonstrates the evolving nature of the criticality concept. These regions provide insight into the multifaceted nature of criticality assessments by acknowledging resources’ strategic role and potential supply vulnerability.

Thus, it is essential to recognise that criticality nowadays is not simply about the risk of scarcity but also the potential for economic prosperity. As awareness grows of the interconnectedness of resources and societal progress, this shift in perception also occurs. This expanded understanding of criticality highlights the importance of comprehensive strategies that consider both vulnerability and strategic significance as the demand for minerals and metals continues to surge worldwide. In this way, sustainable and balanced resource management practices can be fostered globally.

Global definition of criticality

The literature review and the discussions enhanced the understanding of global mineral and metal criticality. It is difficult to narrow down all the findings and determine a simple definition of criticality with just a few words. Nevertheless, a framework for the term is proposed in this section.

The concept of criticality in the context of minerals and metals reflects the interaction of economic, environmental, geopolitical, social and cultural factors. This term refers to the importance and vulnerability of specific resources within various industries, technologies and social advancements. In addition to assessing the risk of supply disruptions, criticality includes an inclusive assessment of the broader impacts of mineral scarcity or disruption on economies, security, innovation and sustainability.

There are several aspects to this definition of criticality, including the dynamics of supply and demand, geopolitical risks, market fluctuations, national security concerns, environmental impacts and cultural considerations. The concept of supply risk has also evolved over the years, covering a more comprehensive range of parameters. Besides being essential for industrial production, minerals and metals have far-reaching effects on national economies, technological advancements and social welfare.

Additionally, criticality recognises that its assessment is contextual. According to specific circumstances and perspectives, different regions, countries and stakeholder groups may prioritise different aspects of criticality. Depending on the region, economic growth may be emphasised while environmental sustainability or social equity may be prioritised. Using the term ‘criticality’ strategically in specific regions where abundant raw materials are considered essential for fostering economic growth and technological advancement is possible.

CONCLUSIONS

As a result of this research, there has been an enhanced understanding of the criticality of minerals and metals worldwide. It is evident from examining the term’s evolution that it encompasses many factors beyond supply disruption.

It was found that the literature review delved into the intricate dimensions of criticality, highlighting the significance of supply-demand dynamics, geopolitical vulnerabilities, market fluctuations, national security concerns and socio-cultural influences in defining criticality. This expanded perspective enhances our understanding of the challenges and opportunities associated with ensuring the sustainable availability of these resources.

Interaction with experts played a pivotal role in the enhancement of this research. The insights from various professionals spanning academia, industry, policymaking, and various aspects of the critical raw material value chain have highlighted the complexity of evaluating criticality based on economic considerations, environmental sustainability, social equity and cultural nuances. It is clear from these insights that a comprehensive approach is necessary to assess the criticality of minerals and metals. Future work entails a more systematic recording of stakeholders' knowledge and expertise through interviews and surveys.

This study has a broad impact on a wide range of beneficiaries. Criticality assessment provides researchers with a solid foundation to build their studies. This information can be utilised by stakeholders, including industries and businesses, to make strategic decisions regarding the procurement of resources and the management of risk. Policymakers must have nuanced perspectives to formulate regulations that ensure the availability and sustainability of resources within a global context. Additionally, transparent resource management practices contribute to the general public's responsible consumption of critical minerals and metals.

Furthermore, this research provides opportunities for optimisation. Understanding that criticality has multidimensional characteristics, strategies can be developed to mitigate supply risks, navigate market volatility and strengthen resource sustainability. An integrated approach incorporating economic, environmental, social, and cultural aspects of resource management promises to lead to more balanced decisions and more effective resource management.

Overall, this study goes beyond traditional notions of criticality, advocating for a holistic approach to evaluation. The world must understand minerals and metals, considering their increasing dependence on them. This study contributes to a more robust, sustainable and global approach to critical raw materials by integrating diverse parameters and expert insights.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the guidance and support from several experts in the field of critical raw materials. The authors received no financial support for the research, authorship and publication of this paper.

REFERENCES

Achzet, B and Helbig, C, 2013. How to evaluate raw material supply risks-an over-view, *Resources Policy*, 38(4):435–447. https://doi.org/10.1016/j.resourpol.2013.06.003

American Institute of Physics, 2023. National Research Council (US). Available from: <https://history.aip.org/phn/21511003.html>

Andersson, P, 2020. Chinese assessments of "critical" and "strategic" raw materials: Concepts, categories, policies and implications, *The Extractive Industries and Society*, 7(1):127–137.

Barakos, G, Dyer, L and Hitch, M, 2022. The long uphill journey of Australia's rare earth element industry: Challenges and opportunities, *Int J Min Reclam Environ*, 2022, pp 1–20. doi:10.1080/17480930.2022.2127248.

Blengini, G A, Nuss, P, Dewulf, J, Nita, V, Talens Peiró, L, Vidal-Legaz, B, Latunussa, C, Mancini, L, Blagoeva, D, Pennington, D, Pellegrini, M, Van Maercke, A, Solar, S, Grohol, M and Ciupagea, C, 2017. EU methodology for critical raw materials assessment: Policy needs and proposed solutions for incremental improvements, *Resources Policy*, 53:12–19. https://doi.org/10.1016/j.resourpol.2017.05.008

British Geological Survey (BGS), 2021. UK criticality assessment of technology critical minerals and metals.

Castillo, R and Purdy, C, 2022. China's Role in Supplying Critical Minerals for the Global Energy Transition What Could the Future Hold? [online], *The Brookings Institution.* Available from: <https://www.brookings.edu/articles/chinas-role-in-supplying-critical-minerals-for-the-global-energy-transition-what-could-the-future-hold/>

Chadha, R and Sivamani, G, 2021. Assessing the Criticality of Non-fuel Minerals in India [online], *Centre for Social and Economic Progress (CSEP)*. Available from: <https://csep.org/discussion-note/assessing-the-criticality-of-non-fuel-minerals-in-india/>

Chadha, R and Sivamani, G, 2022. Critical minerals for India: Assessing their criticality and projecting their needs for green technologies [online], *Centre for Social and Economic Progress (CSEP)*. Available from: <https://csep.org/working-paper/critical-minerals-for-india-assessing-their-criticality-and-projecting-their-needs-for-green-technologies/>

Critical Minerals Association (CMA), UK, 2021. Defining Criticality – What Makes a Critical Mineral? Available from: <https://www.criticalmineral.org/post/defining-criticality-what-makes-a-critical-mineral>

Daw, G, 2017. Security of mineral resources: A new framework for quantitative assessment of criticality, *Resources Policy*, 53:173–189. https://doi.org/10.1016/j.resourpol.2017.06.013

Department for Business, Energy and Industrial Strategy, UK, 2023. Resilience for the Future: The UK's Critical Minerals Strategy, Policy Paper. Available from: <https://www.gov.uk/government/publications/uk-critical-mineral-strategy/resilience-for-the-future-the-uks-critical-minerals-strategy>

Department of Industry, Innovation and Science, 2019. Australia's Critical Minerals Strategy 2019, Australian Trade and Investment Commission, Government of Australia. Available from: <https://apo.org.au/node/227646>

Department of Industry, Science and Resources, 2022. 2022 Critical minerals strategy, Australian Government. Available from: <https://www.australiaminerals.gov.au/__data/assets/pdf_file/0008/120797/2022-critical-minerals-strategy.pdf>

Eheliyagoda, D, Zeng, X and Li, J, 2020. A method to assess national metal criticality: the environment as a foremost measurement, *Humanities & Social Sciences Communications*, 7(1). https://doi.org/10.1057/s41599-020-00537-4

European Commission, 2023. Critical raw materials, Internal Market, Industry, Entrepreneurship and SMEs. Available from: <https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en

Farjana, S H, Huda, N, Parvez Mahmud, M A and Saidur, R, 2019. A review on the impact of mining and mineral processing industries through life cycle assessment, *Journal of Cleaner Production*, 231:1200–1217. https://doi.org/10.1016/j.jclepro.2019.05.264

Fortier, S M, Nassar, N T, Graham, G E, Hammarstrom, J M, Day, W C, Mauk, J L and Seal, R R, 2021. USGS critical minerals review. Available from: <www.miningengineeringmagazine.com>

Frenzel, M, Mikolajczak, C, Reuter, M A and Gutzmer, J, 2017. Quantifying the Relative Availability of High-Tech by-Product Metals – The Cases of Gallium, Germanium and Indium, *Resources Policy*, 52(June):327–335. https://doi.org/10.1016/j.resourpol.2017.04.008.

Girtan, M, Wittenberg, A, Grilli, M L, de Oliveira, D P S, Giosuè, C and Ruello, M L, 2021. The critical raw materials issue between scarcity, supply risk and unique properties, *Materials*, 14(8). https://doi.org/10.3390/ma14081826

Glöser, S, Tercero Espinoza, L, Gandenberger, C and Faulstich, M, 2015. Raw mate-rial criticality in the context of classical risk assessment, *Resources Policy*, 44:35–46. https://doi.org/10.1016/j.resourpol.2014.12.003

Government of South Australia, 2023. Critical mass: SA Government declares copper a critical mineral [online], *Energy and Mining*. Available from: <https://www.energymining.sa.gov.au/home/news/latest/critical-mass-sa-government-declares-copper-a-critical-mineral>

Graedel, T E, Barr, R, Chandler, C, Chase, T, Choi, J, Christoffersen, L, Friedlander, E, Henly, C, Jun, C, Nassar, N T, Schechner, D, Warren, S, Yang, M Y and Zhu, C, 2012. Methodology of metal criticality determination, *Environmental Science and Technology*, 46(2):1063–1070. https://doi.org/10.1021/es203534z

Grohol, M, Veeh, C and European Commission, 2023. Study on the Critical Raw Materials for the EU 2023 Final Report. https://doi.org/10.2873/725585

Gulley, A L, Nassar, N T and Xun, S, 2018. China, the United States and competition for resources that enable emerging technologies, *Proceedings of the National Academy of Sciences of the United States of America*, 115(16):4111–4115. https://doi.org/10.1073/pnas.1717152115

Hammond, D R and Brady, T F, 2022. Critical minerals for green energy transition: A United States perspective, *Int J Min Reclam Environ*, 2022:1–18. doi:10.1080/17480930.2022.2124788

Hatayama, H and Tahara, K, 2015. Criticality assessment of metals for Japan's resource strategy, *Materials Transactions*, 56(2):229–235. https://doi.org/10.2320/matertrans.M2014380

Hayes, S M and McCullough, E A, 2018. Critical minerals: A review of elemental trends in comprehensive criticality studies, *Resources Policy*, 59:192–199. https://doi.org/10.1016/j.resourpol.2018.06.015

Isetani, S, Shimizu, S, Dewit, A and Shaw, R, 2022. Indo-Japanese Collaboration on Energy Security and Critical Raw Materials (CRM), *The Asia-Pacific Journal* | *Japan Focus*, vol 20.

Jin, Y, Kim, J and Guillaume, B, 2016. Review of critical material studies, *Resources, Conservation and Recycling*, 113:77–87. https://doi.org/10.1016/j.resconrec.2016.06.003

Godoy León, M F and Dewulf, J, 2020. Data Quality Assessment Framework for Critical Raw Materials: The Case of Cobalt, Resources, Conservation and Recycling, 157(June). https://doi.org/10.1016/j.resconrec.2019.104564.

Maloney, J, 2021. From mineral exploration to advanced manufacturing – Developing value chains for critical minerals in Canada. Available from: <https://publications.gc.ca/collections/collection_2021/parl/xc49-1/XC49-1-1-432-6-eng.pdf>

Mammadli, A, Barakos, G, Islam, M A, Mischo, H and Hitch, M, 2022. Development of a Smart Computational Tool for the Evaluation of Co- and By-Products in Mining Projects Using Chovdar Gold Ore Deposit in Azerbaijan as a Case Study, *Mining*, 2(3):487–510.

Martins, F F and Castro, H, 2020. Raw material depletion and scenario assessment in European Union – A circular economy approach, *Energy Reports*, 6:417–422. https://doi.org/10.1016/j.egyr.2019.08.082

Ministry of Economy, Trade and Industry (METI), (Japan), 2020. Mineral Resource Infrastructure Development Survey Project. Available from: <https://www.meti.go.jp/english/press/index.html>

Miyamoto, W, Kosai, S and Hashimoto, S, 2019. Evaluating metal criticality for low-carbon power generation technologies in Japan, *Minerals*, 9(2). https://doi.org/10.3390/min9020095

Mosley, J L, 2022. 2022 Final List of Critical Minerals. Available from: <https://www.federalregister.gov/documents/2022/02/24/2022-04027/2022-final-list-of-critical-minerals>

Nansai, K, Nakajima, K, Kagawa, S, Kondo, Y, Suh, S, Shigetomi, Y and Oshita, Y, 2014. Global flows of critical metals necessary for low-carbon technologies: The case of neodymium, cobalt and platinum, *Environmental Science and Technology*, 48(3):1391–1400. https://doi.org/10.1021/es4033452

Natural Resources Canada (NRCan), 2022. The Canadian critical minerals strategy, from exploration to recycling: Powering the green and digital economy for Canada and the world, Natural Resources Canada. Available from: <https://www.publications.gc.ca/site/eng/9.917521/publication.html>

New Energy and Industrial Technology Development Organization (NEDO), 2009. Trend Report of Development in Materials for Substitution of Scarce Metals. Available from: <https://www.nedo.go.jp/english/>

Schrijvers, D, Hool, A, Blengini, G A, Chen, W-Q, Dewulf, J, Eggert, R, van Ellen, L, Gauss, R, Goddin, J, Habib, K, Hagelüken, C, Hirohata, A, Hofmann-Amtenbrink, M, Kosmol, J, Le Gleuher, M, Grohol, M, Ku, A, Lee, M-H, Liu, G, Nansai, K, Nuss, P, Peck, D, Reller, A, Sonnemann, G, Tercero, L, Thorenz, A and Wäger, P A, 2020. A review of methods and data to determine raw material criticality, *Resources, Conservation and Recycling*, 155(2020): 104617. https://doi.org/10.1016/j.resconrec.2019.104617

Skirrow, R G, Huston, D L, Mernagh, T P, Throne, J P, Dulfer, H and Senior, A B, 2013. Critical commodities for a high-tech world: Australia's potential to supply global demand, p 126 (Geoscience Australia: Canberra).

US Department of Energy (US DOE), 2023. Critical Materials Assessment, July. Available from: <https://www.energy.gov/sites/default/files/2023-07/doe-critical-material-assessment_07312023.pdf

Van der Ent, A, Parbhakar-Fox, A and Erskine, P D, 2021. Treasure from trash: Mining critical metals from waste and unconventional sources, *Science of the Total Environment*, 758:143673. https://doi.org/10.1016/J.SCITOTENV.2020.143673

Vidal, O, Le Boulzec, H, Andrieu, B and Verzier, F, 2022. Modelling the demand and access of mineral resources in a changing world, *Sustainability (Switzerland)*, 14(1). https://doi.org/10.3390/su14010011

Watari, T, Nansai, K, Nakajima, K, McLellan, B C, Dominish, E and Giurco, D, 2019. Integrating Circular Economy Strategies with Low-Carbon Scenarios: Lithium Use in Electric Vehicles, *Environmental Science and Technology*, 53(20):11657–11665. https://doi.org/10.1021/acs.est.9b02872

Wood, T, Reeve, A and Suckling, E, 2023. Critical minerals: delivering Australia's opportunity. Available from: <https://grattan.edu.au/wp-content/uploads/2022/12/Green-energy-superpower>

Yan, W, Wang, Z, Cao, H, Zhang, Y and Sun, Z, 2021. Criticality Assessment of Metal Resources in China, *IScience*, 24(6). https://doi.org/10.1016/j.isci.2021.102524.

Raman mapping, a novel approach to quantify the mineralogy of spodumene concentrates and calcination products

J Chischi[1], H C Oskierski[2], M F Alhadad[3], T Becker[4], S A Moggach[5], G Senanayake[6] and B Z Dlugogorski[7]

1. PhD Student, Murdoch University, Perth WA 6150. Email: chischi.j@gmail.com
2. Senior Lecturer, Murdoch University, Perth WA 6150. Email: h.oskierski@murdoch.edu.au
3. PhD Graduate, Murdoch University, Perth WA 6150. Email: mahmoudalhadad2@gmail.com
4. Lecturer, Curtin University, Perth WA 6845. Email: t.becker@curtin.edu.au
5. Associate Professor, University of Western Australia, Perth WA 6009. Email: stephen.moggach@uwa.edu.au
6. Associate Professor, Murdoch University, Perth WA 6150. Email: g.senanayake@murdoch.edu.au
7. Distinguished Research Professor, Charles Darwin University, Darwin NT 0909. Email: bogdan.dlugogorski@cdu.edu.au

ABSTRACT

The battery metal lithium is crucial for a future of clean energy storage, with increasing global demand requiring extraction from the mineral spodumene ($LiAlSi_2O_6$). Clinker formation and incomplete conversion of *α*- to *β*-spodumene during calcination degrade lithium extraction from spodumene. To address both issues, quantification of mineral content in spodumene concentrates and calcines is needed and usually done by Rietveld refinement of XRD data. However, long analysis times required to reach low detection limits and the need for highly skilled personnel limit the on-site application of this method.

Here, we introduce Raman mapping as an alternative to XRD Rietveld refinement, capable of assessing the lithium extraction efficiency by quantifying muscovite, a mineral phase commonly associated with clinker formation, as well as by monitoring the conversion of *α*- to *β*-spodumene. The method is demonstrated on synthetic mixtures with known amounts of spodumene, quartz, albite and Li-muscovite and then applied to natural, unknown materials. A pre-defined area of the sample is mapped by the Raman probe to acquire a large area scan. Reference spectra unique for each mineral are obtained directly from the unknown sample or the prior established reference library and overlain with the acquired large area scan. Peak overlaps are handled by selecting one major, overlap-free peak for each mineral phase. Subsequently, integrated intensities of the selected peaks in the large area scan are summed and normalised to achieve weight percent (wt%) of the mineral.

We demonstrate that Raman mapping achieves a Li-muscovite detection limit, accuracy and precision competitive with XRD Rietveld refinement. Furthermore, lower instrument costs, shorter run-times with easier data processing as well as the option to produce in-house standards directly from the examined material favour an on-site application of the proposed method.

A night at the museum – the Andover lithium discovery story

J B Combs[1] and P D Smith[2]

1. Chief Geologist, Azure Minerals Limited, Perth WA 6005. Email: josh@azureminerals.com.au
2. Exploration Superintendent, Azure Minerals Limited, Perth WA 6005.
   Email: paul@azureminerals.com.au

ABSTRACT

Following the discovery and maiden resource estimates of the Andover and Ridgeline Ni/Cu/Co, deposits between 2020 and 2022, Azure Minerals Limited is now on the cusp of making a potentially world-class lithium discovery in Western Australia's Pilbara region.

Historic reports of beryl, tantalum and tin mining (Ellis, 1962) highlighted the prospectivity for lithium bearing pegmatites on Azure's Andover Project tenure.

Following the identification of outcropping spodumene mineralisation during geological mapping, Azure commenced a dedicated lithium exploration program within the Andover Project area.

The approach was both technical and methodical, facilitating rapid identification and delineation of prospective pegmatites for priority drill testing. Preliminary work included a comprehensive desktop review of existing data sets and literature to identify outcropping pegmatites in the field area, a study of several LCT pegmatite samples from the field area from the WA Museum Boola Bardip and consultation with a pegmatite expert to upskill the Azure team in lithium exploration and planning.

Preliminary field investigations began in April 2022 and involved a combination of monomineralic (k-feldspar and muscovite) sampling to establish pegmatite fertility and whole rock sampling to measure lithium content. These techniques allowed the Azure team to vector in on numerous, previously unmapped spodumene-bearing pegmatite corridors. A helicopter sampling campaign was then used to accelerate the delineation and extension of these corridors defining high quality drill targets.

Parallel to the sampling campaign, Azure geologists rapidly developed the technical understanding of the lithium play using cutting edge technology (eg LIBS core scanning by AXT), whole rock geochemistry, refining remote sensing techniques (radiometric, airborne magnetics, detailed drone imagery) to better define the area extent and quality of the outcropping system, as well as developing high level internal IP to accelerate prospect evaluation.

Azure commenced lithium-focused drilling in March 2023, immediately intersecting thick, spodumene-bearing pegmatites and is accelerating work towards resource definition.

REFERENCES

Ellis, H A, 1962. Report on a Pegmatite Locality 6 miles SE of Roebourne, NW Division, Geological Survey of Western Australia Annual Report 1962, Perth, pp 54–55.

Using commercially available vanadium pentoxide to produce electrolyte suitable for a vanadium redox flow battery

D Connelly[1]

1. Principal Consulting Engineer, METS Engineering Group, Perth WA 6000.
   Email: damian.connelly@metsengineering.com

ABSTRACT

The green revolution using wind generators and solar cells to produce low cost energy will require batteries to store this renewable energy. The vanadium redox flow battery (VRFB) is one type of electrochemical energy storage device ideally suited to store such power. The battery operates by reduction oxidation chemical reactions in liquid vanadium electrolyte (VE) which flows through the battery during charge and discharge.

The study has also looked at the possible technologies that can be used for VE production from vanadium pentoxide, ammonium meta vanadate or pregnant liquor solution.

Based on the technology study, it was found that various methods could be used to produce VE with different options showing different levels of complexity and CAPEX/OPEX. Different electrolyte production methods demonstrated that many different reducing agents could be used and the purity of the feedstock would greatly affect the number of purification stages required. It was found that sulfuric acid would be the recommended solvent due to the best combination of vanadium-ion solubilities and redox-couple reversibility for redox flow cell applications.

The specifications for VE varied depending on the VRFB manufacturer or electrolyte producer. Nonetheless, it seems to be a trend towards higher purity electrolytes.

Two options were selected as the more promising choices based on the options study and they were:

Option 1: VE production using SO_2 as the reducing agent.

Option 2: VE production by electrolysis.

The two options were further assessed and then ranked based on the product quality, plant capability, economics, environmental impacts, and metallurgical risks. The ranking is preliminary in nature and based on a qualitative review given the available information, experience, and vendor feedback.

Bridging the critical talent gap – nurturing the next generation in the critical minerals capability

J Coombes[1]

1. CEO, Sage Ability, Perth WA 6000. Email: jacqui.coombes@sageability.org

ABSTRACT

In the rapidly evolving critical minerals sector, the need for a specialised, future-ready workforce has become more crucial than ever. As industry professionals, we're tasked not just with the exploration, extraction, and processing of these indispensable minerals but also with building the human capacity to drive this sector forward.

This presentation will delve into the emerging talent gaps in the critical minerals industry, identify the core competencies needed in our future professionals and provide actionable strategies for cultivating these skills.

The paper will explore partnerships with educational institutions, innovative training and development programs and strategies for retaining talent within our industry. Further, the importance of fostering an inclusive and diverse workforce will be highlighted as a key element of innovation and sustainability.

This presentation aims to serve as a roadmap for our industry, organisations, and leaders, outlining how we can effectively nurture and equip the next generation of professionals, ensuring the sustained growth and success of the critical minerals industry.

Developing Australia's first 'engine-off' mine site

D Da Cruz[1]

1. Executive ESG and Stakeholder Engagement, Zenith Energy, Rivervale WA 6103.
   Email: dominicdacruz@zenithenergy.com.au

DEVELOPING AUSTRALIA'S FIRST 'ENGINE-OFF' MINE SITE

Zenith Energy has developed Australia's first 'engine-off' mine site at IGO's Nova operations in the Fraser Range WA, proving the following:

- **A mine site can operate on 100 per cent renewable energy:** While there are currently non-industrial micro-grids operating on 100 per cent renewables, Zenith Energy's 'Engine-off' project at IGO's Nova operations will prove it's possible to use 100 per cent renewable energy for up to nine hours per day to meet the demands of a remote operational mine site without interruption to supply.
- **Security of supply and reliability:** The integration and control of generation, network and storage infrastructure is key to successfully operating on 100 per cent renewable energy.
- **Relocatable renewables break the dependency on long mine life for net zero:** The limited life of the IGO Nova project would normally destroy the business case for renewable energy and project decarbonisation. However, Zenith Energy's engine-off solution with solar panels, battery, network infrastructure and control system can and will be relocated to another site in what will be the first practical demonstration at scale of relocatable renewable energy.
- **Reducing emissions is realistic and achievable on existing sites:** The Nova project will highlight that 100 per cent renewable energy penetration can be sustainably achieved and replicated on most if not all mine sites across Australia now, without having to wait for further advancements in technology. For sites where renewables are already part of the power generation system, if land permits, increasing renewable assets to go engine-off is a natural next step on the path to net zero.

Understanding changing expectations of investor requirements in critical minerals development

D Dowdell[1] and T McLaughlin[2]

1. FAusIMM, Executive Consultant, RPMGlobal, Perth WA 6000. Email: ddowdell@rpmglobal.com
2. Executive Consultant, RPMGlobal, Vietnam. Email: tmclaughlin@rpmglobal.com

ABSTRACT

As the global mining community seeks the minerals required for the energy transition, there are growing and evolving community expectations that are presenting new challenges for funding and developing mines. The world is changing at a fast pace and the anti-mining voice of many within the broader community is expecting more. This focus on social and environmental expectations is forcing the finance and investment community to be more aware of where investment is made and to whom.

To be able to develop the mines and resources of the future, companies need to understand the environmental and social expectations of investors and investment institutions and how this aligns with the mining development process. There are also new and evolving standards that are complex and these can be challenging to understand and apply during the project development process.

Our presentation takes mining companies through an understanding of how to interpret the growing suite of ESG standards that are applied during the financing process. We will demonstrate, through practical examples, what the investment institutions, the broader community, stakeholders and affected people expect to see.

We showcase in this presentation some of the key areas of focus for investment institutions within the social and environmental performance areas. These areas are often poorly considered during the feasibility study phase, which can lead to extended project delivery time frames and potential financing at risk or the addition of a premium to the lending outcome.

The ESG elements are now among the key technical areas causing funding to be withheld for the development of new critical mineral projects. Given the importance of the mining industry for society to achieve sustainable development goals and the speed at which these mines need to be developed, failure to achieve financing because ESG elements have not been considered in the financing and feasibility strategy cannot be afforded.

LIBS automated techniques for the mineralogical and elemental characterisation of critical mineral deposits

R Duckworth[1], M Narbey[2] and A Fayad[3]

1. Mineralogy Manager, AMI, Perth WA 6104. Email: rowena.duckworth@axt.com.au
2. General Manager, AMI, Perth WA 6104. Email: melissa.narbey@axt.com.au
3. Mineralogist, AMI, Perth WA 6104. Email: alejandro.fayad@axt.com.au

ABSTRACT

Lithium and rare earth elements are among the critical minerals needed globally to help transition to a carbon free economy. They are necessary components in solar panels, electronics, batteries, medical equipment, and many other applications, hence the minerals containing these metals are in high demand. Therefore, the rapid and accurate characterisation of these elements in drill core and rock chips is vital for the mineral exploration community.

Laser Induced Breakdown Spectroscopy (LIBS) allows for a rapid and accurate quantitative mineral analysis of large sample specimens including drill cores, as well as smaller rock chips and sand fractions (±1 mm). Unlike X-ray based techniques, LIBS can directly and accurately identify areas enriched in light elements such as lithium and boron, which are normally undetectable, as well as all the other elements in the periodic table all the way up to uranium.

Importantly, the LIBS systems have very low detection limits similar to SIMS analysis (10's ppm to ppb in some cases) and produce results in a matter of minutes. As well as producing atomic emission spectra of the complete sample, it also produces a high-resolution photo to complement the spectral data. Element maps and a complete mineral library can be produced from the spectra allowing geologists to have chemical, mineralogical and photographic data of their samples in the field.

Critical minerals and the role of the Australian Government

J Dunlop[1]

1. Principal Consultant, John S Dunlop & Associates, El Arish Qld 4855.
   Email: admin@jsdunlop.com.au

ABSTRACT

Influencers from the technology industries, governments and the general media have emerged as passionate promoters of critical minerals. So much has this been the case in recent years, that governments of developed economies worldwide now all promote their own critical minerals policies, usually all linked to decarbonisation or transition to renewable energy sources. The paradox, however, is that these policies have been lacking a policy reality or framework that has support for what critical minerals requires – and support for the projects that produce them. Currently, there are real impediments to new critical minerals projects, which are discussed here, along with some insights into neighbouring US and other foreign policy.

INTRODUCTION

The international investment landscape is shifting rapidly as governments around the world race to incentivise investment in diversifying and expanding critical minerals supply chains. Recent announcements from the US and EU aim to drive historic investments in clean energy supply chains, turbocharge its decarbonisation efforts and transform the environment for businesses globally (Commonwealth of Australia, 2023). However, the question posed here is this – is government doing enough?

THE ROLE OF GOVERNMENT

State and Federal Governments in Australia have now all published critical minerals (CM) policies. These can easily be found on the internet. Additional examples are NSW (Department of Regional NSW, 2021) and WA (Department of Jobs, Tourism, Science and Innovation, 2023). Both of these states are promoting the idea of being a critical minerals hub.

The Federal position is clearly stated in the 2023–2030 Strategy Document (Commonwealth of Australia, 2023):

> *The Australian Government will take a concerted, targeted and proportionate approach to developing our critical minerals sector so it contributes to broader national security, economic security, emissions reduction, green trade, investment and industry growth outcomes. We will do this by working with partners to build diverse, resilient and sustainable global supply chains for priority technologies.*

Critical minerals lists abound. The Australian Federal Government list (Department of Industry, 2023a) is a useful reference as it sets out the lists for the US, EU, Japan and India as well. Our government sought submissions on the list and one such response was from the Australasian Institute for Mining and Metallurgy (AusIMM, 2023) advising the inclusion of bauxite and alumina. The writer counted 26 metals on most lists, noting that platinum and rare earth elements (REEs) were grouped under those two respective headings.

This is sufficient evidence of the role of governments, state and federal, namely to support the development of a critical minerals industry in Australia, with a preference for locally-based downstream processing, as advocated by some Australian trade unions such as the Australian Workers Union (Chambers, 2023). To date, this support has taken the form of relatively modest financial grants (with at least one notable exception). The question is – is it enough? This paper suggests not, with reasons and recommendations.

HOW ARE OTHER DEVELOPED ECONOMIES POSITIONED?

The main influencers of CM policies globally are arguably the USA, the EU, and to a lesser extent Canada and Japan. Our own government has observed:

> *The United States' Inflation Reduction Act, the European Union's Critical Raw Materials Act and Japan's Economic Security Act. These frameworks seek to incentivise local or regional supply chains through tax credits, government investment, regulation, project facilitation and strategic reserves* (Commonwealth of Australia, 2023).

For example, the USA Inflation Reduction Act passed by Congress and signed into law by US President Joe Biden on August 16 promises to shake up US energy and foreign policy in dramatic ways. The law provides billions of dollars in tax incentives for renewable energy, with provisions supporting offshore oil and gas leasing, and other innovations designed to buttress US energy security while also addressing climate change.

The purpose of the policy is threefold. The Biden administration wants to accelerate the energy transition to low carbon technologies; encourage domestic manufacturing; and improve US energy security, ostensibly by reducing its dependence on foreign supplies of the minerals needed to support the energy transition. For that reason, the IRA's EV tax credits come with important caveats – namely, they only apply if the materials used to construct the vehicle come from either the United States or nations the United States has free trade agreements with (Bazilian and Brew, 2022).

In the Australian press (Gottliebsen, 2023), in commenting on the US Act, noted the need for government assistance was due to the world's current dominant producers elevating production so as to reduce prices – thus creating a barrier to new projects attracting finance.

In March 2023, the European Commission put forward a European critical raw materials act, as demand for rare earths is expected to increase exponentially in the coming years. Critical raw materials (CRMs) are raw materials of high economic importance for the EU, with a high risk of supply disruption due to their concentration of sources and lack of good, affordable substitutes.

The act aims to increase and diversify the EU's critical raw materials supply; strengthen circularity, including recycling; and support research and innovation on resource efficiency and the development of substitutes. In June 2023, the Council adopted its position on the proposal (European Council, 2023).

UNDERSTANDING THE CM SUPPLY CHAIN

It is not intended to deal with the CM supply chain in any detail here. However, I offer some local context briefly explain what is meant by the term. The Australian, Indian, Japanese and US governments are aware that critical minerals, including REEs, will be increasingly in demand as countries transition to renewables. These governments are also aware that, for some critical minerals, there is only one supply chain, or that one or a few sovereign players dominate supply chains. This means the future supply of critical minerals could be at risk. In response to the governments' efforts to build stronger Indo-Pacific partnerships, the critical minerals supply chain workshop series brought together government, corporate, research and industry stakeholders in Australia, India, Japan and other regions to undertake a design-thinking process, helping to generate ideas and possible solutions to this growing sector. For a summary, see Monash University, Australia India Chamber of Commerce and MinterEllison (2023).

The recommendation of these workshops was to develop a Critical Minerals International Alliance (CMIA), with representatives from each participating region with an interest in a supply chain across the Indo-Pacific. It would be managed by industry experts and coordinated by market representatives, who would facilitate an Indo-Pacific critical minerals supply chain. The CMIA would ensure issues raised throughout the workshops were addressed and the objective of facilitating cross border partnerships is achieved.

One notable finding from the workshops was the statement, '*It's difficult for new competitors to get into the industry. Typically, transactions occur with an existing or established supplier because of the uncertainty around those markets. Effectively, they're trying to enter a closed shop*' (Monash University, Australia India Chamber of Commerce and MinterEllison, 2023).

What makes this situation worse is that typically the major REE consumers source their refined REE products from ‘middle man’ suppliers. This has two disadvantages, firstly that provenance is harder to trace and secondly the middle man has no incentive to diversify supply, particularly if pressured not to do so by the existing supplier.

FINANCING OF CM IN AUSTRALIA

There are numerous pathways for the financing of critical minerals projects – be they primary producer or secondary processing projects. The following summary sets out what we might consider to be the main options.

- traditional debt and equity funding
- government buy-in to a project
- untied federal government subsidies
- state government subsidies
- low-cost government loans, export credit (ECA’s)
- pre-paid contract arrangements with product customers.

Traditional debt funding using project finance has become less common in the minerals industry here. Funding institutions have tended to view our industry as a higher ESG risk – a view only lessened when a new venture is tied in some way to decarbonisation, renewable energy, or climate change. Export Finance Australia (EFA, 2023) is a current example albeit still requiring framed offtake contracts.

Governments rarely take a direct share in new minerals projects. In the past, involvement took more the form of joint venture arrangements. A good example might be the PNG Government participation in the Ok Tedi project in association with BHP (as manager) and others. More recently, this has taken the form of government authorities, such as EFA, taking a role in the development of renewable energy projects, but using more indirect means of participation such as tax credits.

Evans (2023) touches briefly on the establishment of the Pilbara and Bowen Basin mining fields and notes that government support for each was through state agreements and project fast tracking, rather than direct financial support. Notably also, the co-commitment for downstream processing in those agreements, some 50 years later, has been the victim of high domestic costs.

More recently the federal government launched what it called the Critical Minerals Development Program. It provides funding for projects producing or planning to produce critical mineral(s) listed in Australia’s Critical Minerals Strategy (Business.gov.au, 2023). This includes activities undertaken post-exploration and before final investment decision. Under tranche 2 of this program, 13 resources companies benefited, the largest recipient receiving $6.5M, from a tranche total of $48.8M.

Similar schemes have also been launched by the states. A typical example might be the NSW scheme entitled Critical Minerals and High-Tech Metals Activation Fund (Department of Regional NSW, 2022).

Low-cost government loans have also entered the local funding mix. For example, in April 2022 the Morrison Government approved a $1.25 billion loan through the Critical Minerals Facility to Australian company Iluka Resources, to develop Australia’s first integrated rare earths refinery in Western Australia (Export Finance Australia *et al*, 2022). The refinery will produce separated rare earth oxide products (praseodymium, dysprosium, neodymium and terbium), which are used in permanent magnets in a wide range of technologies, including electric vehicles, clean energy generation and defence. At the time, the accompanying policy statement read:

> *‘The Eneabba Refinery Project strongly aligns with the objectives of the Government’s Critical Minerals Strategy. It will capture more value onshore from our critical minerals, strengthen Australia’s position as a trusted supplier of critical minerals, and create regional jobs crucial for the new energy economy.’*

A further notable government funding involving the US and ASX-listed Lynas rare earth producer announced it had signed an updated contract with the US Department of Defense (DoD) for the construction of the heavy rare earths component of its rare earths processing facility in Texas (Akhand, 2023). Under the contract, a contribution of about $258 million by the US government is currently allocated to the project, higher than the $120 million contribution announced last year.

Superannuation funds have also been focussing on infrastructure investment (McNair, 2016) and before too long may show an interest for assets that fit their decarbonation investment criteria. This could well lead to an interest in critical mineral investment and could provide a further boost to critical minerals project investment.

The last of the funding pathways touched on here has yet to receive significant interest in the CM industry. It involves the supplier entering into a contract with a customer to take CM product from the supplier for a fixed term (and possibly price as well), in exchange for upfront payment for the entire supply. Obviously, this arrangement provides cornerstone finance for a new project build, but is limited by the liquidity of the customer. Its failure to become commonplace lies in a closer examination of supply chain restraints, caused by supply chain dominance.

OPPORTUNITIES FOR POLICY ENHANCEMENT

Two opportunities for policy enhancement are set out here.

Firstly, the current policy initiatives are a step in the right direction, but need significant and immediate enhancement. Grants of the magnitude of the Iluka or Lynas are needed across the CM landscape to provide cornerstone capital for project ready CM start-ups.

Why? The argument is soundly based on domestic sufficiency and future needs. Our decarbonisation needs into the future alone should be telling us we need to accelerate CM developments much faster, all the while recognising their lead times to production. This picture is clearly set out in the most recent 'call to arms' by the Minerals Council of Australia (MCA, 2023). The five recommendations in that document (beginning at page 45) are very much a call to action by the government.

We read in that document, at the second page, that minerals related royalties and taxes over the last ten years have amounted to $295 billion. Even on a straight-line basis this is almost $30 billion per annum. Seen in that light, the reinvestment by governments has been poor, to say the least. On the data that the author has reported it amounts to about 1.3 percent over the last five years. It is suggested that along with a significant lift in government re-investment, an annual scorecard be kept, thus providing a tracked audit trail against an enhanced commitment. An avenue for this exists – it is the Critical Minerals Office and the quarterly report of the Department of Industry (2023b). Re-investment of $1 billion per annum over the next five years would turbocharge the Australian CM industry.

Secondly, there is need to review and question the process for grant application and approval. This author would like to see existing grants committees morphed into a National CM Grants Commission, chaired by the Federal Minister, supported by independent industry experts, recommended by bodies such as the Australian Institute of Mining and Metallurgy. The Commission would have the power to direct allocations from existing funds set-up for that purpose, such as the National Reconstruction Fund (Department of Industry, 2022), Infrastructure Australia (2023), the Northern Australia Infrastructure Fund (Northern Australia Infrastructure Facility, 2022), and numerous others, the pool for which must be increased. Public infrastructure funds also exist, but cannot be expected to pave the way in a national policy sense (see Australian Securities Exchange (ASX, 2023)).

Downside risk

The obvious downside risk is that of uncompetitive operating costs associated with local production. Elevated labour and energy inputs must not be allowed to offset the economics of local production. The MCA document referred to above touches on this in setting out its five key recommendations in *Future Critical* (MCA, 2023). On this theme, readers are referred to the last few paragraphs in the article by Evans (2023), attributed to the CEO of a well-known critical minerals producer. The comment on this downside risk is thought provoking.

CONCLUSIONS AND RECOMMENDATIONS

Governments, and to a certain extent, the wider community, are now both aware of the need for critical minerals, though possibly unaware of the upward trajectory of demand posing a real and present welfare threat. The need for greater self-sufficiency and downstream processing is also pressing. Enhanced policy action is needed.

To address this threat, this paper proposes two opportunities for this enhancement:

1. Increase the quantum of CM grants significantly so as to aid actual start-ups.
2. Form a National Critical Minerals Grants Commission with additional expert advisors to oversee the accelerated granting process.

REFERENCES

Akhand, H, 2023. Lynas Rare Earths signs updated contract with US government for Texas facility, shares rise [online], Reuters. Available from: <https://www.reuters.com/markets/commodities/lynas-rare-earths-signs-updated-contract-with-us-govt-texas-facility-2023–07–31/>

ASX, 2023. ASX Investment Products – Infrastructure funds, ASX. Available from: <https://www.asx.com.au/markets/trade-our-cash-market/asx-investment-products-directory/infrastructure-funds>

AusIMM, 2023. AusIMM response to Australian Critical Minerals List, The Australasian Institute of Mining and Metallurgy. Available from: <https://www.ausimm.com/globalassets/advocacy/ausimm_submission_aug2023_criticalminerals list.pdf>

Bazilian, M D and Brew, G, 2022. The Inflation Reduction Act Is the Start of Reclaiming Critical Mineral Chains, Foreign Policy. Available from: <https://foreignpolicy.com/2022/09/16/inflation-reduction-act-critical-mineral-chains-congress-biden/>

Business.gov.au, 2023. Funding to progress critical mineral development, Business.gov.au, The Australian Government. Available from: <https://business.gov.au/grants-and-programs/critical-minerals-development-program>

Chambers, G, 2023. Stop treating Australia's critical minerals as 'cash pinata': AWU [online], The Australian. Available from: <https://www.theaustralian.com.au/business/mining-energy/stop-treating-australias-critical-minerals-as-cash-pinata-awu/news-story/7828110be11850da3390f89dbcc95cf8>

Commonwealth of Australia, 2023. Critical Minerals Strategy 2023–2030, June 2023, Department of Industry, Science and Resources, The Australian Government. Available from: <https://www.industry.gov.au/publications/critical-minerals-strategy-2023–2030>

Department of Industry, 2022. National Reconstruction Fund: diversifying and transforming Australia's industry and economy, Department of Industry, Science and Resources, The Australian Government. Available from: <https://www.industry.gov.au/news/national-reconstruction-fund-diversifying-and-transforming-australias-industry-and-economy>

Department of Industry, 2023a. Australia's Critical Minerals List, Department of Industry, Science and Resources, The Australian Government. Available from: <https://www.industry.gov.au/publications/australias-critical-minerals-list>

Department of Industry, 2023b. Resources and energy quarterly, Department of Industry, Science and Resources, The Australian Government. Available from: <https://www.industry.gov.au/publications/resources-and-energy-quarterly>

Department of Jobs, Tourism, Science and Innovation, 2023. Western Australia – A Global Battery and Critical Minerals Hub, Department of Jobs, Tourism, Science and Innovation, Government of Western Australian. Available from: <https://www.wa.gov.au/system/files/2023–08/00178_battery_and_critical_minerals_prospectus_web.pdf >

Department of Regional NSW, 2021. Critical minerals and high-tech metals strategy, Department of Regional NSW, NSW Government. Available from: <https://www.nsw.gov.au/sites/default/files/2021–11/NSW%20Critical%20Minerals%20and%20High%20Tech%20Metals%20Strategy.pdf>

Department of Regional NSW, 2022. Critical Minerals and High-Tech Metals Activation Fund, Mining, Exploration and Geoscience, NSW Government. Available from: <https://meg.resourcesregulator.nsw.gov.au/invest-nsw/nsw-mineral-resources/critical-minerals-and-high-tech-metals/critical-minerals>

European Council, 2023. Infographic – An EU critical raw materials act for the future of EU supply chains, European Council – Council of the European Union. Available from: <https://www.consilium.europa.eu/en/infographics/critical-raw-materials/#:~:text=The%20act%20aims%20to%3A,and%20the%20development%20of%20substitutes>

Evans, N, 2023. The lithium boom has been running for seven years, why are we still waiting on a strategy [online]. The Australian. Available from: <https://www.theaustralian.com.au/business/mining-energy/the-lithium-boom-has-been-running-for-seven-years-why-are-we-still-waiting-on-a-strategy/news-story/e7e35516c83d94b58f9d41c5e5c4673f>

Export Finance Australia (EFA), 2023. Project and structured finance, Export Finance Australia, The Australian Government. Available from: <https://www.exportfinance.gov.au/how-we-can-help/our-solutions/project-and-structured-finance/>

Export Finance Australia, Morrison, S, Frydenberg, J, Tehan, D and Pitt, K, 2022. Transforming Australia's critical minerals sector. Export Finance Australia, The Australian Government. Available from: <https://www.exportfinance.gov.au/newsroom/transforming-australia-s-critical-minerals-sector/>

Gottliebsen, R, 2023. Why Americans Will Spend Big on Our Mining, Processing [online]. The Australian. Available from: <https://www.theaustralian.com.au/business/why-americans-are-set-to-pile-into-australian-mining-processing/news-story/ef563450f25a98b9720f179760bcb476>

Infrastructure Australia, 2023. Funding & Financing, Infrastructure Australia, The Australian Government. Available from: <https://www.infrastructureaustralia.gov.au/funding-financing >

McNair, D, 2016. Investing in Infrastructure – International Best Legal Practice in Project and Construction Agreements – 2016, PwC Australia. Available from: <https://www.lexology.com/library/detail.aspx?g=61b0822c-5e60–4400–8197–86b1c81fa1ce>

Minerals Council of Australia (MCA), 2023. Future Critical, Minerals Council Of Australia. Available from: <https://minerals.org.au/resources/future-critical/>

Monash University, Australia India Chamber of Commerce and MinterEllison, 2022. Supply Chain Workshop Series – Critical Minerals, Monash University, Australia India Chamber of Commerce and MinterEllison. Available from: <https://www.monash.edu/__data/assets/pdf_file/0018/3117204/Supply-Chain-Critical-Minerals-Report.pdf>

Northern Australia Infrastructure Facility, 2022. NAIF supported projects, Northern Australia Infrastructure Facility, The Australian Government. Available from: <https://naif.gov.au>

Creating value for Australian nickel with ethical provenance and supply chain traceability

B C Dunsmore[1], P Darcey[2] and G Iwanow[3]

1. Executive, Mincor Resources NL, Perth WA 6005. Email: b.dunsmore@mincor.com.au
2. General Manager, Mincor Resources NL, Perth WA 6005. Email: p.darcey@mincor.com.au
3. Managing Director, Mincor Resources NL, Perth WA 6005. Email: g.iwanow@mincor.com.au

ABSTRACT

With the exponential growth in electric vehicles comes pressure to provide the critical minerals needed for their batteries. In turn, unless controlled, this pressure may cause unwanted environmental impact from the world's supply chain for such minerals.

Consumers, manufacturers and other stakeholders are already demanding reliable provenance of critical minerals to ensure that the mining and processing which creates their products is ethical and minimises adverse impact to the environment.

Here, for the first time, a detailed calculation shows that the carbon footprint of mining nickel from one area of the Kambalda region of Western Australia was 18 tCO_2/t Ni. The calculation includes figures for the extraction, smelting, concentration, transportation and processing steps required to produce nickel sulfate.

These novel Western Australian figures are compared against the carbon footprint for producing nickel from other sources. The potential difference in environmental impact depending on sourcing decisions is evident. For example, nickel sulfate produced from class 2 nickel pig iron has a carbon footprint of 78 tCO_2/t Ni, which is more than four times greater than the carbon footprint of nickel sulfate which originates in the Kambalda region.

In addition, accurately mapping carbon impact also highlights that the best way to further reduce the impact of mining in this case is to decrease the use of electricity and diesel, which are responsible for ~40 per cent of the 18 tCO_2/t Ni.

Finally, demand for ethically sourced raw materials will only continue to increase. Clear supply chain provenance, combined with verifiable traceability, as expected by consumers, should make such materials more valuable. Studies such as this, which define carbon footprint, are not only essential to support sustainable mining and processing but will also encourage needed further improvement throughout the worldwide battery metals supply chain.

Optimising cost estimation in mineral processing operations using the MAFMINE 3.1 tool – modelling with parametric equations

T Fernandez[1] and C Petter[2]

1. Universidade Federal do Rio Grande do Sul (UFRGS), Graduate Program in Mining, Metallurgical and Materials Engineering, Porto Alegre – RS 90010-150, Brazil. Email: tracyfer888@gmail.com
2. Universidade Federal do Rio Grande do Sul (UFRGS), Graduate Program in Mining, Metallurgical and Materials Engineering, Porto Alegre – RS, 90010-150, Brazil. Email: cpetter@ufrgs.br

ABSTRACT

Mineral processing is an activity that requires significant financial and human resources. To estimate the associated costs, planning is necessary. In this context, the MAFMINE tool is a viable and reliable option for cost estimation at the PEA level in mineral processing operations. There are several ways to estimate costs quickly, one of which is the parametric method. In the mining sector, the MAFMINE software uses parametric models to estimate investment and operational costs and is based on a computer model known as client-server. This article presents a case study of cost estimation in mineral processing operations using the MAFMINE 3.1 tool, which generates an order of magnitude estimate of CAPEX and OPEX to establish a first discounted cash flow (DCF), the results are very promising.

A national-scale assessment of carbonatite-related rare earth element mineral system potential in Australia

A Ford[1], D Huston[2], J Cloutier[3], A Schofield[4], Y Cheng[5] and E Beyer[6]

1. Activity Leader – Integration and Prospectivity, Geoscience Australia, Canberra ACT 2609.
   Email: arianne.ford@ga.gov.au
2. Principal Research Scientist, Geoscience Australia, Canberra ACT 2609.
   Email: david.huston@ga.gov.au
3. Senior Research Fellow – Mineral Systems, Geoscience Australia, Canberra ACT 2609.
   Email: jonathan.cloutier@ga.gov.au
4. Director – Mineral Potential of Australia, Geoscience Australia, Canberra ACT 2609.
   Email: anthony.schofield@ga.gov.au
5. Senior Geoscientist, Geoscience Australia, Canberra ACT 2609.
   Email: yanbo.cheng@ga.gov.au
6. Activity Leader – National Geological Mapping, Geoscience Australia, Canberra ACT 2609.
   Email: eloise.beyer@ga.gov.au

ABSTRACT

The production of rare earth elements (REEs) is critical to the global transition to a low carbon economy. Carbonatites represent a significant source of REEs, both domestically within Australia, as well as globally. Given their strategic importance for the Australian economy, a national mineral potential assessment has been undertaken as part of the Exploring for the Future program at Geoscience Australia to evaluate the potential for carbonatite-related REE (CREE) mineral systems. Rather than aiming to identify individual carbonatites and/or CREE deposits, the focus of the mineral potential assessment is to delineate prospective belts or districts within Australia that indicate the presence of favourable criteria that may lead to the formation of a CREE mineral system.

This study demonstrates how national-scale multidisciplinary precompetitive geoscience data sets can be integrated using a hybrid methodology that incorporates robust statistical analysis with mineral systems expertise to predictively map areas that have a higher geological potential for the formation of CREE mineral systems and effectively reduce the exploration search space. Statistical evaluation of the relationship between different mappable criteria that represent spatial proxies for mineral system processes and known carbonatites and CREE deposits has been undertaken to test previously published hypotheses on how to target CREE mineral systems at a broad-scale. The results confirm the relevance of most criteria in the Australian context, while several new criteria such as distance to large igneous province margins and distance to magnetic worms have also been shown to have a strong correlation. Using a hybrid knowledge- and data-driven mineral potential mapping approach, the mineral potential map predicts the location of known carbonatite and CREE deposits, while also demonstrating additional areas of high prospectivity in regions with no previously identified carbonatites or CREE mineralisation. The mappable criteria in this study can be applied to exploration for CREE mineral systems globally.

Critical metals – a matter of confidence?

N J Gardiner[1], J P Sykes[2,3] and S M Jowitt[4]

1. Senior Lecturer, School of Earth and Environmental Sciences, University of St Andrews, St Andrews KY16 9AJ, Scotland. Email: nick.gardiner@st-andrews.ac.uk
2. PhD Candidate, Centre for Exploration Targeting (CET), School of Earth Sciences, The University of Western Australia (UWA), Crawley WA 6009. Email: john.sykes@uwa.edu.au
3. Lecturer (MBA Program), Business School, UWA, Crawley WA 6009; Strategist, MinEx Consulting, South Yarra, VIC, 3141; Director, Greenfields Research, Leeds, West Yorkshire LS19 7XY, UK.
4. Director, Ralph J Roberts Center for Research in Economic Geology, Nevada Bureau of Mines and Geology, University of Nevada Reno, Reno Nevada, USA. Email: sjowitt@unr.edu

ABSTRACT

Many of the metals necessary to deliver transformative energy technologies, such as copper, cobalt, lithium, nickel and tin, are considered critical in that they are important for new technologies; leading to increasing demand on top of existing production, but for which they also have insecure supply chains – for a variety of different reasons. The criticality of these metals has highlighted that metals supply may well become the biggest barrier to policy objectives such as global energy decarbonisation, leading to a new focus on the securing of their value (supply) chains.

A major societal goal therefore is to make critical metals 'uncritical', which is largely accomplished by freeing up the respective bottlenecks in their value chains. Given limited resources, from a policy perspective, it is thus important to determine where positive impacts can be maximised. It is also important to acknowledge that, paradoxically, value chain 'criticality' (ie bottlenecks) from a business perspective is typically where money is made – at least, in the short-term. Over the longer-term, however, even the private sector shares an interest in value chain debottlenecking and the market growth that subsequently occurs.

Nonetheless, in terms of solutions, not all critical metals are similarly 'critical'. They are not all alike in terms of their market size, maturity and structure; in our geologic understanding of their formation; in our ability to prospect for them and process them; and in their recyclability. On the other side of economic equations, some metals may suffer from price volatility or other pricing or demand issues, and thus may represent an unattractive long-term investment risk unless they undergo growth and transformational change in supply, despite predicted potential demand. Other metals may ultimately never be in sufficient supply to meet structurally increased demand, leading to efforts to find substitutions, or implement thrifting and similar activities.

In this context, perhaps an underappreciated aspect of metal criticality is the degree of confidence, or level of uncertainty, that applies to the assessment of the criticality of a given commodity, which in turn adds uncertainty and reduces confidence in proposed criticality solutions. Here, we argue that this uncertainty is an important qualification to the definition of a critical metal – and in assessing the value of proposed supply chain criticality solutions.

In this presentation, we begin to define what uncertainty of metal criticality means and apply a broad qualitative classification to a suite of critical metals, which in future may act as a framework for quantifying the uncertainty around the criticality of various metals and the value of proposed criticality solutions. This assessment will enable the development of more targeted future policy efforts on freeing up bottlenecks in critical metals value chains. Similar assessments can also highlight for areas of potentially higher value and lower uncertainty for the private sector, further identifying key areas where policy-supported value chain business activities may be focused.

Thorium waste management from rare earth processing – current practice and challenges

C Griffith[1], S Brown[2], M Emett[2], M Anvia[2] and A Roper[2]

1. ANSTO, Minerals Business Unit, Lucas Heights NSW 2234. Email: chris.griffith@ansto.gov.au
2. ANSTO, Minerals Business Unit, Lucas Heights NSW 2234.

ABSTRACT

In November 2019, the Australian Government committed to securing the future of rare earth and critical mineral projects with new financial options and a dedicated Critical Minerals Office established within the Department of Industry, Science and Resources (DISR). The government also committed $4.5 million to fund critical minerals research by key Commonwealth scientific agencies through the Advancing Research and Development for Critical Minerals program (the 'AR&DCM Program').

As part of discussions with relevant stakeholders, the management of thorium-bearing waste was raised as a key issue with the development of RE projects in Australia. Although not all RE minerals contain elevated levels of thorium, and therefore this issue is not universal to all RE projects both in Australia and worldwide, the societal and political concerns with the generation of waste containing elevated levels of thorium and other naturally occurring radioactive materials (NORMs) is a key issue for developers of RE projects.

Australia is endowed with an abundance of heavy mineral sands (HMS) deposits and has been, and continues to be, a significant supplier of zircon and other products from such operations. Monazite ($REPO_4$) occurs in all such HMS deposits, but is not always separated effectively losing/ forfeiting the contained value of the RE. For developers of HMS projects to realise the contained value of RE, separation of the monazite/xenotime is required. Further processing of this REMC produces various waste streams which are radioactive.

In light of the RE opportunity from HMS deposits and in support of the AR&DCM Program, specific effort by ANSTO was directed towards developing options for dealing with thorium-bearing waste from the processing of RE-host minerals, principally monazite.

We will present the results of that effort which contained specific attention/focus on radioactive waste management current practices (international and Australian context), the critical assessment of leach testing protocols (ASLP and LEAF) relevant to NORM-affected waste particularly from sulfation baking and caustic conversion monazite process flow sheets and the assessment of engineered waste forms applicable to such wastes.

Unlocking the value in Australia's critical minerals – high purity silica/quartz processing at ANSTO

C Griffith[1], N Syna[2], R Fowles[2], C Delva[2] and E Cameron[2]

1. ANSTO, Minerals Business Unit, Lucas Heights NSW 2234. Email: chris.griffith@ansto.gov.au
2. ANSTO, Minerals Business Unit, Lucas Heights NSW 2234.

ABSTRACT

Since the establishment of the Critical Minerals Office (formerly the Critical Minerals Facilitation Office) in 2019, within the Department of Industry Science and Resources (DISR), ANSTO has been providing expert advice on the processing of Australia's critical minerals, especially relating to the processing of rare earths.

As part of the 2022 Critical Minerals Strategy, the National Critical Minerals Research and Development Hub (the Hub) was established in 2022, as a joint effort between CSIRO, Geoscience Australia (GA), ANSTO and DISR, to:

- Address technical bottlenecks across the critical minerals value chain and work with industry to focus R&D efforts on national priorities.
- Help unlock new resources of economically viable critical minerals and diversify supply chains of interest to Australia and our allies.
- Drive breakthrough collaborative research.
- Build Australian IP in critical minerals processing.

The intention of the Hub is to provide a 'one stop shop' to connect critical minerals projects to the scientific and technical expertise they need, coordinate, guide and prioritise R&D efforts by government and industry and scale up and commercialise critical minerals R&D, including by leading and supporting innovative research projects.

To this end, ANSTO's initial program as part of the Hub has begun working on the 'High Purity Silica/Quartz (HPS or HPQ)) Program' which aims to develop processing routes for high purity quartz production from Australian silica/quartz projects.

High purity quartz (HPQ) refers to quartz material that contains extremely low concentrations of impurity elements which is employed for the manufacture of components and materials critical to optical fibre manufacture, solar and semiconductor crucibles, semiconductor fabrication glassware and speciality optics applications. The quality of HPQ required for these applications varies significantly, but is often only determined by <1 ppm differences of given impurities or key physical properties such as viscosity (of the associated melt).

This program dovetails with GA's program on HPQ which is examining Australia's silica/quartz resources, their geological genesis and signatures and outlining the potential that Australian silica/quartz holds with regard to the HPQ and elemental silicon supply chains.

Currently, there are very limited process development and piloting facilities available globally for Australian project developers to determine the suitability of their material for supply into such high-tech markets. The key objective of ANSTO's HPS/HPQ program is to provide such a facility for validation and qualification purposes and to develop the related technology and know-how for the advantage of Australian producers.

This presentation will provide an overview of the program, HPQ processing fundamentals and applications and the associated beneficiation and high temperature chlorination facilities being installed at ANSTO.

Latin America's paradox in the energy transition

J C Guajardo[1]

1. Executive Director, Plusmining, Santiago 7550653, Chile.
   Email: juan.carlos.guajardo@plusmining.com

ABSTRACT

Latin America faces a paradox in the global energy transition. Despite having a rich diversity of natural resources such as lithium and copper, as well as many other minerals, major obstacles have arisen that make it difficult to exploit them. Latin America has 47 per cent and 36 per cent of the world's reserves of lithium and copper respectively, which represent a great opportunity due to the growing global demand for critical minerals.

One of the main obstacles is the resurgence of resource nationalism in the region, which has created a more complex environment for mining companies. Ideas such as state-controlled mining to articulate industrial development strategies have strongly re-emerged.

In addition, the empowerment of indigenous communities and movements has gained relevance, as they claim their territorial rights and demand greater participation in decisions related to the exploitation of natural resources, which has led to conflicts and the cancellation of mining projects.

Environmentalism also plays a crucial role in this paradox, as pressure has increased to implement, at full speed without regard for gradualism, high standards in mining activity. This is compounded by other challenges, such as corruption, lack of adequate infrastructure and social and labour problems.

In this context, the Latin American mining industry is at a crossroads, trying to find a balance between the great opportunity for economic development presented by the global energy transition through accelerated investment in mining projects and, on the other hand, the resolution of major obstacles created by the expectation that mining will deliver economic benefits beyond the usual, increasing environmental protection, respect for indigenous and local communities' rights. Overcoming this paradox will require a comprehensive and collaborative effort among the different actors involved.

Conscious circularity – the role of mining in a circular economy

C Hayes[1], G Roodenrys[2], A Lane[3] and P Muricy[4]

1. Director, Deloitte, Perth WA 6000. Email: chayes@deloitte.com.au
2. Partner, Deloitte, Brisbane Qld 4000. Email: groodenrys@deloitte.com.au
3. Partner, Deloitte, Africa. Email: alane@deloitte.co.za
4. Partner, Deloitte Brazil, São Paulo 04711–130, Brazil. Email: pmuricy@deloitte.com

ABSTRACT

The global economy is undergoing a metamorphosis. The way that value is defined is changing to support a bid for greater sustainability, as evidenced by the introduction of carbon pricing; environmental, social and governance (ESG) measures; and the evaluation of natural capital. Driven by this change, mining and metals companies are beginning to reconsider their traditional roles as metal producers, finding ways to capitalise on previously untapped sources of value and exploring new avenues for value creation.

The intensification of climate change, environmental degradation and widespread pollution are products of a linear economic model, one that has reached peak maturity and is starting to fail. A circular economy (CE) presents a more sustainable alternative. It provides a framework for an economy decoupled from finite materials, while minimising negative impacts to people and the planet. CE is underpinned by the move to renewable energy and, as the providers of the raw materials needed to create these technologies, no industry is better positioned than mining and metals to lead this change.

In general, the mining and metals industry is well progressed in **unconscious** circularity – the sector has a strong history of waste recycling and water reuse and recycling, and the creation of products from tailings is accelerating. However, these initiatives have been mainly driven by liability, regulation and resource scarcity, rather than by value creation. When it comes to '**conscious**' circularity and shifting mindsets around value and materials reuse further down the value chain there is still much work to be done.

Rethinking the flow of value throughout the metals and minerals ecosystem is one of the biggest opportunities this sector has to positively influence sustainable development, both today and tomorrow. The journey will not be easy, but organisations that are willing to try will likely be rewarded tenfold through greater longevity.

Walford Creek copper-cobalt project

F W Hess[1] and B Wedderburn[2]

1. Managing Director and CEO, Aeon Metals Limited, Brisbane Qld 4006.
   Email: fred.hess@aeonmetals.com.au
2. Principal, Malachite Process Consulting, Melbourne Vic 3150.
   Email: consult@malachiteconsulting.com

ABSTRACT

Walford Creek deposit in north-west Queensland already hosts one of Australia's largest (85 kt) and highest grade (0.12 per cent) primary cobalt resources. In addition, it hosts substantial copper, zinc, lead, silver and nickel resources that render it a substantial polymetallic resource, rich in renewable metals (currently 1,300 kt Cu Eq). Polymetallic complexity has typically been a barrier to economic success for similar projects, especially when physical separation processes like flotation are employed to selectively recover metal concentrates.

The flow sheet adopted at Walford relies on the hydrometallurgical recovery of the payable metals. With a high pyrite content, controlling the extent of pyrite oxidation while maximising metal recovery was achieved in an autoclave operating at medium temperature and pressure (MTPox). This is followed by sequential recovery and refining to produce high quality metal and sulfate products.

Given the rising importance of achieving critical minerals production independence, Walford Project will deliver a suite of finished, rather than intermediate, products including copper cathode, and chemical grade cobalt, zinc and nickel sulfate which will not require further (international) processing ahead of their consumption.

Given the remote location of Walford, the project development envisages the production of a bulk sulfide concentrate at the mine site and a separate downstream refining facility located at Mount Isa. A 350 km slurry pipeline, largely following an existing power line route, is expected to minimise project logistics costs and risk, leverage existing infrastructure and services, and offer the capability to act as a regional processing facility for polymetallic and/or cobalt rich ores and tailings.

With the forthcoming development of CopperString 2.0 unlocking renewable electricity to the Mount Isa region, the opportunity to produce the metal products necessary to underpin the Net Zero by 2050 objective is even further enhanced by the use of a flow sheet that will deliver the lowest possible carbon footprint per unit of metal produced.

The planned cobalt (critical mineral) production, averaging 2750 tpa over a minimum 15-year mine life, as battery grade Cobalt Sulfate Heptahydrate, would represent the largest source of refined cobalt for Australia. In so doing, it would join Murrin Murrin as the only other producer of a finished cobalt product that is necessary to secure Australia's cobalt independence.

The role of autonomous data capture and analysis in addressing the critical minerals demand

S Hrabar[1]

1. CEO, Emesent, Milton Qld 4064. Email: stefan@emesent.io

ABSTRACT

The current Clean Energy Transition (the move to renewable energy sources, electric vehicles etc) is driving increased demand for the critical minerals needed for this transformation.

This demand is predicted to grow almost twenty-fold between 2020 and 2050, putting more pressure on the mining industry to supply these. The mining industry is also under increasing environmental, social, governance (ESG) pressure to operate more sustainably, with reduced carbon footprints. Many mining companies have set aggressive 'net-zero' targets to be achieved in the next 5–10 years as a result.

Increasing productivity while driving towards net-zero targets is an urgent and global challenge for the industry, not just in the coming decades ahead but in the immediate future.

A move to increased levels of automation and autonomy has already been identified as a viable solution for increasing productivity and safety of mining operations and progress has been made in this space (autonomous haul trucks, remotely operated loaders, haulers and dumpers (LHD's) etc). The ultimate objective is to operate 'zero entry' mines, where people are not required to work underground or in hazardous environments.

The move to zero entry mining has significant ESG benefits (besides the safety benefits), as mines will not need to be cooled or ventilated to suit human needs (ventilation can account for up to 50 per cent of a mine's power consumption). This will also enable new mining methods which more precisely target the high-grade ore, reducing waste and the associated environmental impacts (waste dumps, tailings dams etc). The reduced cost of operations will also enable the mining of lower-grade orebodies that are currently not viable based on today's mining costs and commodity prices. This will help to satisfy the growing demand for critical minerals.

To fully realise the benefits of autonomous mining operations, many other aspects of the operation will need to be automated, however. This includes many tasks that currently require 'boots on the ground' such as capturing survey and geotechnical data, inspecting areas post-blast prior to re-entry and many more. It also will require the automation of data processing tasks so that ultimately the complete end-to-end workflow from data capture to insights and decisions can be achieved with minimal human intervention.

This paper discusses data capture and processing tasks that will require automation. It presents solutions that have been developed or are currently being developed to address various operational challenges and discusses the role these tasks play in helping with the increased demand for critical minerals. In particular, the paper describes how an autonomous underground drone can be used to map stopes for end of month reconciliations (with associated automated data workflows) and how an autonomous ground vehicle can be used to conduct post-blast re-entry inspection missions. These solutions can be operated remotely from the surface and will be essential for zero entry mines of the future.

Are supergene ore deposits a guarantee of environmental, social and governance (ESG)?

M Iglesias-Martinez[1] *and J A Espi Rodriguez*[2]

1. Research Scientist, Mineral Resources, CSIRO, Kensington WA 6151.
   Email: mario.iglesias-martinez@csiro.au
2. Retired Professor ETSI Minas y Energía, Universidad Politécnica de Madrid, Madrid 28003, Spain. Email: joseantonio.espi@upm.es

ABSTRACT

Supergene ore deposits represent a significant source for precious and critical metals (CM, Au, Al, Ni, Co, V, Ti, PGE, REE, Sc etc). Current demand and rising prices for these elements have triggered an increased interest on CR supergene deposits based on their potential low-cost productivity. This is evidenced by systematic reductions in the average metal grades of new projects. Supergene deposits are close to the surface and tend to have low stripping ratios than primary mineralisation, in addition to being characterised by a greater rock friability and consuming less explosives, which means a smaller carbon footprint. However, water resources needed to process supergene deposits can be significantly high since processing clay-rich ore requires greater amounts of non-recoverable water. From a social point of view, it is challenging to attribute any differentiating property to supergene ore deposit projects compared to their primary counterparts. However, most of the supergene deposit projects are in emerging countries, where sustainable mining is an important factor and a development inducer. Oxidised and lateritic domains have historically been neglected both due to their low-grades or tonnages. Nevertheless, supergene mineralisation presents significant differences and specificities compared with other deposits and domains within the same deposit. The analysis of public reporting of supergene deposits shows a need for more rigour in characterising and evaluating these deposit types. As a result, most mining operations on weathered ores need more foundation and experience to ensure good practices and international quality standards. Therefore, the review of supergene ore deposit models with a new perspective, including their technological, economic, and environmental dimensions, based on the principle of the circular economy, is required for the global mining industry.

Technospheric mining of rare earth elements from acid crack leach tailings

Y Kannappan[1] and L Dyer[2]

1. Western Australian School of Mines: Minerals, Energy and Chemical Engineering, Faculty of Science and Engineering, Curtin University, Kalgoorlie WA 6430.
   Email: yamini.kannappan@postgrad.curtin.edu.au
2. Western Australian School of Mines: Minerals, Energy and Chemical Engineering, Faculty of Science and Engineering, Curtin University, Kalgoorlie WA 6430.
   Email: laurence.dyer@curtin.edu.au

ABSTRACT

Due to the increasing demand for critical metals, the extraction process has expanded its scope to encompass secondary sources such as slag, tailings and end-of-life materials. The primary objective of this research is to extract rare earth elements (REE) from sub-economic ores and waste streams. A novel approach currently in development involves a two-stage leaching process that utilises oxalic acid and EDTA (Ethylenediaminetetraacetic acid) as leaching agents. In the first stage, rare earth phosphate is converted into an oxalate salt, while the second stage focuses on dissolving and recovering the REE present in the solution. Combining these two stages has proven to be a unique and effective method for REE recovery. However, further investigation is required to optimise the flow sheet and better understand the behaviour of various feed types within the system. This study employs the concept of technospheric mining to extract rare earth elements from acid cracking and leach (ACL) tailings and analyse its reaction with the developed flow sheet. The experimental approach utilised a one variable-at-a-time (OVAT) method to optimise parameters such as temperature, time and reagent concentration.

Observations revealed that most of the reaction for the oxalic acid leach occurred within the first hour, reaching a plateau thereafter. Unlike other feed materials where the REEs reprecipitate, leaving Fe and P in solution among other ions in the oxalic acid leach, testing on the ACL left significant quantities of REE in solution. However, at 85°C, the recovery dropped after six hours due to the reprecipitation of elements within the system. An additional dose of oxalic acid was introduced into the reactor to explore the possibility of reprecipitating REE from the system. A brief comparison of the reaction between ACL tailings and other feedstocks will be presented for a better understanding.

Artificial intelligence in mineral exploration – enhancing sustainability and critical mineral supply

H Kaushal[1] and A Bhatnagar[2]

1. MAusIMM, PhD, Research Scholar, Department of Mining Engineering, College of Technology and Engineering, MPUAT, Udaipur, Rajasthan 313001, India.
   Email: hitanshukaushal01@gmail.com
2. Professor, Head of Department of Mining Engineering, College of Technology and Engineering, MPUAT, Udaipur, Rajasthan 313001, India. Email: anup10@rediffmail.com

ABSTRACT

This abstract investigates the profound impact of artificial intelligence (AI) within the domain of mineral exploration, with a primary emphasis on ensuring a sustainable supply chain for critical minerals. The study area, characterised by a complex interplay of verdant landscapes, leased territories and rugged topography, underscores the pivotal importance of road connectivity to existing mineral leases. Against this backdrop, the integration of AI-driven drone technology emerges as a transformative force. This region encompasses quartz, quartzite, China clay, silica sand, and other indispensable critical minerals with multifaceted applications across diverse industries.

By harnessing AI-powered drones, we undertook a meticulous examination of mineral reserves, analysing their geological features, outcrops and extensions with unparalleled precision. These endeavours culminated in the creation of a highly detailed 3D model of the intricate hilly terrain, affording a comprehensive understanding of its topographical intricacies. Beyond its role in optimising mining operations, this 3D model has redefined infrastructure planning, offering a multidimensional view of the landscape that enables the pinpointing of locations conducive to minimal environmental impact. Furthermore, it facilitated the identification and assessment of the distribution and concentration of quartz, quartzite, China clay and critical minerals, thus laying the foundation for strategically targeted mining ventures.

The primary aim of the drone mapping initiative was to unveil the geological extensions of quartz and quartzite and their adjoining regions, spanning a substantial expanse of 711.13 hectares along an east–west flight path. The establishment of ground control points, meticulously executed in collaboration with advanced DGPS technology-equipped Rovers, underpinned the precision of these groundbreaking experiments. This abstract delves into the results, providing comprehensive insights into their implications.

This case study extends beyond a mere mineral composition assessment to encompass the critical acquisition of revenue land details that profoundly shape mining leases and operational strategies. The assimilation of AI-driven drone technology emerged as instrumental in quantifying mineral reserves through an exhaustive examination of geological formations, outcrops and extensions. The resultant 3D model significantly enriched our comprehension of the region’s topography, affording an enhanced foundation for the formulation of effective blueprints for proposed mining operations. This comprehensive model provided invaluable insights into the structural composition of the land, transcending traditional perspectives.

In summation, this abstract offers a pioneering demonstration of the transformative synergy between AI and drone technology in the realm of mineral exploration. This convergence optimises resource assessment, elevates environmental consciousness and strategically targets critical mineral deposits. By advancing sustainability and bolstering the global supply chain for essential and critical minerals, this amalgamation stands poised to catalyse innovation across a spectrum of industries and technologies in the foreseeable future.

Concentrating lithium brine by CSIRO membrane distillation technology

A Khosravanihaghighi[1], J Cooper[2] and T Van Der Laan[3]

1. CSIRO, Lindfield NSW 2070. Email: ayda.khosravanihaghighi@csiro.au
2. CSIRO, Lindfield NSW 2070. Email: james.cooper@csiro.au
3. CSIRO, Lindfield NSW 2070. Email: tim.vanderlaan@csiro.au

ABSTRACT

Extraction of lithium from brines featuring very low concentrations of lithium presents significant challenges and is typically not economically feasible (Xu *et al*, 2021). The conventional method to extract lithium is through staged solar evaporation of water from brine ponds. This requires large-scale infrastructure, long time scales (typically beyond 2 years), and wastes a significant volume of water (Vera *et al*, 2023). Further, it is typically done in arid environments where there is competing interests for water from other sectors, in particular domestic use, and leaves a substantial environmental footprint (typically in excess of 10 000 m^2) (Cha-umpong *et al*, 2021). Lithium can also be found in mining tail water, although the concentration may vary depending on the geological conditions and the mining operation (Ferreira *et al*, 2022). Alternatively, mine tailings can also feature lithium however, concentrations are typically lower than lithium brines (Sanjuan *et al*, 2022). Developing an effective filtration technique capable of concentrating the lithium-enriched solution could potentially provide economic justification to extract lithium from different sources and reduce the need for evaporation ponds.

This work explores a membrane-based alternative method to the way lithium is extracted from lithium mining tail water and brine. CSIRO's Membrane Distillation Technology can process dilute lithium brines to produce concentrated solutions. These processes are also being developed to selectively remove the other salts from the solutions. These processes have already been successful at concentrating low lithium-brines (as shown in Figure 1) by a factor of 2. Critically they also harvest a pure water stream. This technology suite also has the capacity to be environmentally friendly, cost-effective and energy efficient.

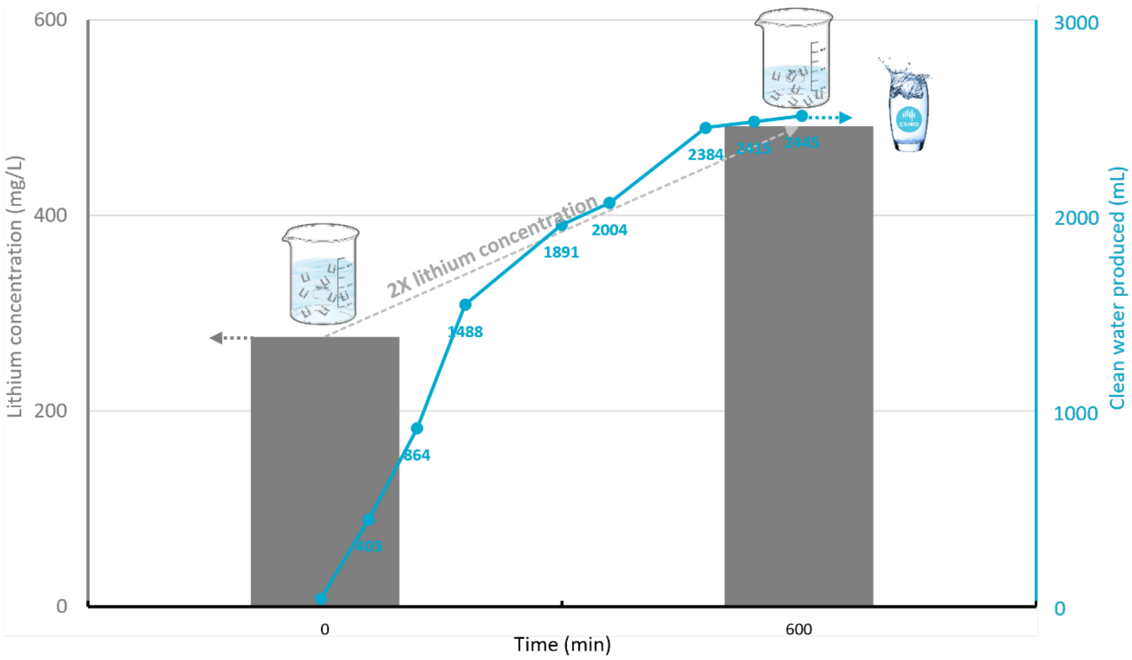

FIG 1 – Bar chart: Lithium concentration increase. Point chart (blue colour): clean water produced over short 600 min operation time. Line provided as a guide and does not suggest a trend.

REFERENCES

Cha-umpong, W, Li, Q, Razmjou, A and Chen, V, 2021. Concentrating brine for lithium recovery using GO composite pervaporation membranes, *Desalination*, 500:114894. https://doi.org/10.1016/j.desal.2020.114894

Ferreira, M F S, Capela, D, Silva, N A, Gonçalves, F, Lima, A, Guimarães, D and Jorge, P A S, 2022. Comprehensive comparison of linear and non-linear methodologies for lithium quantification in geological samples using LIBS, *Spectrochimica Acta Part B: Atomic Spectroscopy*, 195:106504. https://doi.org/10.1016/j.sab.2022.106504

Sanjuan, B, Gourcerol, B, Millot, R, Rettenmaier, D, Jeandel, E and Rombaut, A, 2022. Lithium-rich geothermal brines in Europe: An up-date about geochemical characteristics and implications for potential Li resources, *Geothermics*, 101:102385. https://doi.org/10.1016/j.geothermics.2022.102385

Vera, M L, Torres, W R, Galli, C I, Chagnes, A and Flexer, V, 2023, Environmental impact of direct lithium extraction from brines, *Nature Reviews Earth and Environment*, 4(3):149–165. https://doi.org/10.1038/s43017-022-00387-5

Xu, S, Song, J, Bi, Q, Chen, Q, Zhang, W-M, Qian, Z, Zhang, L, Xu, S, Tang, N and He, T, 2021. Extraction of lithium from Chinese salt-lake brines by membranes: Design and practice, *Journal of Membrane Science*, 635(2021):119441. https://doi.org/10.1016/j.memsci.2021.119441.

Critical minerals in a world of transactional diplomacy – where Australia sits in relation to China, the US and the EU

M Kirby[1]

1. Managing Partner, Sharpe and Abel, Melbourne Vic 3000.
   Email: melissa.kirby@sharpeandabel.com

ABSTRACT

That critical minerals are, in fact, critical is not in doubt, even though the political will and funds to effect a clean energy transition are perhaps less certain.

There is the American-led Minerals Security Partnership, the Canadian-led Sustainable Critical Minerals Alliance, the EU's new industry policy, including existing initiatives such as the Critical Raw Materials Act as well as China's long-term strategy that it started executing 30 years ago.

Where does Australia sit among the jungle of policies and cross-border initiatives, given its existing relationship with all of them? How secure are diplomatic and trade relationships that Australia already has and to what extent can Australia rely on them to form the basis for investment? Does the rhetoric about geopolitical alliance and trying to break existing monopolies have any bearing on investment decisions?

We will identify the key strands of the actual policy positions of China, the US and the EU that lie behind the rhetoric. We then proceed to examine this landscape of geopolitical relations and the extent to which those relations support Australia's aim to build a critical mineral processing industry. Then, we will analyse and evaluate the risks and the opportunities for Australian policy makers to support investment into the critical minerals processing industry as Australia navigates the uncertain world of transactional diplomacy.

Characterisation of clay-hosted REE projects in WA

M Knorsch[1], A Piechocka[2], M Gazley[3], M Kartal[4], K Lilly[5] and E Trunfull[6]

1. Consultant Geoscientist, RSC, West Perth WA 6007. Email: m.knorsch@rscmme.com
2. Principal Geoscientist, RSC, West Perth WA 6007. Email: n.piechocka@rscmme.com
3. General Manager Geoscience, RSC, Wellington 6010, New Zealand. Email: m.gazley@rscmme.com
4. Project Mineralogist, RSC, West Perth WA 6007. Email: m.kartal@rscmme.com
5. Principal Geoscientist, RSC, Dunedin 9054, New Zealand. Email: k.lilly@rscmme.com
6. Consultant Geoscientist, RSC, West Perth WA 6007. Email: e.trunfull@rscmme.com

ABSTRACT

Rare earth elements (REEs) are in high demand due to their application in renewable technologies and electromobility. Recent REE exploration has focused on clay-hosted REE deposits that contain a high proportion of valuable heavy REEs (including terbium and dysprosium), used to enhance the high-temperature properties of permanent magnets. Clay-hosted REE deposits are typically low-grade and high-tonnage and resource estimates in Western Australia report from ~500 to 1400 ppm total rare earth oxide (TREO), lower than carbonatite deposits that typically grade >10 000 ppm TREO. Academic research to date has been largely restricted to clay-hosted REE deposits in China, and little is known about the mineralogy and viability of REE clay projects in Australia.

A preliminary review of exploration activity identified 61 clay-hosted REE projects in Australia. The majority of those projects (43) are within WA, and they are predominantly located in areas with granitic bedrock in the Esperance Region and central Yilgarn Craton. Almost all discoveries in Australia were made within the last two years and information on their mineralogy and genesis, and by extension effective exploration strategies, is limited.

To address these knowledge gaps, RSC instigated a research project in June 2023 co-funded by the Minerals Research Institute of WA (MRIWA), RSC, and eight participating exploration companies (Auric Mining, Dreadnought Resources, Golden Mile Resources, HRE, MTM Critical Metals, Mount Ridley Mines, Terrain Minerals, Voltaic Strategic Resources). In this study, we examine the mineralogical and geometallurgical characteristics of clay-hosted REE mineralisation using scanning electron microscopy (SEM), X-ray diffraction (XRD), hyperspectral analyses, various geochemical analysis techniques and leaching tests.

An SEM study of Australian clay-hosted REE projects has identified the presence of primary REE-bearing minerals including allanite, apatite, Ca-REE fluorocarbonate, fluorite, monazite, xenotime, titanite and zircon. These primary magmatic minerals occur within granitic source rocks and release REEs upon weathering. In the clay horizon, some primary granular monazite remains intact, suggesting that at least some REEs remain immobile and locked within primary magmatic minerals during weathering. In other instances, monazite is partly dissolved at the expense of secondary acicular rhabdophane [$REE(PO_4){\cdot}nH_2O$] which precipitates during the breakdown of monazite. Rhabdophane is abundant in the clay horizon of multiple REE clay projects and hosts a portion of the REE content, which is not adsorbed onto the surface of clay minerals.

There is enormous potential in clay-hosted REE projects in WA but the knowledge base across the geoscience community is low. Through this project, we aim to upskill geoscientists across the industry, develop best-practice analytical workflows and reporting protocols, characterise the deportment of REEs, draw metallurgical conclusions, and break down the mineralogical complexity of clay-hosted REE projects.

Exploring hyperspectral technologies for rapid identification of rare earth elements across scales

C Laukamp[1], I C Lau[2], H M Lampinen[3] and B Pejcic[4]

1. Principal Research Scientist, CSIRO Mineral Resources, Discovery Program, Perth WA 6151. Email: carsten.laukamp@csiro.au:
2. Senior Experimental Scientist, CSIRO Mineral Resources, Discovery Program, Perth WA 6151. Email: ian.lau@csiro.au:
3. Research Engineer, CSIRO Mineral Resources, Discovery Program, Perth WA 6151. Email: heta.lampinen@csiro.au
4. Senior Research Scientist, CSIRO Mineral Resources, Discovery Program, Perth WA 6151. Email: Bobby.Pejcic@csiro.au

ABSTRACT

Rare earth elements (REE) are essential for a wide range of industries, including high-tech electronics and renewable energy technologies. However, the supply chains for many REEs are fragile and the minerals industry is exploring new technologies that support the rapid identification of REEs across scales.

This presentation provides an overview of the latest 'REE-tuned' spectral sensing technologies that allow the rapid identification of selected REEs and their host minerals. Furthermore, the gaps in technological development are highlighted that could improve the exploration for and characterisation of REE-deposits.

Visible-near infrared (VNIR) reflectance spectroscopy has been shown to be an efficient method for identifying neodymium (Nd) in the field and drill core sheds. However, the spectral resolution of most commercially available reflectance spectrometers is too coarse to discriminate Nd from potentially overlapping dysprosium (Dy)-related absorptions. Depending on the mineral assemblage, other REEs that can be detected across the VNIR and short wave infrared (SWIR) include praseodymium (Pd), samarium (Sm) and erbium (Er). A main challenge for detecting these REE-related absorption features is the presence of other, more dominant absorbers, such as ferrous and ferric iron. Better spectral reference libraries are required to address non-unique unmixing solutions of the collected spectra. Despite these challenges, preliminary studies have demonstrated that Nd can be detected by means of airborne and even spaceborne hyperspectral sensors. This opens a huge potential for REE-exploration at the regional scale. Furthermore, the combination of VNIR-SWIR with hyperspectral thermal infrared sensors allows the characterisation of the mineral assemblage hosting the REEs. This is shown by case studies currently developed by the Australian National Virtual Core Library (NVCL) infrastructure program, which hosts a collection of hyperspectral drill core data sets from a wide range of Australian REE-deposits, including carbonatite-related (Mt Weld, Cummins Range; WA), peralkaline-hosted (Toongi; NSW) and apatite vein-hosted (Nolans Bore; NTGS).

Get your mine funded – how they did it

G Lee[1] and P Leung[2]

1. Partner, Model Answer Commercial Analytics, Perth WA 6000.
   Email: gavin.lee@modelanswer.com.au
2. Principal, Naust Capital, Perth WA 6000. Email: patrick@naust.com.au

ABSTRACT

This is a presentation about the complex dynamics involved in securing finance for mining projects. By leveraging historical funding data and industry experiences, the presentation aims to simplify the multifaceted landscape of project funding in the mining industry. Attendees will benefit from practical advice rooted in proven financing practices, empowering them to advance their own mining project funding journeys. An analysis of contemporary project funding data will highlight key trends and essential factors that lead to successfully financing ventures.

The presentation will examine the crucial role of equity markets in development funding, dispelling common misconceptions and highlighting the full gamut of funding support available. To underscore these principles, the presentation will focus on some case studies. In addition, the presentation will glimpse into current project financing trends and shed light on the Government's crucial role in supporting critical minerals projects. Set to be both interactive and insightful, this presentation promises to reveal the strategic underpinnings of successful mining project financing, providing attendees with the opportunity to fine-tune their own funding strategies.

Recovering critical minerals from mining wastes

C Lenzo[1], S Ulrich[2] and J Gillow[3]

1. Senior Environmental Engineer, Arcadis, Sydney NSW 2000.
   Email: courtney.lenzo@arcadis.com
2. Senior Scientist, Arcadis, Highlands Ranch CO 80129, United States.
   Email: shannon.ulrich@arcadis.com
3. Technical Expert, Arcadis, Highlands Ranch CO 80129, United States.
   Email: jeffrey.gillow@arcadis.com

ABSTRACT

The transition to renewables, including electric vehicles, wind turbines and photovoltaics, is rapidly increasing demand for critical minerals and rare earth elements (CM/REE). However, conventional ore deposits for many of these elements are limited, and select countries hold a monopoly on the supply of certain CM/REE.

Mining waste has potential as an alternative source of critical minerals. Many commonly mined metals are collocated with CM/REE. For example, rhenium, selenium and tellurium are concentrated in minerals associated with porphyry copper deposits, along with rare earth elements including neodymium and praseodymium. Energy-critical elements are also associated with gold deposits in alkaline igneous rock, including tellurium and indium.

Australia is well suited to CM/REE recovery from waste due to its well-established mining industry and the ongoing challenge of waste management, both during operation and mine closure. CM/REE recovery from waste not only presents an additional revenue stream, but waste's hazardous characteristics, often acidity and high metals content, are at least partially addressed during the recovery process.

To assess site potential for CM/REE resource recovery, key considerations include mine geology and geochemistry and the site's historic operations and current conditions. The assessment also includes an engineering component to identify strategies for recovering CM/REE from waste media and possible synergies with existing water management and treatment equipment. This information along with factors such as mineral resale prices and recovery efficiency are used to estimate the potential value of identified CM/REE, defining the focus of future efforts.

This presentation reviews the initial resource assessment and investigation process. It will discuss both the occurrence of CM/REE in mining waste and process engineering approaches to recovery at operating mines and mines undergoing reclamation, including a case study. Mining wastes present a sustainable opportunity to help meet CM/REE demand.

Carbothermic reduction for lithium metal production – LithSonic™: process development update

D Liu[1], L Melag[2], T Barton[3], W Bruckard[4], D Freeman[5] and C Chen[6]

1. Research Scientist, CSIRO Mineral Resources, Clayton Vic 3168. Email: dongmei.liu@csiro.au
2. CERC Postdoctoral Fellow, CSIRO Mineral Resources, Clayton Vic 3168. Email: leena.melag@csiro.au
3. Senior Engineer, CSIRO Mineral Resources, Clayton Vic 3168. Email: tim.barton@csiro.au
4. Research Group Leader, CSIRO Mineral Resources, Clayton Vic 3168. Email: warren.bruckard@csiro.au
5. Senior Experimental Scientist, CSIRO Manufacturing, Clayton Vic 3168. Email: david.freeman@csiro.au
6. Principle Research Scientist, CSIRO Mineral Resources, Clayton Vic 3168. Email: chunlin.chen@csiro.au

ABSTRACT

Lithium metal shows immense potential as a replacement for the incumbent graphite as anode material in lithium batteries, offering potentially enhanced energy density for these battery systems. With extensive ongoing research focused on this step change, demand for lithium metal will greatly increase in the near future. However, obtaining high-purity metallic lithium reliably has proven to be a significant challenge. The current industrial electrolysis process for lithium metal production suffers from severe environmental issues due to emission of toxic chlorine gas. It is imperative to develop more sustainable processes for metal production to meet the growing demand for this critical metal and ensure a secure supply for sovereign countries.

An innovative process, LithSonic™, has been developed and patented by CSIRO for producing lithium metal. It involves carbothermic reduction of lithium oxide to generate lithium metal vapour, followed by a rapidly quenching process employing a de Laval nozzle to directly convert the produced vapour into lithium metal powder, minimising the occurrence of the reversion reaction commonly observed otherwise. This process offers several advantages over the existing electrolysis route.

Laboratory work is currently underway to demonstrate the LithSonic™ process at kg-scale and an update on progress is provided. Specifically, studies establishing optimal process conditions for the reduction step coupled with thermodynamic modelling and small-scale fundamental experimental work to develop insights into the melt and gaseous chemistry at elevated temperatures are described. The insights from this work have been invaluable in progressing development and scale up of this technology paving the way for further advancements in lithium metal battery technology.

Innovative process for extraction of metals from end-of-life lithium-ion batteries for cathode synthesis

J Lu[1], K Mumford[2], G Stevens[3] and W Li[4]

1. Research Fellow, The University of Melbourne, Parkville Vic 3010.
   Email: john.lu1@unimelb.edu.au
2. Head of Chemical Engineering Department, The University of Melbourne, Parkville Vic 3010.
   Email: mumfordk@unimelb.edu.au
3. Emeritus Laureate Professor, The University of Melbourne, Parkville Vic 3010.
   Email: gstevens@unimelb.edu.au
4. Research Fellow, The University of Melbourne, Parkville Vic 3010.
   Email: wen.li@unimelb.edu.au

ABSTRACT

This presentation introduces a hydrometallurgical process for efficiently recovering metals, including lithium, cobalt, nickel, manganese and iron from end-of-life lithium-ion batteries. The main objective is to reduce the associated recycling costs. The process focuses on refining the black mass leachate, obtained from lithium-ion battery recycling facilities and to produce a battery-grade precursor solution for manufacturing lithium-ion battery cathode materials.

The method involves a sequence of liquid-liquid extraction and stripping steps with advanced operating controls, enabling the separation of multiple battery metals using a single organic solvent. This eliminates the need for multiple solvents and subsequent extraction and purification steps, thereby preventing solvent contamination. Stripping is performed in cascading units, resulting in multiple streams enriched with battery metals, that can be directly used to manufacture new lithium-ion battery precursor materials.

A key novelty of this study lies in the avoidance of individually separating and purifying of metals. Instead, solvent extraction process is adjusted with varying operating conditions based on the changing feeding solution. The novel approach generates streams with mixed compositions that align stoichiometrically with the production of cathode active material precursors. This innovative strategy significantly reduces costs when compared to conventional recovering strategies, making it highly recommended for lithium-ion battery circular economy.

The method can be applied to a wide range of black mass leachate derived from the recycling industry of end-of-life lithium-ion batteries. It produces battery-grade solutions for production of cathode materials without further purification. The cost-efficient and versatile proposed represents a big step towards closing the loop of the circular economy in the battery industry. By presenting this process, our aim is to contribute to the ongoing dialogue on battery recycling and waste utilisation, specifically in the context of achieving a sustainable value chain for lithium-ion batteries.

Critical minerals and the global clean energy transition – assessing national strategies and Australia's potential contribution to supply chain resilience

R Markoski[1]

1. Director, IME Consultants, West Perth WA 6005.
   Email: robert.markoski@imeconsultants.com.au

ABSTRACT

The author examines the growing global demand for critical minerals in the context of the clean energy transition and provides a comparative analysis of the policies and strategies adopted by major consuming countries, including the US, China, Japan, and South Korea, to secure access to critical minerals. Focusing on Australia's role as a potential supplier, the author evaluates the effectiveness of different strategies, such as domestic production, international cooperation, and stockpiling, in addressing the supply risks associated with critical minerals. Whilst also examining the implications of these strategies for the competitiveness of industries, the environment, and geopolitical relationships, and the potential impact of Australia's critical mineral production on the global supply chain.

Innovative financing mechanisms for critical mineral exploration and development – a global overview

R Markoski[1]

1. Director, IME Consultants, West Perth WA 6005.
   Email: robert.markoski@imeconsultants.com.au

ABSTRACT

The author will provide a global overview of innovative financing mechanisms for critical mineral exploration and development; by assessing the role of various financial instruments, such as green bonds, blended finance and public-private partnerships, in mobilising capital for the critical minerals sector. The study explores the potential of crowdfunding and other alternative financing models to address funding gaps and reduce financial risks for investors. And concludes with recommendations on how governments, financial institutions and industry stakeholders can collaborate to promote investment in critical mineral projects.

The challenges of the creation of a lithium-ion battery recycling ecosystem

J Masson[1]

1. VP Strategy, ERAMET, Paris, France. Email: julien.masson@eramet.com

ABSTRACT

Eramet has been researching lithium-ion battery recycling, and is proposing to build a European-based facility.

This project, on which Eramet has been engaged since 2018, is fully aligned with Eramet's strategic roadmap and purpose to 'become a reference for the responsible transformation of the Earth's mineral resources', by closing the loop at the end of the battery value chain. It will ensure a responsible use of the metals it produces (nickel, cobalt and lithium).

The project started with an initial R&D program supported with an engineering benchmark on existing technologies. Following promising market conditions and a preliminary scoping business, a PFS (Pre-Feasibility Study) was launched in 2022 to firm up assumptions and update business models for the construction of the first recycling plant in Europe.

The start of a recycling activity comes with many challenges.

Battery recycling itself is an already existing process, but it must be optimised to be competitive and adapted to local requirements. The full process of recycling has therefore been tested in Eramet R&D lab facilities, process improvements have been identified and a demonstration plant at a 1/1000th scale is currently under construction and planned to start at the end of September 2023. This demonstration plant will be used to test the innovative part of the process, to train future employees and to produce commercial samples.

The biggest unknown lies in the underlying business model where no market currently exists outside of Asia. Where a traditional mining company would rely on an orebody to derive its business plan, a recycling project needs to go through partnership agreements to secure its feedstocks, with no visibility on pricing models that could emerge over time. The only certainty is that volumes to recycle both from end-of-life vehicles and scraps from battery makers should grow significantly over time and that there will be many synergies between actors in the value chain.

The success of a li-ion recycling project therefore lies in the creation of an ecosystem where metal companies collaborate with scrap collection companies, car manufacturers and battery makers.

Field instrumentation advancements for critical minerals processing

T McKertich[1] and M Kiem[2]

1. Regional Industry Manager – Mining, Endress+Hauser, Artarmon NSW 2064.
   Email: taylor.mckertich@endress.com
2. Strategic Account Manager, Endress+Hauser, Osborne Park WA 6017.
   Email: matthew.kiem@endress.com

ABSTRACT

As the demand of critical minerals increases with the energy transition, mining operations are forced to process lower grade ores, harder to process deposits and further purify final product more than ever before. These changes in feed for processing plants in the critical minerals industry have migrated towards the use of more intensive processing and harsher applications that reach the limit of existing sensor technology.

In this paper, technologies, and applications of in-line instruments to bring lab sampling data and previously not available information into field sensors in the critical are explored. Liquid analysis parameters are focused on as this field is evolving the fastest and is most crucial for optimising critical minerals processing. The more information that is available from the field, the easier it is to optimise the process for critical mineral plants.

In addition to the trend of bringing lab measurements to the field, a summary of best practices in critical mineral processing plants to reduce maintenance cost, improve accuracy and reliability of measuring points is discussed. Case studies from lithium, rare earth and nickel processing field instrumentation applications are also included.

Greenfield critical minerals projects – managing complexity and uncertainty with strategic system of systems integration

A McLean[1] and C McRae[2]

1. Partner and Large Capital Projects Strategic Advisor, DTP Partners, Brighton Vic 3186. Email: andrewm@dtp.partners
2. Partner and Large Capital Projects Strategic Advisor, DTP Partners, Bellingen NSW 2454. Email: cameronm@dtp.partners

ABSTRACT

The energy transition necessitates a significant increase in greenfield critical mineral mines and processing plants. These megaprojects pose major challenges for companies, with budgets often exceeding US$1 billion and development horizons of a decade plus. In contrast to many brownfield projects, greenfield projects face heightened complexity and uncertainty, in unfamiliar locations and jurisdictions, with increased stakeholder involvement, longer lead times, more decisions and material overall impacts. These challenges will be further amplified as the energy transition progresses, by factors such as more complex orebodies, geo-political pressures and extended value chains with joint venture partners, gaps in infrastructure, skills and institutions, evolving technologies, and ever-higher environmental, social, and governance (ESG) requirements.

This is important, as research emphasizes the poor delivery record, where a majority of projects fail to meet their schedule and cost goals, their business case objectives, or both. A key reason for project underperformance is the inadequate management of complexity including the resulting interdependencies between the parts within the project, with the broader owners' organisation, external stakeholders and more delivery partners which collectively creates greater uncertainty. In addressing complexity, the corporate focus is too often weighted toward technical dependencies inside the mine fence. Failure to manage the broader drivers of complexity through effective systems integration places planned milestone dates and the overall business case at significant risk. And this is at a time when critical mineral projects must be accelerated to meet energy transition targets and to deliver the corporate promises to stakeholders.

This paper utilises multiple case studies from greenfield and large brownfield projects drawing upon research on megaprojects in other industries; and complexity theory, to argue that an additional level of program management is necessary for strategic system of systems (SSoS) or meta-systems integration. We present different models of SSoS to establish governance structures to ensure alignment, cooperation, and coordination among sponsors, owners, operators, clients and delivery partners. Notably, this project delivery capability is often missing and/or under-resourced within the owners' team or the client delivery organisation. For aspiring developers or mid-tier miners, this responsibility too often falls to the overstretched CEO. We argue that flexible and adaptive SSoS integration is essential for greenfield mining projects to manage the critical path from discovery to delivery of the full potential of the opportunity.

Securing project approvals for emerging technology involving nickel and cobalt processing facilities

A McRae[1], D Falconer[2], E Campbell[3] and S Grocott[4]

1. Senior Environmental Scientist, EMM Consulting Pty Ltd, Brisbane Qld 4000. Email: amcrae@emmconsulting.com.au
2. Associate Environmental Planner, EMM Consulting Pty Ltd, Brisbane Qld 4000. Email: dfalconer@emmconsulting.com.au
3. Senior Environmental Engineer, EMM Consulting Pty Ltd, Brisbane Qld 4000. Email: ecampbell@emmconsulting.com.au
4. CEO/MD, Queensland Pacific Metals Pty Ltd, Brisbane Qld 4000. Email: sgrocott@qpmetals.com.au

ABSTRACT

Queensland Pacific Metals (QPM) proposes to construct and operate the Townsville Energy Chemicals Hub (TECH) Project, a new high purity battery materials refinery processing imported laterite ore to produce high-grade nickel sulfate, cobalt sulfate and other products such as hematite and high-purity alumina. The primary products will be used in batteries for the rapidly expanding electric vehicle markets. The refinery utilises the proprietary Direct Nickel Process™ (DNi), a closed loop extraction method. This process recovers the main lixiviant, nitric acid and saleable products and minimises waste outputs compared to traditional HPAL nickel refineries. A key advantage of the DNi process™ is the absence of a wet tailings by-product instead prioritising the conversion of the ore product into saleable by-products. The waste product, comprising approximately 20 per cent of the initial ore mass, is an inert silica rich residue which does not require a tailings dam. The residue is currently undergoing re-classification as a marketable product beneath Queensland's End of Waste framework. Future approval of the End of Waste Code will result in the TECH project having unparalleled ESG credentials.

Assessing environmental impacts, obtaining statutory approvals and securing a social license to operate this emerging technology has been a complex process. EMM Consulting on behalf of QPM has led the environmental and statutory approvals for the project and supported QPM's engagement with Traditional Owners, the wider community and regulatory authorities.

The approvals process required extensive and collaborative engagement with local, State and Commonwealth agencies and, in many instances, required a partnership approach during assessment to achieve project timelines. Evolution of the project design (process, layout and function) required adapting typical environmental assessment methodologies to allow for ongoing design optimisation. An iterative assessment approach was employed to share key information and technical results with regulatory agencies as design confidence matured.

Social impact and community engagement (including Traditional Owner engagement) commenced early in the assessment process prior to application materials being submitted. The project was re-designed following stakeholder engagement to reflect community expectations and avoid impacts on surrounding land uses.

QPM demonstrated that the DNi Process™ would achieve an acceptable environmental performance at a commercial scale by adopting a 'beyond-compliance' assessment ethos that demonstrated best practice stewardship for biodiversity offsets, air, water, noise and waste management.

Primary approvals for the project were secured in December 2022. QPM is currently working through 'operational amendments' to primary approvals with EMM.

The impact of deglobalisation and geopolitics on the supply of critical minerals

G Njowa[1] and A Beifus[2]

1. Associate Partner, EY, Johannesburg, Gauteng. Email: godknows.njowa@za.ey.com
2. Global Lead Mining and Metals Analyst, EY, Sydney NSW 2000.
   Email: angie.beifus@au.ey.com

ABSTRACT

The structural forces of deglobalisation and geopolitical trade tensions are fuelling resource nationalism as the energy transition accelerates.

Global geopolitical uncertainty, eg the war in Ukraine and the current US–China tensions, pose **the most significant risks to the global economy this year and beyond**. Russia's invasion of Ukraine has rapidly inflated energy prices, caused supply chain disruption and has *fuelled fragmentation and the emergence of geopolitical blocs*. As a result, there has been a dramatic reduction in cooperation among major powers.

Within this volatile environment, the race for minerals and metals required for the energy transition is accelerating and so too are a range of incentives and restrictions. Many governments are introducing initiatives aimed at fast tracking renewables while also reducing reliance on other countries, particularly strategic rivals and in critical sectors. The pursuit of self-sufficiency is creating a plethora of green incentives and subsidies, including the EU strategic autonomy agenda and *US Inflation Reduction Act (IRA)*. These are influencing investment, with countries re-shoring technology and energy, as well as the mining and processing of minerals and metals.

There are also concerns that climate change-related regulations and subsidies in developed countries will exacerbate the global wealth divide. Countries are scrambling for influence in, and access to, mineral resources in emerging markets, attempting to balance economic interests with regional stability and governance concerns. In Africa, investment from China means governments have become more indebted to the country. But China's dominance could be threatened, with both the EU and US eyeing Africa's role in the battery metal value chain, offering indirect support through incentives and grants.

In addition, with demand for critical minerals high, countries with these valuable resources are moving to optimise their economic returns. We expect to see an increase in government participation in mining, as well as more taxes, royalties and restrictions. In some countries, critical minerals may be nationalised or increased government participation.

Mining companies will need to be agile, ready to manage the risk of losing assets as governments increase control, while also being open to capturing new opportunities.

Discounted cash flow analysis of a process for vanadium extraction from titaniferous slag

S B Nkosi[1], X C Goso[2], T Mokone[3], J Petersen[4] and T K Bungane[5]

1. Research Scientist, Mintek, Gauteng, Johannesburg 2125, South Africa.
   Email: sanelen@mintek.co.za
2. Head: Technology Development, Mintek, Gauteng, Johannesburg 2125, South Africa.
   Email: xolisag@mintek.co.za
3. Senior Lecturer, University of Cape Town, Western Cape, Cape Town 7700, South Africa.
   Email: thebe.mokone@uct.ac.za
4. Professor, University of Cape Town, Western Cape, Cape Town 7700, South Africa.
   Email: jochen.petersen@uct.ac.za
5. Techno Mineral Economist, Mintek, Gauteng, Johannesburg 2125, South Africa.
   Email: thandukwazib@mintek.co.za

ABSTRACT

Vanadium (V) is listed as a critical raw material by the European Union for which the supply might be at risk. Commercial V extraction from titaniferous magnetite resources is achieved through V primary production or V and steel co-production processes. The co-production process contributed about 73 per cent of the global V production in 2021. This process produces large volumes of a by-product slag, referred to as titaniferous slag, which can contain significant concentrations of residual V. A modified V primary production process has been proposed for the extraction of V from the titaniferous slag containing about 0.9 per cent V_2O_5 left behind by the now-defunct Evraz Highveld Steel and Vanadium Corporation in South Africa as a case study. The residue from the modified V primary production process is rich in titania (TiO_2) and has potential to produce TiO_2 feedstock. In the current study an economic analysis using the Discounted Cash Flow (DCF) modelling approach is presented to investigate the economic viability of the proposed process. Economic indicators such as the internal rate of return, net present value and payback period have been determined for the evaluation of the technical viability of the proposed process and identification of specific stages in the process that need further optimisation. The economic viability of the proposed process is sensitive to variation in the OPEX, with the fact that the V resource is contained in a by-product slag, which is easily accessible, contributing significantly to the economics of the process. The DCF analysis of the proposed process indicates that the valorisation of the by-product solids to produce a TiO_2 feedstock has the potential to maximise the process economics and realise bulk utilisation of the titaniferous slag.

Lithium pegmatite deposits – a geometallurgical approach

J Oppelaar[1]

1. Senior Geology Consultant, Mining Plus, Perth WA 6105.
   Email: jamie.oppelaar@miningplus.com.au

ABSTRACT

As companies look to develop lithium pegmatite prospects into operating mines, a multidisciplinary approach to deposit modelling and economic evaluations must be considered. The integration of geological, mineralogical, and metallurgical information to form a geometallurgical (GeoMet) model is required to ensure that the specifications and recoverability of the spodumene concentrate (SpodCon – $AlLi(SiO_3)_2$) are realised and met upon initial production, ensuring the quality of the final product and optimising the value of the prospect.

The merit of a lithium-bearing pegmatite prospect relates directly to its ability to produce a lithium-rich SpodCon that is suitable for lithium carbonate or hydroxide production. The SpodCon must meet the specific requirements set by potential customers, which are dictated by the intended downstream application. These specifications include requirements for a minimum Li_2O (lithia) grade, plus upper limits of deleterious elements, such as iron (Fe) and manganese (Mn).

The production of a SpodCon usually relies on physical separation methodologies, such as dense media separation and/or flotation. These processing methods call for distinct physical properties of the pegmatite material, which can be highly variable at the regional and deposit scale. Due to the nature of its emplacement and associated magmatic fractional crystallisation, the skin of a pegmatite contacting the host rock is often physically and chemically unique to that of the core. This finer-grained and often mineralogically variable material at the margins can lead to reduced recoverability compared to the coarser-grained, spodumene-rich interior.

The local and regional chemical variation affects the deportment of lithium and associated deleterious elements. Lithia grades alone do not directly represent the presence of spodumene, nor the value of a pegmatite. Lithia-bearing minerals such as petalite and/or lepidolite necessitate alternative treatment techniques to that of spodumene. In addition, the post-emplacement hydrothermal alteration of spodumene may impact processing efficiencies and material quality due to the pseudo-morphic replacement of spodumene with micaceous mineral assemblages.

Quantifying the value of a lithium pegmatite prospect requires an intricate understanding of the physical and chemical characteristics of the pegmatite, which influence the product specifications and consequent quality of the SpodCon produced.

Lithium – the element of surprise

C Perks[1]

1. Principal Analyst, Benchmark Mineral Intelligence, Melbourne Vic 3000.
   Email: cperks@benchmarkminerals.com

ABSTRACT

Lithium is now a vital component of modern life.

Previously dominated by industrial end uses such as metallurgy, refractories and air filtration, lithium is now an essential component in lithium-ion batteries (LiBs), the main end use for which is now electric vehicles (EVs). EVs are in high demand due to consumer preference, increasing level of automakers adopting EV models, as well as government incentives and emissions targets related to decarbonisation. This hastened global uptake of EVs has led to a forecasted base case growth rate of 14 per cent compound annual growth rate (CAGR) for lithium demand over the next ten years.

But while lithium is experiencing an unprecedented level of growth linked to something that is likened to a new industrial revolution, supply is far from certain. The nascency of the market has meant that there have been extreme fluctuations in lithium prices. In 2012, spodumene prices were ~\$300/t while lithium carbonate was ~\$5000/t. Just five years later, spodumene rose close to \$1000/t and lithium carbonate prices spiked to \$21 500/t. But EV penetration rates were just 1.3 per cent, having doubled in the space of about two years. This meant that while growth was strong, supply was able to keep up; in 2018, the market experienced an influx of spodumene concentrate and direct shipping ore (DSO) from Australia. Prices began to decline, hitting lows of ~\$375/t in late 2020 for spodumene and ~\$7950 for carbonate.

In 2021, as investment in new projects tapered off, supply waned and projects consolidated, EV penetration rates hit 8 per cent and the lithium market entered a deficit position with inventories quickly worked-through. By late 2022, the rally in prices had surprised most by peaking at around US\$80/kg in the Chinese market. Contracts linked to spot prices began to tick up and those that weren't linked to market pricing were beginning to be re-written. The spot price for lithium in China subsequently crashed, due to a variety of reasons, an oversupply was not one of them. This again, was a surprise to most. Strong underlying fundamentals should have ensured that lithium prices remained high in perpetuity. In reality, this was not the case; in this presentation, we explore reasons why fundamental supply and demand is not the only factor at play particularly in short- and medium-term price forecasting, and how this can lead to many wanted and unwanted surprises.

Similarly, this presentation explores how price forecasts, and supply and demand fundamentals must also be balanced against supply chain security and sustainability factors. China's dominance in spodumene conversion (China is forecast to supply 61 per cent of refined lithium in 2023 despite supplying just 16 per cent of mined supply), cathode production (China is forecast to supply 82 per cent in 2023), anode production (China is forecast to supply 93 per cent in 2023) and LiB production (China is forecast to supply 79 per cent in 2023) have been key factors leading to the United States' Inflation Reduction Act (IRA), legislation encouraging the onshoring of EV-related manufacturing. Meanwhile, sustainability factors are beginning to factor into automaker's procurement strategies, partnerships and funding arrangements.

Design of rare earth solvent extraction circuits – key to downstream processing

J Quinn[1], M Fainerman-Melnikova[2] and K Soldenhoff[3]

1. Senior Hydrometallurgist, ANSTO, Lucas Heights NSW 2234. Email: jamesq@ansto.gov.au
2. Senior Hydrometallurgist, ANSTO, Lucas Heights NSW 2234. Email: mfm@ansto.gov.au
3. Principal Consultant, ANSTO, Lucas Heights NSW 2234. Email: khs@ansto.gov.au

ABSTRACT

The rare earth elements (REE) are a group of 15 elements defined here as the lanthanides and yttrium. Particular REE, notably Pr, Nd, Tb and Dy, are used to make permanent magnets and have become increasingly critical as the world transitions towards greener technologies including electric vehicles and wind turbines. While the 15 REE are always encountered together in orebodies, at present the basket price of a deposit is dominated by the four magnet materials. Therefore, the next step after extracting the REE from the mineral phase and separating from the gangue non-rare earth constituents, is to separate the individual REE from each other and produce high purity oxides. This step is currently a bottleneck as the world strives to diversify rare earth supply chains.

Separation of the REE is notoriously challenging owing to the chemical similarity of the adjacent elements. Of the techniques that have been applied at an industrial scale, solvent extraction (SX) is by far the dominant method used presently. While the chemistry of the extraction process has been well understood for many decades, the know-how associated with the design and operation of industrial REE SX separation facilities, which might contain up to 1000 individual mixer-settler stages, remains tightly guarded.

ANSTO is one of few organisations outside of China that has developed expertise in the modelling and continuous mini-plant validation of REE SX circuits.

This presentation will discuss the techniques developed in order to allow for complex circuit design, operation of multi-outlet streams, model optimal start-up strategies and approach to steady-state, that enables experimental validation and definition of process design criteria for engineering designs.

Direct lithium extraction

A Razmjou[1,2,3] and Y Boroumand[3,4]

1. Mineral Recovery Research Centre (MRRC), School of Engineering, Edith Cowan University, Joondalup WA 6027. Email: amir.razmjou@ecu.edu.au
2. UNESCO Centre for Membrane Science and Technology, School of Chemical Engineering, University of New South Wales, Sydney NSW 2052.
3. School of Engineering, Edith Cowan University, Joondalup WA 6027.
4. Mineral Recovery Research Centre (MRRC), School of Engineering, Edith Cowan University, Joondalup WA 6027. Email: y.boroumand@ecu.edu.au

ABSTRACT

The direct extraction of lithium (DLE) from different brines has led to the development of numerous technologies. These advancements have shown the potential to recover up to 90 per cent of lithium through laboratory studies. However, challenges persist in establishing a sustainable process that can support a lithium-dependent low-carbon economy. The ongoing pursuit of DLE technologies aims to minimise pre-treatment requirements, reduce material usage, and streamline extraction processes while ensuring high selectivity for lithium.

This abstract provides an introduction to DLE technologies, highlighting the various methods and techniques used for extracting lithium directly from different sources. The principles, advantages, and challenges associated with different DLE technologies are discussed. Additionally, the environmental benefits, sustainability considerations, and carbon footprint reduction achievable through DLE processes are emphasised, underscoring their potential to minimise environmental impacts compared to conventional extraction methods.

The economic aspects of DLE are also explored, including cost-effectiveness, scalability, and the market potential of these technologies. Furthermore, membrane technology is presented as an emerging and disruptive method that can significantly enhance the large-scale implementation of DLE. Dr Razmjou's team has made notable progress in this area by experimentally fabricating membranes using diverse building blocks such as nano-clay, metal/covalent organic frameworks, graphene/oxide, and MXene. This overview summarises their findings and presents material design strategies for the development of lithium-selective membranes featuring nanochannels and nanopores.

Australian governments' critical mineral strategies – onshore mineral processing and ESG as a comparative advantage

L Sinclair[1] and N M Coe[2]

1. Postdoc Research Associate, School of Geosciences, The University of Sydney, Sydney NSW 2006. Email: lian.sinclair@sydney.edu.au
2. Professor of Economic Geography, School of Geosciences, The University of Sydney, Sydney NSW 2006. Email: neil.coe@sydney.edu.au

ABSTRACT

Australia is experiencing a rapid growth in exploration, extraction and downstream processing of critical and battery minerals. This is the biggest transformation of extractive industries in Australia since the development of offshore gas in the late 1970s and the biggest economic opportunity since the 2005–2014 mining boom. The current boom is driven by changing geopolitics and global demand for low carbon technologies. Australian governments at all levels are implementing strategies to plug into the global production networks of renewable energy and lithium-ion batteries. How do these strategies manage social license risk associated with a boom industry?

This paper is based on a state-by-state comparison of government strategies for critical mineral exploration, mining and onshore mineral processing. The strategies are remarkably similar in rhetoric, funding mechanisms and support for regional processing hubs. Comparative analysis produced four main findings:

1. Since 2020, Commonwealth and state governments together have contributed $3.68 billion in concessional loans, $575 million in grants, and $335 million in research and development and common infrastructure – over and above general grants and subsidies for resources and manufacturing sectors and infrastructure. The large majority of this funding is for critical mineral processing.
2. NSW, WA, Queensland, NT and the Commonwealth's strategies each promote regional hubs as a development model, with regional planning, common infrastructure and expediated approvals processes as incentives to locate processing facilities in strategic locations. The Central West NSW, Kalgoorlie and Kwinana in WA, and Townsville in Queensland are all located near existing and planned mineral processing infrastructure, between mines and export facilities.
3. All these strategies recognise the importance of ESG and point to Australia's existing high standards as a competitive advantage over other resource rich countries. None promise any improvement or upgrading of ESG standards.
4. Most of the strategies do not mention First Nations people – or only mention First Nations in the acknowledgement of country, without any safeguards for land, consent, or heritage protection during the coming boom.

The global boom in critical minerals presents a once-in-a-generation chance for governments, industry and communities, through regional planning, to improve the environmental and social standards associated with mineral extraction and processing, including around cumulative impacts, legacy mines, rehabilitation and cultural heritage management. An ambitious approach to regional planning of critical mineral processing hubs will help secure a social licence for the industry for the coming decades.

Unlocking the economic potential of global critical minerals – navigating political pressures

R Smit[1]

1. Study Manager, GHD, Townsville Qld 4810. Email: riaan.smit@ghd.com

ABSTRACT

As the world transitions towards a greener and technologically advanced future, the demand for critical minerals (CM) has surged, underpinning key industries such as renewable energy, electric vehicles and advanced electronics. This highlights the need to scale up investment and development in mining operations to meet future demands. Geographically diversified CM mining operations are essential for strategically sourcing these minerals in a complex geopolitical landscape. Failure to address this challenge can lead to increased reliance on geographically concentrated global supply chains. This risks potential CM and metals shortages, jeopardising various industries dependent on them. Additional risks, such as political and economic tensions between major global economies, also need consideration.

Western economies, recognising the threats associated with over reliance on China for future energy minerals, actively seek to diversify their supply chains. Australia emerges as a pivotal player due to its abundant mineral resources and potential to meet the growing global demand for key CM. Understanding the global CM environment, combined with favourable mineral policies and a stable economy and government, positions Australia to leverage its mineral wealth effectively. However, this journey is not without its challenges, as political pressures come into play, influencing global trade policies and creating uncertainties.

Navigating these political pressures requires a comprehensive understanding of the economic and entrepreneurial potential surrounding CM. Effective engagement with stakeholders, including governments, industry players and communities, becomes paramount in developing sustainable supply chains and mitigating geopolitical risks. This involves adopting a proactive approach towards policy frameworks, mineral beneficiation strategies and minerals marketing, fostering resilience and ensuring long-term stability in the supply of CM.

As big businesses push for investment, entrepreneurs will push to saturate the value chain and politicians their geopolitical agendas, but in all this lies a sweet spot with the potential for a regional and global win-win. This paper explores the challenges and opportunities in unlocking CM's global economic potential, focusing on strategic sourcing and the intricate economic overlay of a multi-industry supply.

Lithium processing – challenges and priorities to meet carbon neutral goals

R Surendran[1]

1. CEO, Tianqi Lithium Energy Australia, Perth WA 6000.
   Email: raj.surendran@tianqilithium.com.au

ABSTRACT

The Paris agreement committed world leaders to limit global warming to 2°C above preindustrial levels. A key strategy in achieving this goal is to become carbon neutral, and a prerequisite to becoming carbon neutral is to shift from the use of fossil fuels to clean energy.

As a lithium ore rich country, fast tracking mining and ore to chemical processing in Australia will deliver the largest impact in the decarbonisation of the energy and transport sectors.

Demand in 2023 for the lithium used in the production of batteries for electric vehicles is expected to be 910 000 metric tons of lithium carbonate equivalent (LCE), exceeding the 900 000 tons in supply. Benchmark Minerals Intelligence estimates that by 2030 around 2.7 million tons of LCE will be required annually, outstripping supply by 300 000 tons.

Tianqi Lithium Energy Australia's (TLEA) Kwinana refinery is the first to begin production of battery-grade lithium in Western Australia and will soon commence commercial export, ramping up to an annual capacity of 24 000 tons per annum.

Collocating the mine and processing facility reduces our carbon footprint by eliminating the need to transport hundreds of thousands of tons of spodumene concentrate to China for processing, but there is much more that needs to be done if we are to achieve net zero carbon emissions throughout the supply chain.

In this presentation, we will address the challenges facing Western Australia's lithium processing industry and its plans and priorities for meeting this goal.

Among them is the importance of early adoption of ESG, increasing renewables in our electricity mix, the importance of circulatory and creating beneficial uses for by-products, as well as ensuring we have the right systems in place and an ISO approach to management systems.

Lithium deportment and mineral liberation studies using TIMA automated mineralogy technique

Z Swierczek[1]

1. Principal Mineralogist, AXT Pty Ltd, Belmont WA 6104. Email: zofia.swierczek@axt.com.au

ABSTRACT

Spodumene is the most valuable Li-bearing mineral present in the LCT pegmatites. Depending on the type of the orebody, it can either present fine-grained mosaics or form large crystals that are coarsely intergrown with quartz, albite and potassium feldspar. The spodumene-rich pegmatites also contain accessory minerals such as beryl, tourmaline and spessartine garnet that present a small amount of lithium. Mica, a primary or secondary alteration mineral, can be very common and the lithium content can range from 0.1–3 per cent. Considering that spodumene is the major mineral target, complex mineral intergrowth relationships and the presence of deleterious elements must be well understood to achieve high lithium grades in the final product.

TIMA automated mineralogy technique from TESCAN is commonly used for the mineral liberation studies of the crushed ore and metallurgical stream samples. The acquired X-ray spectra are compared with a pre-defined mineral library that includes spodumene, sulfides and many other minerals. The data are collected at a few µm resolution, hence the elemental variability in a single particle can be detected. Quantitative mineralogical data includes mineral mass distribution, mineral grain size, elemental deportment and the mineral liberation statistics.

The mineralogical information which describes physical and chemical characteristics of the minerals can be used to predict behaviour of the ore minerals in the processing plant. This information is often used to optimise metallurgical flow sheet design for griding and flotation and to minimise the consumption of the chemicals during leaching processes. By understanding the mineral assemblage and lithium deportment, informed decisions can be made about the origin and extraction of the valuable minerals.

‘Novel scenarios’ on the energy transition for 2023 onwards

J P Sykes[1,2], A Trench[3,4], T C McCuaig[5,6] and M Jessell[7,8]

1. PhD Candidate, Centre for Exploration Targeting (CET), School of Earth Sciences, The University of Western Australia (UWA), Crawley WA 6009. Email: john.sykes@uwa.edu.au
2. Lecturer (MBA Program), Business School, UWA, Crawley WA 6009; Strategist, MinEx Consulting, South Yarra, VIC, 3141; Director, Greenfields Research, Leeds, West Yorkshire LS19 7XY, UK.
3. Professor (MBA Director), Business School, UWA, Crawley WA 6009. Email: allan.trench@uwa.edu.au
4. Senior Research Leader (Risk and Value), CET, School of Earth Sciences, UWA, Crawley WA 6009; Associate Consultant, CRU, London WC1V 6EA, UK; Director, Emmerson Resources, West Leederville WA 6007; Advisory Board Member, Wireline Services Group, Osborne Park WA 6017.
5. Head of Geoscience Excellence, BHP, Perth WA 6000. Email: cam.mccuaig@bhp.com
6. Adjunct Professor, CET, School of Earth Sciences, UWA, Crawley WA 6009.
7. Winthrop Professor, CET, School of Earth Sciences, UWA, Crawley WA 6009. Email: mark.jessell@uwa.edu.au
8. Project Manager, West African Exploration Initiative (WAXI), CET, School of Earth Sciences, UWA, Crawley WA 6009; Director, Agate Project, Perth WA 6000.

ABSTRACT

The energy transition is underway; however, its nature – the speed, winning technologies, associated infrastructure re-development, policy drivers, political fallout, financial sources, re-structuring of energy markets, business implications, sociopolitical impact, ultimate environmental success, its impact on the mining industry and particularly the market for ‘critical minerals’, remains unclear.

Contemporary events including the war between Russia and Ukraine, natural gas shortages, volatile fossil fuel prices, USA-China (and China-Australia) trade wars, Covid-19 pandemic, artificial intelligence (AI) technologies, ESG investing, recent substantive government and private investment in ‘green technologies’ and the hydrogen economy, and the continued rise of electric vehicle companies such as Tesla and BYD (China), exemplify the mixed signals emerging from the energy transition, never mind how these signals translate into implications for minerals markets and mining and exploration companies.

For the interpretation of the future of complex problems like the energy transition, scenario planning is commonly used by private, public sector and non-governmental organisations, including many large mining and energy companies. One such example is the Centre for Exploration Targeting ‘Future of Mining and Exploration’ Scenarios (CET Scenarios). The overriding questions under investigation were *‘for what will be exploring’* (ie the future of mining) and *‘how will we be exploring’* (ie the future of exploration). The workshops were run in Perth in 2016 and involved over 60 experts in mining, exploration and other relevant fields. Since then, work has continued in understanding the implications of the scenarios and updating the scenarios in line with contemporary developments.

One set of scenarios arising from the original CET Scenarios programme were the ‘Novel Scenarios’ (based on famous books), which included four scenarios covering the progression of the energy transition:

1. **Discworld:** the ‘old world’ – the fossil fuel economy.
2. **Wardrobe:** a world in transition – in part, the present and two potential future worlds.
3. **Wonderland:** a successful unified energy transition driven by a collective sense of purpose, international cooperation, and the commercial and social forces of globalisation.
4. **1984:** a partially successful, fragmented energy transition characterised by panic and reaction in different parts of the world, business and society, nationalistic government policy and competing approaches to the energy transition.

Scenario sets such as the above are not meant to be predictions, rather ‘mental models’ that help decision-makers understand change as it emerges. In this regard, the ‘Novel Scenarios’ have proved useful in understanding components of the energy transition over the last seven years, and even apparently unrelated global events, such as the Covid-19 pandemic.

This paper and presentation updates the ‘Novel Scenarios’ to help explain the contemporary events described and their implications for the critical minerals’ markets and mining and exploration companies. The ‘Novel Scenarios’ framework will be used to plot the position of key energy transition technologies (renewables, batteries, hydrogen, carbon capture, nuclear power, the circular economy etc), and critical minerals (lithium, rare earths, vanadium, nickel etc) in the energy transition. The implications for mining industry business models and the work of miners and explorers will also be discussed.

Greener lithium battery materials

M Tamlin[1]

1. Head of Lithium, Neometals Ltd, West Perth WA 6009. Email: mtamlin@neometals.com.au

ABSTRACT

Energy storage sector demand for lithium is putting pressure on lithium supply. A modern production response is needed that combines:

- lower carbon footprint to assist production of lower carbon footprint batteries for EVs
- lower OPEX to insulate producers across the lithium price cycles.

Neometals Ltd's answer is electrolytic lithium – ELi™ – which is a modern production process for high purity lithium hydroxide that uses proven industrial equipment. Reed Advanced Materials (RAM, 70 per cent Neometals and 30 per cent Mineral Resources) has developed the ELi™ process over the last ten years and is proposing the first commercial-scale operation in Portugal in venture with Bondalti, Portugal's largest chemical company.

When combined with renewable-source electricity, ELi™ delivers a low carbon footprint lithium hydroxide product that will, in turn, reduce the footprint of the batteries and cars it is used in.

ELi™ eliminates most bulk reagents that are used in the conventional production process. The result is the reduced cost and carbon footprint of producing, procuring and transporting these reagents, particularly to remote locations.

Development of the process to commercial operation is well advanced and the piloting will be completed during 2023 and sub-commercial demonstration projected for construction in the first half of 2024.

Styles and controls on lateritic Ni-Co-Sc ores – insights from New Caledonian deposits

Y Teitler[1], S Favier[2], J L Grimaud[3], S Grangeon[4] and M Cathelineau[5]

1. Research Scientist, CSIRO, Kensington WA 6151. Email: yoram.teitler@csiro.au
2. Research Scientist, CNRS – Université de Lorraine, Vandœuvre-lès-Nancy 54500, France. Email: sylvain.favier@univ-lorraine.fr
3. Research Scientist, Centre de Géosciences/Mines Paris – PSL, Fontainebleau 77305, France. Email: jean-louis.grimaud@minesparis.psl.eu
4. Research Scientist, BRGM, Orléans 45100, France. Email: s.grangeon@brgm.fr
5. Research Leader, CNRS – Université de Lorraine, Vandœuvre-lès-Nancy 54500, France. Email: michel.cathelineau@univ-lorraine.fr

ABSTRACT

New Caledonia is the world's fourth-largest producer of nickel and hosts world-class lateritic Ni deposits developed from serpentinised peridotite. Saprolitic Ni silicate ore, formed through the dissolution of mantle minerals and the redistribution of Ni in the lizardite mesh, commonly grades over 2 wt per cent Ni. Nickel enrichment in the mesh is spatially variable and largely controlled by the mesh geometry and the intensity of serpentinisation. *In situ* mineral chemistry and TEM analysis show that such enrichment is mostly related to:

- the formation of Ni-rich talc-like at the expense of lizardite
- the moderate incorporation of Ni in the 6T lizardite polytype.

The Ni-Co-Sc oxide ore, formed through the replacement of lizardite by goethite, grades between 1 and 2 wt per cent Ni together with Co and Sc concentrations up to 3000 and 100 ppm, respectively. Whereas Co is mostly concentrated in Mn phyllomanganates within the saprolite to limonite transition zone, goethite is the predominant host for Ni and Sc in the oxide ore. There, sequential extractions suggest that Sc has a higher affinity for amorphous iron oxides/oxyhydroxides than crystalline goethite, despite the predominance of crystalline goethite throughout the lateritic sequences. Scandium concentration in the oxide ore is mostly controlled by the Sc content of the parent rock and more specifically by the abundance and the composition of pyroxenes in the peridotite. Aluminium is found to be the best geochemical proxy for assessing Sc grades in Ni oxide ores. Scandium-aluminium calibration lines can be readily established at deposit scales to evaluate Sc distribution and grades from assay data. More generally, the authors show that assay data can be used to assess the nature of the protolith (harzburgite, dunite, lherzolite) and the mineral abundances throughout the entire lateritic sequences, such information being useful for both resource exploration and ore processing.

Lithium-ion battery recycling – patents as a lead indicator of trends and technology

M Turonek[1]

1. Principal, Wrays Pty Ltd, Perth WA 6000. Email: mary.turonek@wrays.com.au

ABSTRACT

Increasingly, governments are legislating that a significant proportion of the critical minerals consumed in manufacturing lithium-ion batteries be sourced sustainably. The European Parliament has, on 14 June 2023, approved new rules for the design, production and waste management of all types of batteries sold in the EU. These rules include stricter battery waste collection targets, minimum levels of materials recovered from waste batteries and minimum levels of recycled content for use in new batteries. China is perhaps arguably ahead of Europe, and certainly ahead of the US, in terms of regulation in dealing with these issues.

The variety of chemistries of lithium-ion batteries make them harder to deal with when compared with, say, lead-acid batteries. As a result, a range of technologies are employed in the recycling of lithium-ion batteries. The available technologies for the recycling of lithium-ion batteries are predominantly either hydrometallurgical, pyrometallurgical or direct technologies. Some lithium-ion battery chemistries are only appropriately recycled using one of these technologies, for example LFP and LMO, whereas LCO, NCA and NCM can in theory be recycled using any of these technologies.

Patent filings are, by legal necessity, a lead-indicator of trends in technology generally and lithium-ion battery recycling technology is no exception. A recent review article has noted that patent publications account for 74 per cent of available lithium-ion battery recycling literature whilst only being 33 per cent across all technologies. This emphasises the commercial importance of patents in this technological space and provides an indication of how recycling technologies are improving.

This presentation will provide an overview of the current recycling environment, both political and technical, and investigate recycling technology trends through the lens of patent filings as a lead indicator of future directions.

Advancing mineral processing through innovation – integrating instrumentation, advanced process control and sustainable organisational practices

D Vassallo[1]

1. APAC MMM Director, Honeywell Inc, Brisbane Qld 4170.
   Email: damian.vassallo@honeywell.com

DEVELOPING A CULTURE OF INNOVATION IN MINERAL PROCESSING

This presentation at the Critical Minerals Conference in Australia focuses on implementing innovative programs in the mineral processing space, targeting an audience comprising academic and industry personnel. The extraction and utilisation of critical minerals are paramount to multiple industries, necessitating innovative approaches to enhance mineral processing operations.

Baseline instrumentation forms the cornerstone for effective process monitoring and control. By employing reliable sensors and data acquisition systems, operators can gather real-time data on key process variables such as temperature, pressure, pH levels and particle size distribution. This empowers proactive decision-making, improves process stability, optimises resource allocation and enhances productivity while minimising the mill's energy consumption.

Advanced process control techniques play a pivotal role in maximising mineral processing efficiency. By integrating sophisticated algorithms, statistical models and machine learning, operators gain deeper insights into the complex dynamics of mineral processing systems. This facilitates the development of advanced control strategies that adapt to changing conditions, minimise process variability, optimise energy consumption and enhance overall performance. Integrating real-time process data with predictive models further enables predictive maintenance, early fault detection and optimised process scheduling.

Culture is critical in successful innovation programs within the mineral processing industry. Fostering a culture of continuous improvement, collaboration and knowledge sharing encourages active participation from both academia and industry personnel. Creating an environment that promotes experimentation, risk-taking and open communication allows for exploring and implementing novel approaches and technologies. Additionally, a culture of sustainability and environmental responsibility ensures that innovation efforts align with broader goals of resource efficiency, waste reduction and ecosystem preservation.

In conclusion, this presentation emphasises implementing innovative programs in the mineral processing space citing use cases to underscore the success of such programs. By leveraging baseline instrumentation, advanced process control techniques, and a culture of innovation, mineral processing companies can significantly improve operational efficiency, environmental stewardship, and the sustainable extraction and utilisation of critical minerals.

Using synthetic biology to accelerate critical metals recovery from mine waste

D Villa Gomez[1]

1. Australian Institute for Bioengineering and Nanotechnology, The University of Queensland, Brisbane Qld 4000. Email: d.villagomez@uq.edu.au

ABSTRACT

The mining sector has a key role as a greenhouse gas contributor and as a supplier of critical metals facilitating the zero-carbon transition. A paramount solution to these challenges is to recover critical metals from mining and processing wastes. Valorisation of mine waste is a current industry challenge, partly due to the lack of technological development and technology transfer. Some promising technologies can be developed based on bioprocesses (biomining). These can be more sustainable, safe and economically better as compared to sole chemical-based processes. For the last 40 years, biomining has successfully recovered 20 per cent of the world's copper and 5 per cent of the world's gold. Nevertheless, biomining has not fully extended to the extraction of metals from a greater range of mining and processing wastes partly due to the reduction of metabolic efficiencies. Now, the advent of publicly available sequence data on microbial strains and the progress in synthetic biology tools are unravelling biological parts and conditions that will improve biomining processes. The work to be presented here provides our laboratory and industry developments in nickel, cobalt, rare earths and gallium recovery using three bio-based processes: biological sulfate/sulfur reduction, biosorption and enzymatic complexation/reduction. By using omics and synthetic biology tools, we identified key biological components, ie genes/gen-systems, enzymes, proteins and mechanisms, that facilitate the recovery of these critical elements and we have designed novel low-carbon footprint bioprocesses and low-cost biocatalysts with high commercial and R&D potential. For example, we have identified three strains (eg *Desulfomicrobium baculatum*) that produce ten proteins that are capable of binding nickel (52–99 per cent), thus allowing to separate cobalt (99 per cent) from mine impacted waters. Work in progress is now on gallium and rare earth elements recovery from red mud tailings, where over 59 kt of only gallium is contained in these tailings in Australia.

Sustainable hydrometallurgical solution for producing critical minerals from lithium mica and lithium phosphate minerals

J Walsh[1] and G Johnson[2]

1. Managing Director, Lepidico Ltd, Perth WA 6005. Email: joe.walsh@lepidico.com
2. Chairman, Lepidico Ltd, Perth WA 6005. Email: gary.johnson@lepidico.com

ABSTRACT

Lepidico, an Australian resource development and technology company, in collaboration with Perth-based Strategic Metallurgy have developed technologies that unlock lithium from lithium mica and phosphate mineral ores in a process that is more sustainable and cheaper to build and operate than lithium derived from conventional roasting, including of spodumene. Lepidico's proprietary L-Max process also produces an important set of by-products containing potassium, caesium and rubidium, critical elements for the future. Its conversion plant which is under development in Abu Dhabi will be a zero solid waste facility where all materials entering the plant will emerge as some form of saleable product.

Feedstock to L-Max is a lithium mica or phosphate mineral concentrate, produced by conventional flotation. The first L-Max process step is a low selectivity saturation sulfuric acid leach at atmospheric pressure and modest temperature of up to 120°C, which efficiently takes the metals into solution. Metal salts are then selectively extracted by precipitation and filtration from the solution by adjusting temperature and pH using lime or limestone, while keeping the lithium in solution. The final product is a lithium sulfate solution. The leach residue is a reactive amorphous silica that can be used as a supplementary cementitious material. Potassium, caesium and rubidium report as a sulfate stream that is processed further to produce individual alkali metal sulfates. And the gypsum-rich residue that also contains various alunites has application in construction and is being evaluated as an agri-product.

Along the development journey Lepidico also developed process technology for converting lithium sulfate solutions, which is the intermediate solution in both Lepidico's process and conventional spodumene conversion, which avoids the production of by-product sodium sulfate. The proprietary LOH-Max process involves the reaction of lithium sulfate, lime and aluminium hydroxide to produce lithium hydroxide and ettringite. This technology provides an effective means of avoiding production of a low value, but is expensive to produce, and a chemical (sodium sulfate) that is becoming increasingly difficult to sell due to the large volumes being generated by both new lithium producers and cathode manufacturers coming on stream.

The occurrence of lithium in bauxite deposit in the southern margin of the North China block – implication for a new lithium resource

R Wang[1], E Ramanaidou[2] and A Bath[3]

1. Research Scientist, Mineral Resources, CSIRO, Kensington WA 6152.
   Email: ruixue.wang@csiro.au
2. Senior Principal Research Scientist, Mineral Resources, CSIRO, Kensington WA 6152.
   Email: erick.ramanaidou@csiro.au
3. Principal Research Scientist, Mineral Resources, CSIRO, Kensington WA 6152.
   Email: adam.bath@csiro.au

ABSTRACT

The growing demand for lithium in batteries, particularly for electric vehicles (EVs), has drawn attention to the sufficiency of existing and projected lithium resources. Current lithium resources primarily rely on lithium-rich spodumene and lithium brines. However, there is increasing interest in clay minerals (such as muscovite, illite and kaolinite) as potential future lithium sources due to their abundance. The mechanisms behind lithium enrichment in clay minerals are still a subject of debate.

In the southern margin of the North China block, clay layers within bauxite deposits have been found to be enriched in lithium, with concentrations reaching approximately 1300 ppm. A total of eight samples were collected from different layers of the Upper Carboniferous Mianchi bauxite deposit.

Laser-induced breakdown spectroscopy (LIBS) analysis revealed the presence of the lithium emission line (670.77 nm) in the spectra of four clay samples from various horizons. Notably, one sample (MC-7), predominantly composed of kaolinite, illite and diaspore, exhibited the highest intensity compared to the other seven samples. LIBS mapping and scanning electron microscopy-energy-dispersive X-ray spectroscopy (SEM-EDS) results demonstrated that areas with a higher concentration of lithium corresponded to regions where kaolinite was prevalent. Mineralogical investigations have revealed that the lithium-rich kaolinite in these deposits has a detrital origin as supported by the XRD results and was formed through continental weathering.

EU rules and regulations that impact Australian battery raw material supply chains

P Whattoff[1]*, R Pell*[2] *and L T Tijsseling*[3]

1. Head of Consultancy, Minviro Australia, Perth WA 6000. Email: phoebe@minviro.com
2. CEO and Founder, Minviro UK, London SE1 0LH, UK. Email: robert@minviro.com
3. Clients Solutions Director, Minviro SE1 0LH, UK. Email: laurens@minviro.com

ABSTRACT

The world needs more raw materials for the growing sustainable economy; however, few know the variability in the environmental impacts of existing and emerging raw material production assets. The embodied impact of battery-grade materials are the largest climate change driver for lithium-ion (LIBs) battery manufacturing, and the demand for LIBs is rapidly increasing. The EU rules and regulations for selling batteries with a capacity of more than 2 kWh into the EU are making carbon dioxide (CO_2) reporting mandatory in July 2024, with the battery passport in July 2026. This considers the cradle-to-cradle CO_2 footprint of a battery, including scope 1, 2 and 3 emissions and is calculated using a life cycle assessment (LCA) approach. In 2027, maximum CO_2 thresholds for batteries will be set, and it will be mandatory to declare the CO_2 footprint of the battery and decarbonisation plans to reach net-zero. The largest area to minimise the CO_2 impact of a battery is in the upstream raw material production processes itself.

Asset-specific LCA studies on projects in development and in operation will help resource companies communicate and mitigate climate change impacts. This study will introduce LCA and how it differentiates from standard greenhouse gas reporting, and how the results can be used to enable environmentally informed decision-making. Additionally, key differences between Australian nickel, lithium and graphite against alternative production routes will be presented, highlighting the opportunity for Australian producers to mitigate the most damaging hotspots in their production streams. This will allow them to work towards truly sustainable energy solutions for our future.

The market characteristics of critical minerals

D Whittle[1] and M Yellishetty[2]

1. Adjunct Professor, Resource Engineering, Monash University, Clayton Vic 3168. Email: david.whittle@monash.edu
2. Associate Professor, Resource Engineering, Monash University, Clayton Vic 3168. Email: mohan.yellishetty@monash.edu

ABSTRACT

Lists of critical minerals issued by sovereign states contain many minerals that will be required to transition to a low-carbon economy. However, there are exceptions, including metallurgical coal and potash, which are classified as critical minerals by the European Union and India, respectively. Some people are surprised by such exceptions, but it is no surprise when the definition of minerals criticality is studied. In this presentation, we briefly cover the history of minerals criticality assessment and consider matters such as why critical minerals are often defined by their elemental names (and what is wrong with this). We then examine the market-based roots of minerals criticality and the implications globally, for Australia and for the minerals industry in general. Key observations include:

- Many critical minerals markets are too small to be of interest to major mining companies. That leaves it up to mid-tier and small miners to bridge the gap between rapidly growing demand and supply.
- Many critical minerals markets are immature and lack basic market mechanisms such as price discovery. This puts miners at a disadvantage in achieving fair prices for their products and in attracting finance.
- Supply chains are often complex and cross sovereign borders.
- Downstream, enterprise size usually increases, meaning that large buyers are often dealing with smaller suppliers, which can lead to an imbalance of power in the marketplace.
- Although new supply will likely come from mid-tier and small market players, the incumbent suppliers are usually geographically concentrated, leading to the potential for sovereign interference.

These observations and more have implication as to how governments can best support the industry to grow and what the industry can do to help itself.

The critical minerals landscape – an analysis using patent data

R Wulff[1] and R Moore[2]

1. Principal, Griffith Hack, Sydney NSW 2060. Email: robert.wulff@griffithhack.com.au
2. Trainee Patent Attorney, Griffith Hack, Sydney NSW 2060.
   Email: radhika.moore@griffithhack.com.au

ABSTRACT

Australia is uniquely placed to exploit the growing demand for critical minerals, given our status as a leading destination for lithium, titanium, zirconium, cobalt, manganese, antimony, rare earths and vanadium. The mining sector remains one of the greatest contributors to the Australian economy, accounting for ~15 per cent of our GDP in 2023. For Australia to be able to fully realise its potential as a supplier and producer of critical minerals, we must first understand the current landscape of the sector.

Using patent data, an analysis of the critical minerals technology landscape both in Australia and internationally is provided. In particular, patent data shows who dominates the Australian and global patent landscapes, the major jurisdictions in which filings are occurring and the key technology areas being pursued by patent protection.

As companies start to stake out their intellectual property monopolies within Australia and beyond, Australian companies hoping to stand their ground in the competitive market need to ensure they are strengthening their intellectual property positions. One way of doing this is by filing patents into key (dominant and emerging) technology areas. This ensures they are in a strong position to exploit and monopolise the technologies that they have invested money in developing and/or deploying.

From our analysis, key recommendations are presented in which we show the areas of biggest growth over the past decade and highlight the key areas of the patent landscape which are less crowded. We also show how the number of local applicant versus international applicant filings in Australia have changed over the years, as an indication of how strong Australia's position in the market is.

Energy metals supply chains – a new world order?

C Yates[1]

1. CEO, RDA Perth; Chair, Lithium Valley Inc, Maylands WA 6051. Email: eo@rdaperth.org

ABSTRACT

In 2018, RDA Perth, in partnership with Kwinana Industries Council and Curtin University, released the report *Lithium Valley: Establishing the Case for Energy Metals and Battery Manufacturing in Western Australia*. In this historic report, the need to establish secure supply chains for the energy metals sector had been identified.

Since then, surging private and public investment in renewable energy generation, distribution infrastructure and battery storage has driven the biggest reorganisation of global supply chains, trade dynamics and human settlements since fossil fuels triggered the industrial revolution. This presentation will review the changes since 2018 and where we need to go to further unlock diversification across supply chains.