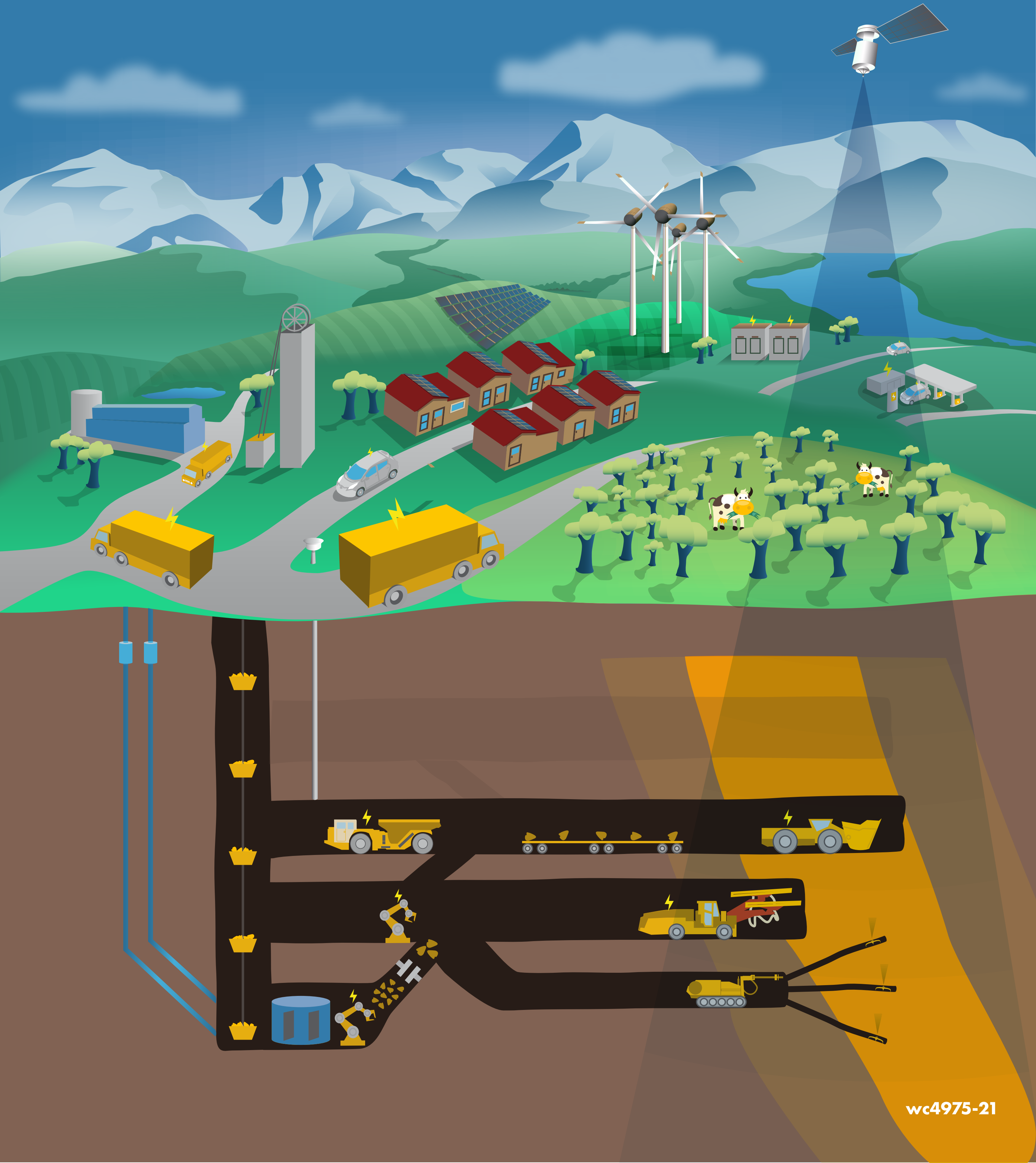
THE WARREN CENTRE

Zero Emission Copper Mine of the Future



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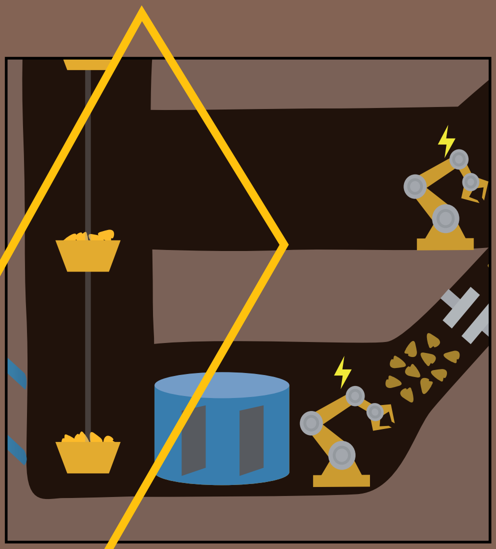

Zero Emission Copper Mine of the Future

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1. Message from the Warren Centre

1.1. About this Report

This report builds upon the Warren Centre's previous work with the International Copper Association Australia. In 2015 and 2016, the Warren Centre undertook a research study that produced the "Copper Technology Roadmap 2030: Asia's growing demand for copper".

That work reviewed socio-demographic, economic and technology trends in the Asian region to estimate demand for copper. Rapid economic development, urbanisation and growing middle classes in China, India and other countries in the region were predicted to drive demand for copper in housing and transport. Another trend towards the preference in Asia for lower energy emissions indicated a boom in solar photovoltaics, wind power, electric automobiles and electrified public transport. Combined, these two megatrends indicated strong demand for copper. That report is available for free download at https://thewarrencentre.org.au/project/the-copper-technology-roadmap-2030/.

Indeed, the Paris Accord and growing recognition for the United Nations Sustainable Development Goals have created impetus in both developing and well-developed nations for changes in economic growth to yield sustainable future pathways.

This report was funded by the International Copper Association Australia. It includes insights on how to achieve direct emissions reduction at mining and smelting sites from leading industry experts with first hand experience of the pragmatic challenges faced by industry. This report is in the tradition of Warren Centre work that builds industry collaboration to create the possibility for improvements that advance engineering, deliver innovation, support economic growth and benefit the whole of society.

1.2. About the Warren Centre

The Warren Centre brings industry, government and academia together to create thought leadership in engineering, technology, and innovation. We constantly challenge economic, legal, environmental, social and political paradigms to open possibilities for innovation and technology to build a better future.

The Warren Centre advocates for the importance of science, technology and innovation. Our 30 years' experience in leading the conversation through projects, promotion, and independent advice drives Australian entrepreneurship and economic growth.

The Warren Centre promotes excellence in innovation through delivering collaborative projects, supporting and recognising innovators across the engineering profession, and providing independent advice to government and industry.

For more information about the Warren Centre visit www.thewarrencentre.org.au. For enquiries about this report please email: warrenc@sydney.edu.au.

1.3. About the Research and Editorial Team

This project was completed by a blended team from the Warren Centre, LarkinSykes Pty Ltd, and University of Sydney engineering research assistants.

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This report draws on the expertise, advice and insights of many individuals including industry leaders, researchers and subject matter experts. The Warren Centre gratefully acknowledges the contributions gained from interviews with the following International Copper Association Australia members and industry subject matter experts.

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2. Message from the ICAA

The ***Zero Emission Mine of the Future*** was commissioned by the International Copper Association Australia Ltd (ICAA), the pre-eminent marketing arm of the Australasian copper industry that is closely aligned with the International Copper Alliance.

An earlier report, the Copper Technology Roadmap 2030 -- also by the Warren Centre -- forecasts strong copper demand over the next 15 years driven by technology, decarbonisation, urbanisation, clean energy and mobility.

The Zero Emission Mine of the Future is focused on upstream challenges to find and produce copper sustainably.

As the world moves rapidly to deal with the impacts of climate change, every economy and industry will need to reduce their carbon footprints. Not only must the end products contribute to a reduction in emissions, but the companies that produce the materials, the products and the transport exchange must also look to play their part.

To this end, the global copper industry has introduced the new Copper Mark Certification program to guide mines to comply with the U.N. Sustainable Development Goals.

Over the next 20-30 years the challenge for copper mines to become zero emission will be immense in face of falling ore quality, the difficulty of finding new, accessible deposits and growing community pressures on 'licence to operate'. This Report identifies short term, medium term and longer term technological breakthroughs and processes to move the industry to achieve this goal.

The value to the Australasian economy and environment as we progress along this path is enormous. It is quite likely that by building collaboration between copper miners, research institutes and universities, the METS Industry and governments we will uncover valuable technologies we can also sell to the rest of the world.

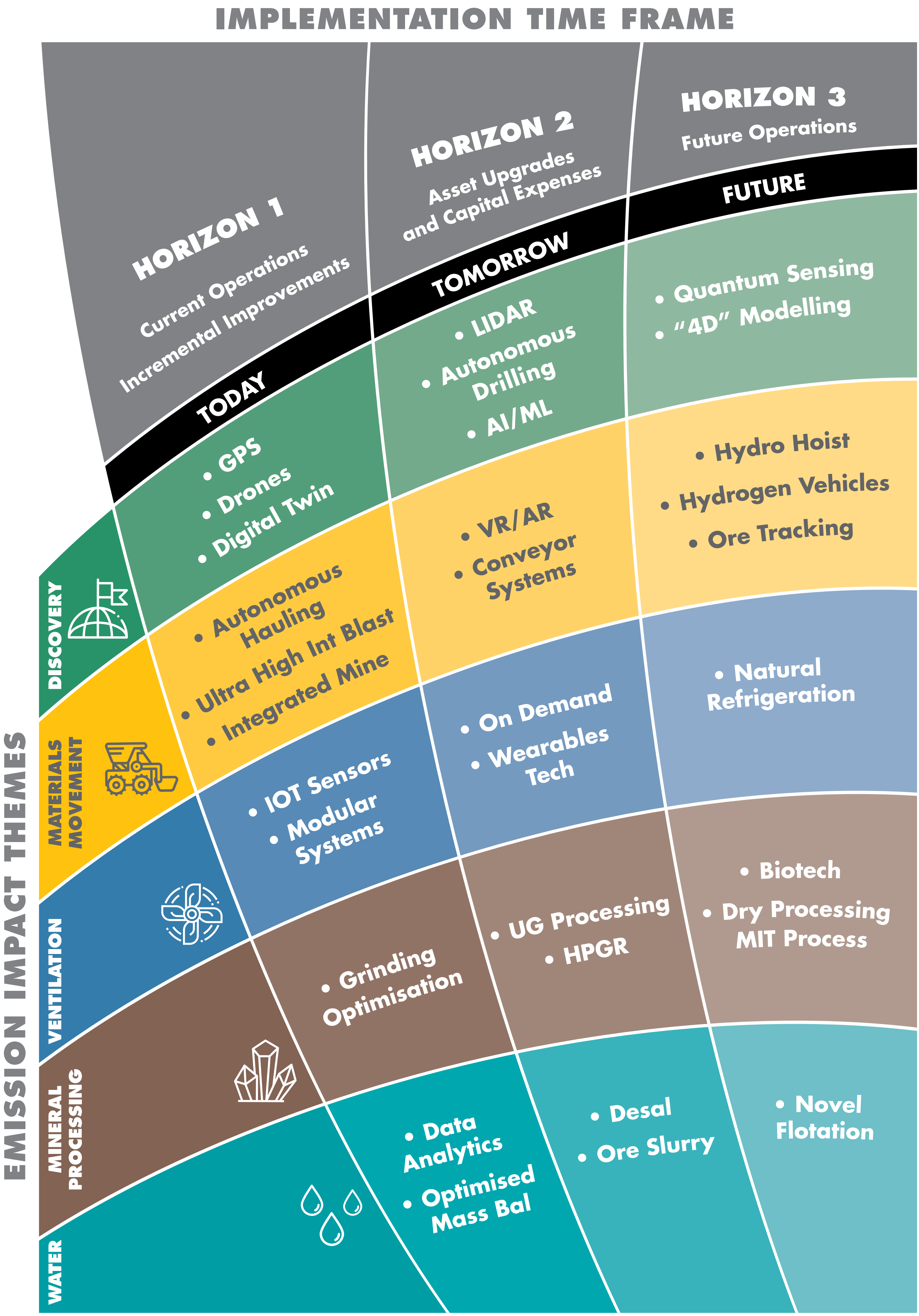
We hope this Report will be followed by a Stage 2 Report to identify which key short term technology breakthroughs we should target. Ultimately Stage 3 will initiate a global collaboration to achieve these breakthroughs.

Yours Sincerely
John Fennell
CEO, ICAA

Cu International Copper Association Australia
Copper Alliance

For more information about the International Copper Association visit: www.copper.com.au

The United Nations Sustainable Development Goals.
Source: UN.org.


IMPLEMENTATION TIME FRAME
HORIZON 1
Current Operations
Incremental Improvements
TODAY
HORIZON 2
Asset Upgrades and Capital Expenses
TOMORROW
HORIZON 3
Future Operations
FUTURE
EMISSION IMPACT THEMES
DISCOVERY
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• Drones
• Digital Twin
• LIDAR
• Autonomous Drilling
• AI/ML
• Quantum Sensing
• "4D" Modelling
MATERIALS MOVEMENT
• Autonomous Hauling
• Ultra High Int Blast
• Integrated Mine
• VR/AR
• Conveyor Systems
• Hydro Hoist
• Hydrogen Vehicles
• Ore Tracking
VENTILATION
• IOT Sensors
• Modular Systems
• On Demand
• Wearables Tech
• Natural Refrigeration
MINERAL PROCESSING
• Grinding Optimisation
• UG Processing
• HPGR
• Biotech
• Dry Processing MIT Process
WATER
• Data Analytics
• Optimised Mass Bal
• Desal
• Ore Slurry
• Novel Flotation

3. Executive Summary

A Zero Emission Copper Mine of the Future – A Strategic Imperative

The International Copper Association Australia (ICAA) commissioned the Warren Centre to develop a strategic Roadmap to achieve a Zero Emission Copper Mine of the Future.

There is a rapidly evolving global trend toward a lower-carbon economy. Copper is well placed to facilitate this process through its real-world applications, but there is also a compelling need in the upstream segment of the copper mining process to achieve a zero-emission future.

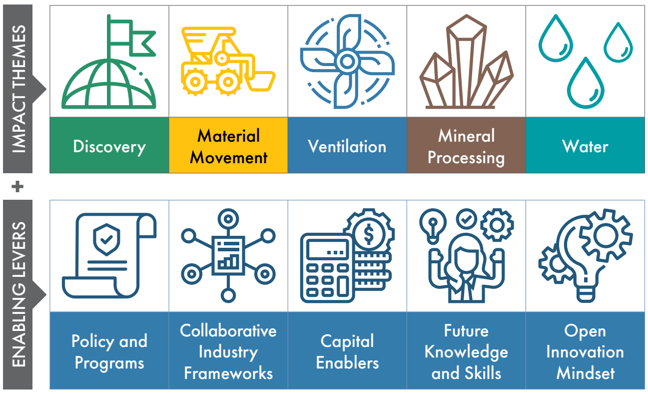
Copper mining has remained mostly unchanged for many years, and while breakthrough innovation has occurred -- for example adaptation of flotation and smelter techniques or leaching-solvent extraction -- significant technological innovation in the industry has been slow to evolve.

A Zero Emission Copper Mine of the Future will be significantly different from the current copper mining system and will require fundamental changes in how energy is consumed, sourced and abated. The Warren Centre believes this is possible with an appropriate delivery framework, coordinated vision, and imagination.

The Report identifies five Emission Impact Themes, including discovery, ventilation, water, processing underground, and materials movement. Within each of these are a series of horizon 1 near-term technology adoptions, progressing to horizon 3 future technology breakthroughs. This includes the adoption of copper mining technologies that are available 'off-the-shelf' and which can be proven to provide emission efficiency gains.

Five Enabling Levers are also identified across policy and programs, capital enablers, collaborative frameworks, future knowledge and skills, and innovation to optimise the opportunity for success and mitigate risk in a complex and variable operating environment. A collaborative vision coupled with an underlying framework to activate and enable innovation is essential to achieve impactful decarbonisation scenarios and pathways.

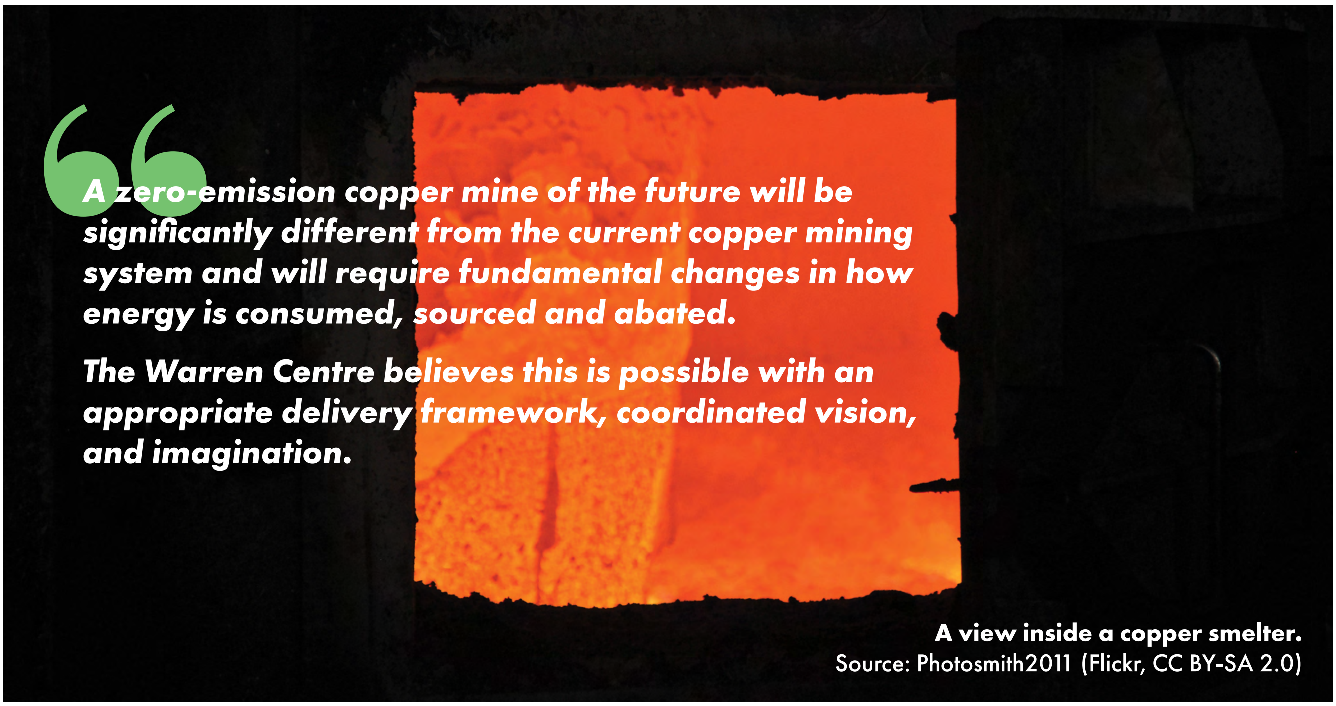
The Elements of a Zero Emission Mine of the Future



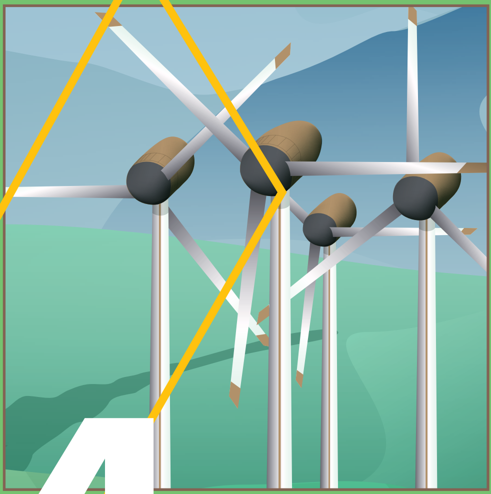
The roles of renewable energy and environmental abatement technologies will not only continue to evolve but play an important role in addressing energy supply at a primary producer level.

A zero emission mine of the future must recognise the difference between incremental versus breakthrough innovation. There are different horizons of impact to enable producers to maintain a balance between economic viability and the challenges presented by the development of lower grade, deeper orebodies in the future with a zero-emission mindset.

A Zero Emission Copper Mine of the Future will only be realised by connecting innovators to producers and establishing a framework that enables trust so as to deliver success.



A view inside a copper smelter.
Source: Photosmith2011 (Flickr, CC BY-SA 2.0)



4.

The era of carbon transparency and reporting

– an important factor for decarbonisation in copper mining

THE EXTRACTIVE AND MANUFACTURING PROCESSES REQUIRED IN THE MINING OF COPPER YIELD GREENHOUSE GAS EMISSIONS THAT CONTRIBUTE TO GLOBAL WARMING, AND IT IS ESTIMATED THAT ALL MINING (INCLUDING COPPER) ACCOUNTS FOR UP TO 11% OF GLOBAL ENERGY USE.[1]

1 www.worldbank.org, 2020. *Climate Smart Mining - Minerals for Climate Action.* [Online]. Available at: https:// www.worldbank.org/en/topic/extractiveindustries/brief/climate-smart-mining-minerals-for-climate-action

Although copper as a material plays a vital role in energy transition and industrial decarbonisation pathways, the current state of the art of copper mining and copper ore purification is also under pressure to be upgraded to provide for better sustainability, lower carbon emissions, lower environmental impact and lighter surface impacts. The industry recognises the role it plays in supplying the new technologies for a low carbon future but faces operational challenges to maintain competitiveness, while reducing energy and water requirements.

Other forces also drive the mining sector to a lower emission future. Investment criteria is constantly adapting to a changing world, with investors increasingly monitoring carbon emissions as they assess climate risk in their investment portfolios.[2] Consumers and manufacturers are also increasingly seeking transparency and visibility in whole of material supply chains and circular business models, underpinning the rapid evolution of green procurement guidelines. Activities and programs such as the United Nations Sustainable Development Goals, the Responsible Minerals Initiative, the Responsible Copper Initiative, the World Bank Climate Smart Mining Initiative, and also actions of downstream consumer-facing brands like Apple, Daimler and BMW are driving high accountability and transparency in minerals supply.

Case Study – A whole of supply chain approach

In 2018 BMW Group, in partnership with Codelco established the “Responsible Copper Initiative” as a step towards advancing transparency in the supply chain. The aim of the Responsible Copper Initiative is to achieve a commitment to ecological and social responsibility in the copper industry.

The BMW Group is also a founding member of the Aluminium Stewardship Initiative, a supporter of the Responsible Steel Initiative and a member of the Responsible Cobalt Initiative.[3]

In 2018 Apple signed an agreement with Alcoa and Rio Tinto to reduce the carbon footprint of the aluminium in its products.

The Colorado based Rocky Mountain Institute[4] argue that, while carbon transparency in the minerals sector is increasing, there remains a challenge to compare CO_2 emissions between mining and other sectors due to the complexity and variability of the mining process and the lack of a universal calculation framework.[5]

The Institute recognise that while measurement remains a challenge the Greenhouse Gas Protocol (GHG Protocol) offers a widely accepted foundation and overarching framework that distinguishes between an organisation’s direct and indirect emissions, as well as the total emissions along its value chain from the manufacture and delivery of its products to their eventual disposal or recycling.

To address the application to the minerals sector, three notable institutions are collaborating together and have formed the ‘Materials Initiative’ working group. The objective of the working group is to engage stakeholders who are advancing calculation frameworks and methodologies. These institutes include:

- The MIT Center for Transportation & Logistics - Sustainable Supply Chains initiative,
- The Columbia Center for Sustainable Investment, and
- The Rocky Mountain Institute.

The group works collaboratively and intends to develop a certified joint carbon accounting framework built on the GHG Protocol and tailored to meet the needs of the minerals industry and its supply chain partners. The Institute argues that an accepted emissions calculations framework for the minerals industry is the first step in the journey toward carbon transparency that will be needed for consumers and investors to more accurately understand and further drive the decarbonisation of industrial sectors, including mining.[6]

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2 Rocky Mountain Institute, 2019. *How much CO2 is embedded in a product?*. [Online]. Available at: https://rmi.org/how-much-co2-is-embedded-in-a-product/

3 BMW Group, 2018. *“BMW Groups and Codelco agree on cooperation to establish the Responsible Copper Initiative”*. [Online]. Available at: https://www.press.bmwgroup.com/global/article/detail/T0277850EN/bmw-group-and-codelco-agree-on-cooperation-to-establish-the-responsible-copper-initiative?language

4 Rocky Mountain Institute, 2019. *How much CO2 is embedded in a product?*. [Online]. Available at: https://rmi.org/how-much-co2-is-embedded-in-a-product/

5 Ibid

6 Ibid

Case Study: The Copper Mark™

The Copper Mark™ is an example of an initiative that was recently launched in mid-2019 as a driver in the race towards zero emissions copper production. Initiated by the International Copper Association (ICA), The Copper Mark™ is an assurance system that aims towards a beneficial and sustainable development for the global copper production operations, which will also reap social and environmental benefits for all parties involved in the supply chain. By acting as a communication tool between stakeholders, The Copper Mark™ will allow responsibly produced copper to be recognised by investors and copper consumers worldwide and can therefore directly contribute to the goal of a sustainable production of copper. This will be done in the form of a mechanism that guarantees that the copper production operations are responsible, in terms of managing their environmental, social, and governance risks within their procedures.[7]

The newly established system was inspired by the United Nations Sustainable Development Goals (SDGs), which is a universally adopted framework for sustainable development that addresses global challenges with regards to poverty, inequality, climate change, environmental degradation, peace, and justice, with a target to complete all of its 17 goals by 2030.[8] In the first phase of development, The Copper Mark™ will mainly contribute towards SDG 12 titled "Responsible Consumption and Production"[9] through the assurance process created by this initiative.

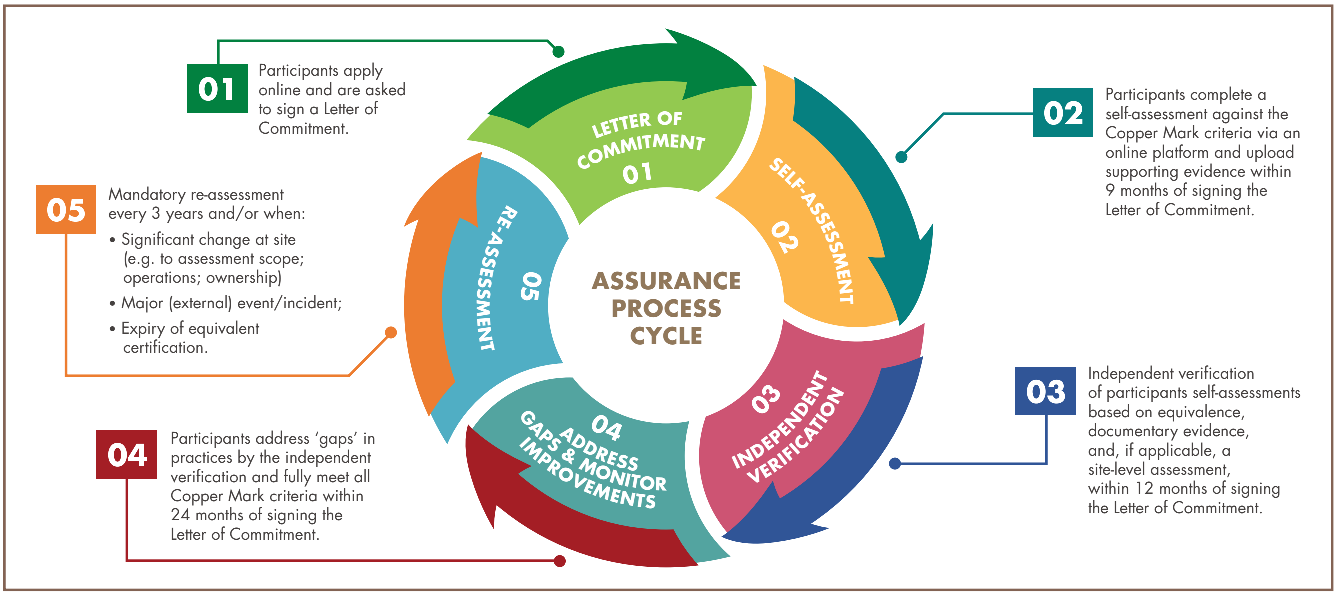
The process, named The Copper Mark™ Assurance Process, will assess the performance of upstream companies in the supply chain (copper mines, smelters, and refiners) against standards defined by a responsible production criteria, which follows the Risk Readiness Assessment (RRA) created by the Responsible Minerals Initiative.[10] In essence, the RRA covers 32 risk areas including environmental, social, and governance topics that can be used as pointers to assess the performance of the manufacturing side of the copper supply chain.

Applications for The Copper Mark™ have commenced in early 2020, whereby copper mines, smelters, and refiners apply online and provide suitable evidence of their practices which will be checked against the criteria. The process will then continue as outlined in Figure 1, where the current scope of the program is set to be completed within two years from the start of the process.

The vision of The Copper Mark™ beyond 2022 aims for further contributions to the UN SDGs through additional programs to support the 2030 Agenda for Sustainable Development.

THE COPPER MARK® | RESPONSIBLY PRODUCED COPPER

Figure 1: The Copper Mark Assessment Cycle[11]



7 The Copper Mark, 2019. *Features of The Copper Mark.* [Online] Available at: https://coppermark.org/about/
8 United Nations, 2015. About: United Nations Sustainable Development Goals. [Online]. Available at: https:// sustainabledevelopment.un.org/
9 United Nations, 2015. *Sustainable Development Goal 12: Ensure Sustainable Consumption and Production Patterns.* [Online]. Available at: https://sustainabledevelopment.un.org/sdg12.
10 The Copper Mark, 2019. *Copper Mark Requirements.* [Online]. Available at: https://coppermark.org/copper-mark- requirements/.
11 The Copper Mark, 2019. *Assurance Process.* [Online]. Available at: https://coppermark.org/copper-mark-requirements/ assurance-process/

The Paris Agreement was adopted by consensus on 12 December 2015.
Photo by UNClimateChange, CC-BY2.0.

4.1. EXPLORING THE GHG PROTOCOL

The GHG Protocol is a standardised framework that establishes the method of measurement and management of greenhouse gas (GHG) emissions produced from private and public sector industries. The protocol is a result of the collaboration between World Resources Institute (WRI) and the World Business Council of Sustainable Development (WBCSD) to service governments, NGOs, businesses and other organisations.[12]

The GHG Protocol Corporate Accounting and Reporting Standard is a framework that provides the regulations, requirements and advice to companies and organisations that are prepared to take an inventory of their GHG emissions output.[13] The protocol defines GHG based on the six gases considered as GHG by the Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCC) – CO_2, CH_4, N_2O, HFCs, PCFs, SF_6.[14,15]

The GHG Protocol Corporate Standard has been designed to be program or policy neutral. However, many existing GHG programs use it as a foundation for their own accounting and reporting requirements, and it is compatible with most programs.[16]

4.2. EMISSIONS TYPES REPORTED IN THE COPPER MINING VALUE CHAIN – AN AUSTRALIAN CONTEXT

The National Greenhouse and Energy Reporting (NGER) Scheme was introduced in Australia in 2007 to provide data and accounting in relation to greenhouse gas emissions, energy consumption and energy production, with accounting aligned to UNFCC.

The Scheme's legislated objectives are to:

- inform policy making and the Australian public
- meet Australia's international reporting obligations under UNFCCC
- provide a single national reporting framework for energy and emissions reporting.[17]

Aligned to GHG Protocol, NGER have classified greenhouse gas emissions into three different scopes. Other bodies relevant to the minerals industries such as the International Council of Minerals & Metals (ICMM)[18] and the Minerals Council of Australia (MCA)[19] also support the following Scope definitions.

12 GHG Protocol Initiative, 2020. The Greenhouse Gas Protocol. [Online]. Available at: https://ghgprotocol.org/sites/default/ files/standards/ghg-protocol-revised.pdf
13 Ghgprotocol.org. (2020). *Corporate Standard | Greenhouse Gas Protocol.* [online] Available at: https://ghgprotocol.org/ corporate-standard
14 UNFCCC, 2020. *What is the Kyoto Protocol?*. [Online]. Available at: https://unfccc.int/kyoto_protocol
15 UNFCCC, 2008. Kyoto Protocol Reference Manual: On Accounting of Emissions and Assigned Amount. [Online].
16 GHG Protocol Initiative, The Greenhouse Gas Protocol, op. cit.
17 Australian Government - Department of Industry, Science, Energy and Resources, 2020. *Greenhouse Gas Measurement.* [Online]. Available at: https://www.environment.gov.au/climate-change/climate-science-data/greenhouse-gas-measurement/ nger
18 Icmm.com, 2020. *Competitiveness implications for mining and metals.* [Online] Available at: https://www.icmm.com/website/publications/pdfs/climate-change/competitiveness-implications-for-mining-and- metals
19 National Resources Review, 2020. *NSW laws proposed to prevent scope 3 being considered in mining approvals - National Resources Review.* [Online]. Available at: https://www.nationalresourcesreview.com.au/news_article/new-emissions- laws-proposed-in-nsw/

SCOPE 1 emissions	which are often referred to as ***direct emissions***, are emissions that have been released into the atmosphere directly as a result of an activity or activities carried out at an industrial level. In the case of copper mining operation, direct emissions occur from sources that are owned and controlled by the reporting entity and include onsite power generation.
SCOPE 2 emissions	which are often referred to as ***indirect emissions***, are emissions that have been released into the atmosphere due to the **consumption** of an energy commodity. In the case of copper mining this would include the emissions from the generation of purchased electricity to enable the copper production process.
SCOPE 3 emissions	are all other emissions that are generated indirectly as a result of activities from sources that are not owned or controlled by the reporting entity business. In the case of copper this could include the emissions as a consequence of the use of the sold copper cathode for the manufacture of semi-fabricated products.

In Australia Scope 1 and 2 emissions have been specified by NGER legislation and must be reported, whereas, Scope 3 emissions are currently not included in the NGER scheme.

While a number of mining companies are exploring the improvements of transparency and reporting of Scope 3 emission types, including the ability to address reporting overlap, there does not currently exist a consistent methodology, and hence specific reference to Scope 3 emission is excluded from this report.[20]

4.3. THE EMISSION REPORTING FRAMEWORK – UNITS OF MEASURE

Measurements of greenhouse gases are recorded relative to carbon dioxide equivalence (CO_2-eq). For instance, a manufacturing or processing company emitting 1 tonne of methane into the atmosphere has the same global warming potential as emitting 25 tonnes of carbon dioxide. Hence, 1 tonne of methane would be expressed as 25 tonnes of carbon dioxide equivalence.[21]

Emissions can be reported in absolute terms (total CO_2-equivalent emissions, or CO_2- eq) and intensity terms (CO_2-eq per unit).

The unit of absolute measure is important as a comparative tool to compare sector emissions to total industry, and/or to other industries. However absolute measurements must be combined with efficiency metrics to understand performance at a company or sector level.[22]

4.4. ZERO EMISSION / ZERO WASTE / ZERO FOOTPRINT MINING

The complex nature of the extraction of copper in the mining process presents many challenges within the broader context of sustainability. Rankin (2015) outlines the industry response to this challenge and argues that in recent times there has been a shift toward an integrated strategy along the value chain including managing the ore stocks from which materials are obtained, the use of the commodity itself, and the recycling of the goods, products and infrastructure that contain materials.[23]

The 2030 Agenda for Sustainable Development, adopted by United Nations Member States in 2015, provides a shared blueprint for peace and prosperity for people and the planet, now and into the future. At its heart are the 17 Sustainable Development Goals (SDGs), which are an urgent call for action by all countries, developed and developing, in a global partnership.[24]

20 Australian Financial Review, 2019. *Scope 3 accountability inevitable for miners, says EY*. [Online].
21 Cleanenergyregulator.gov.au, 2020. *Greenhouse gases and energy*. [Online] Available at: http://www.cleanenergyregulator.gov.au/NGER/About-the-National-Greenhouse-and-Energy-Reporting-scheme/Greenhouse-gases-and-energy
22 Kirk, T. & Lund, J., 2018. *Decarbonization Pathways for Mines: A Headlamp in the Darkness*. [Online].
23 Rankin, W. J., 2015. *Re-evaluating the traditional production cycle*. [Online]. Available at: https://www.ausimmbulletin.com/feature/towards-zero-waste/
24 United Nations, 2015. About: United Nations Sustainable Development Goals. [Online]. Available at: https://sustainabledevelopment.un.org/

For the copper industry a contribution to this vision involves a shift in governance structures, economic frameworks, and operating practice. Sustainable Development Goal 9 seeks to build resilient infrastructure, promote inclusive and sustainable industrialisation. SDG 9.4 outlines a target linked to CO_2 emission per unit of value. Sustainable Development Goal 12 seeks to address material consumption, with SDG 12.2 seeking to achieve the sustainable management and efficient use of natural resources measured by material footprint.[25]

The response by the industry to address SDGs and other transparency initiatives has yielded the increased participation of catalyst organisations such as the International Council of Mining and Metals (ICMM) Global Resource Initiative (GRI), The Canadian Mining Innovation Council (CMIC) as well as action within peak mineral industry bodies such as the ICA. Addressing the future challenge of accessing lower grade and more complex ore systems in a sustainable manner have also prompted the evolution of other commonly used terms such as Zero Waste, Zero Footprint and Green Mining.

The Zero Waste mining concept aims for the minimisation of impacts through a reduction in physical waste generation and material disturbance, while minimising inputs such as energy and water. Zero Footprint Mining also seeks to reduce the extent of environmental impact around a mine site. Organisation such as the Canadian Mining Innovation Council (CMIC) targets Zero Waste Mining initiatives and aims to transform the mining industry by enabling the deployment of technologies that will reduce by 50% the mining industry's energy use, water use, and environmental footprint. The goal is to have such technologies developed and proven by 2027.[26]

While well aligned to other terms as indicated in Zero Waste and Zero Footprint, the concept of Zero Emissions represents a shift from a traditional industrial model in which emissions as a result of energy consumption and intensity are an accepted output of the process to:

> ***an integrated systems approach in which emissions are accounted for, action taken, and balanced to target net zero.***

For business, an outcome of a drive toward Zero Emissions could translate to a drive toward greater energy efficiency, lowered emission output, improved operational competitiveness, and wider industry acceptance.

The central challenge for businesses posed by a Zero Emission approach is how to achieve emission reduction outcomes while maximising economic resource productivity at the industrial level, rather than simply offsetting or abating emissions associated with a given product cycle.[27]

The Zero Emission Copper Mine of the Future concept seeks to address GHG emissions in the copper mining process. There are many examples of positive steps that producers are taking at the site level toward decarbonisation. For example, recent years have seen a rapid uptake in the application of renewables and clean energy as it increasingly becomes an economically viable option to meet part of the energy demands of a producing site. Other mitigation and offset measures include carbon capture and storage.

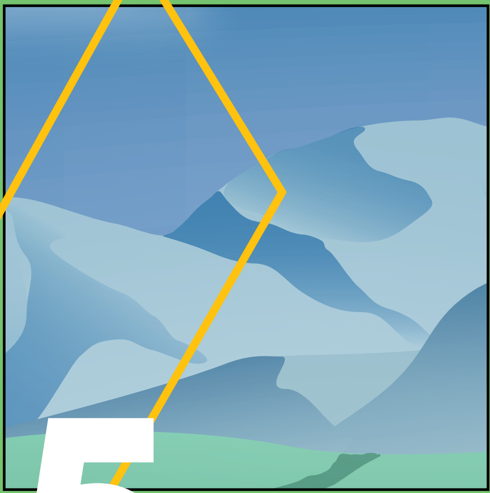
The copper industry holds a unique position to not only provide the low emission technologies of the future but also to take ownership and play a leading role in the transition to zero-emission from the operations that drive copper output. This report seeks to explore the shift to zero emission as an integrated systems approach at the operating level and to present technologies that will offer competitive and efficient solutions for the whole of operation.

The report recognises the important role that renewables and hydrogen technologies play to a advancing a Zero-Emission Copper Mine of the future. However in-depth discussion on specific advances in renewables, hydrogen and other offset measures from land use is excluded from this study except where it relates to emission intensity reduction measures at the operating level.

25 United Nations, 2015. Sustainable Development Goal 9: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation. [Online]. Available at: https://sustainabledevelopment.un.org/sdg9

26 CMIC, 2019. *Transform Mining Towards a Zero Waste Industry.* [Online]. Available at: https://cmic-ccim.org/about/

27 GDRC, 2020. *Sustainability Concepts - Zero Emissions.* [Online]. Available at: http://www.gdrc.org/sustdev/concepts/25-zero.html



5. The copper mining landscape

5.1. THE ROLE OF COPPER IN MODERN SOCIETY

Copper is one of the world's most versatile and useful metals, playing a prominent role necessary for modernisation. It enjoys both uniqueness and versatility in its end use, based on inherent physical and chemical properties. Best known for its conductive efficiency, copper is tough, malleable and ductile, corrosion-resistant, and recyclable.[28]

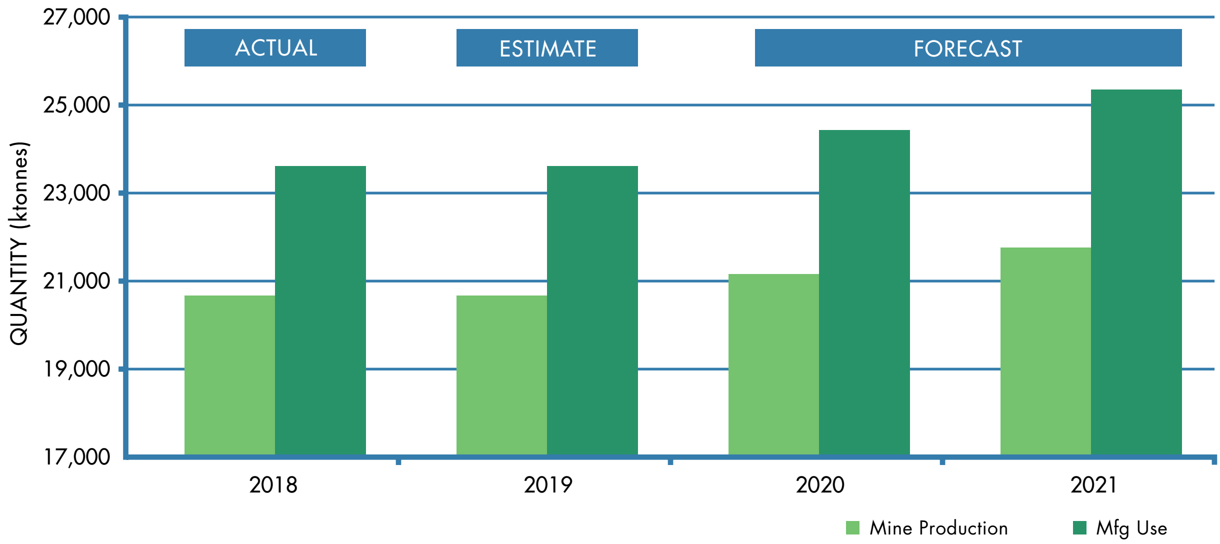
In 2018 global annual copper mine production was 20.674 million tonnes,[29] and as the world continues to modernise, copper use is projected to grow 5% to 21.701 million tonnes in 2021 from 2018 levels as shown below in Figure 2.

Use indicators suggest that the global demand for copper is expected to generally outpace supply in the foreseeable future.

28 Rio Tinto, 2019. Rio Tinto Website. [Online]
Available at: https://www.riotinto.com/products/copper? utm_source=adwords&utm_medium=search&utm_campaign=brand_2019.

29 Australian Government Department of Industry, Innovation and Science, 2019. *Resources and Energy Quarterly - December 2019.*

Figure 2 - Global Copper Mine Production vs Manufacturing Use from 2018 - 2021[30]

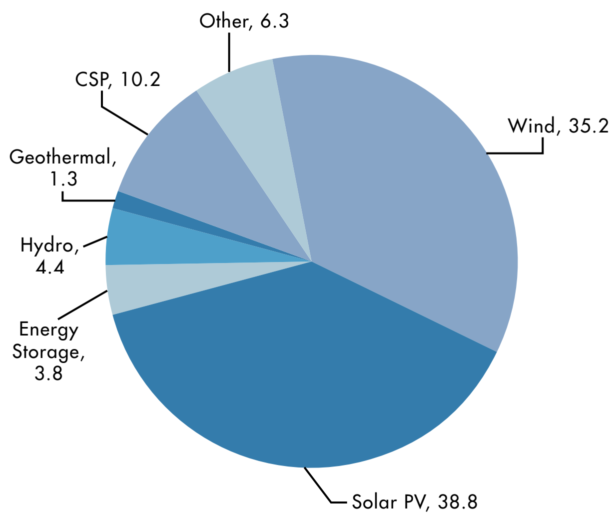


The highly conductive properties of copper make it favourable for power generation, electricity transmission, and heat exchange. Both flexible and recyclable, copper is widely used in a variety of end use products including electronic devices, electrical wiring, plumbing, building construction, infrastructure, manufacturing, transport, consumer and health products.

Copper is a metal at the forefront of green innovation, used by industries seeking to reduce environmental impact. Hybrid and electric vehicles rely on copper, as do renewable energy sources such as solar photovoltaic, wind farms, solar thermal, hydroelectricity and associated grid infrastructure. Constructing a renewable energy system demands significantly more copper than traditional systems.[31]

As the world transitions to low-carbon technologies it is recognised that these technologies require large amounts of minerals, including copper to meet the growing demand[32], as shown in Figure 3 below. For example, the copper intensity required to produce a wind turbine can range from 2.54 - 6.75 tonnes per MW of installed capacity.[33] It is predicted by the World Bank (2019) that while 550mt of copper has been produced over the past 5,000 years, the same amount will be required in the next 25 years to meet global demand for the metal.

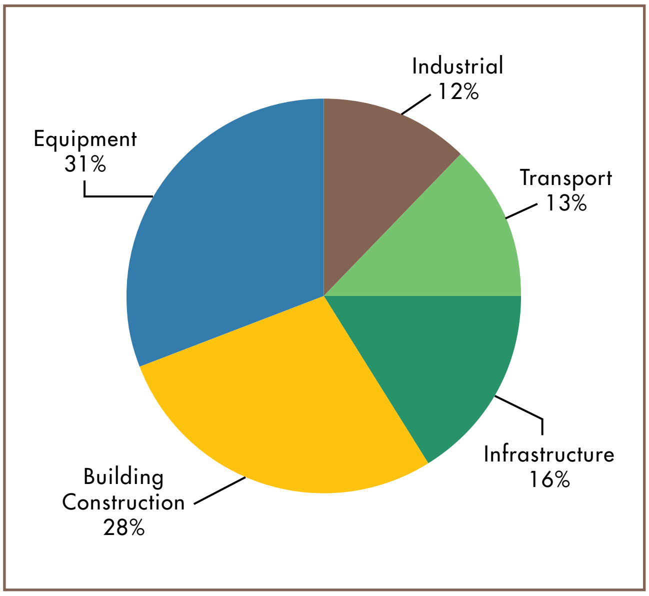
Figure 3 - 2050 Copper demand by energy Technology (%): (World Bank, 2019)



30 Ibid. Data Source Page 102
31 Teck Pty Ltd, 2019. *Connecting the Dots: Decarbonization, Mining and the Shift to a "Copper Economy"*. [Online] Available at: https://www.teck.com/news/connect/issue/volume-26,-2019/table-of-contents/connecting-the-dots
32 www.worldbank.org, 2020. *Climate Smart Mining - Minerals for Climate Action.* [Online]. Available at: https:// www.worldbank.org/en/topic/extractiveindustries/brief/climate-smart-mining-minerals-for-climate-action
33 Navigant Research, 2018. *North American Wind Energy Copper Content Analysis, prepared for Copper Development Association, Q3 2018*

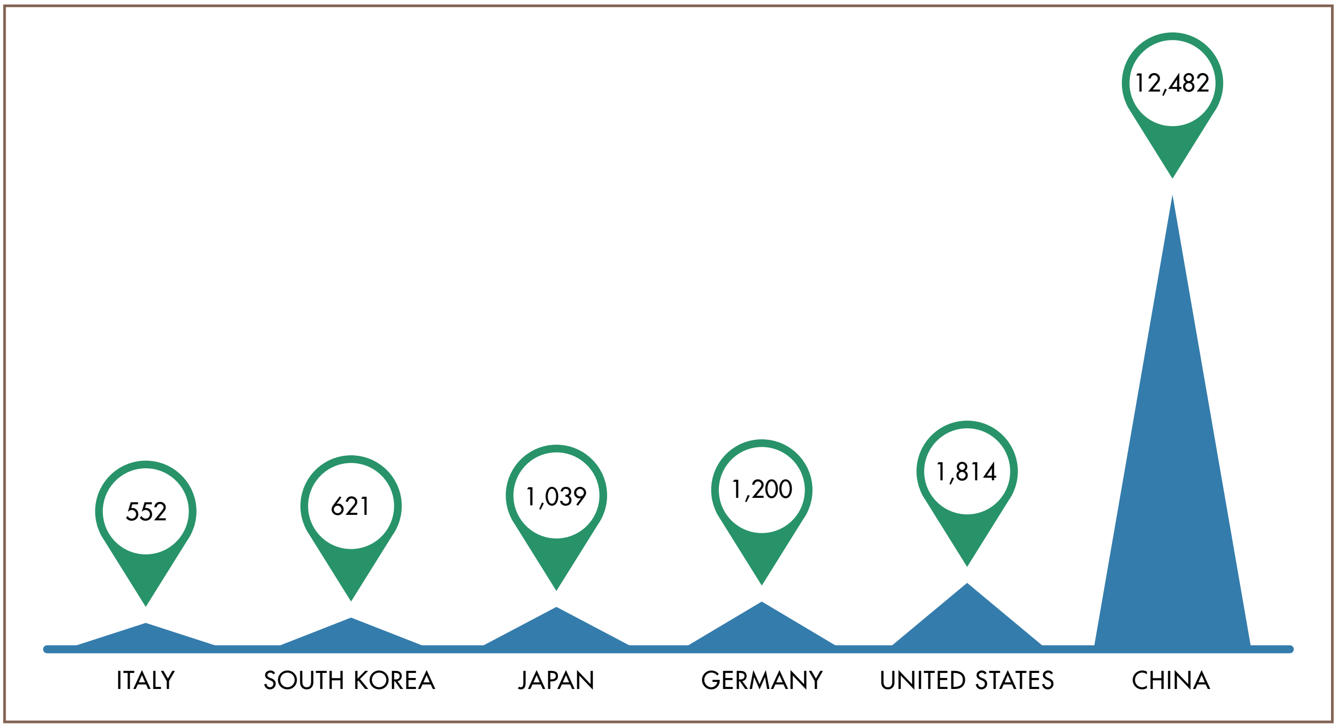
Copper also plays an essential role to modern life as an integral component in household goods, construction and infrastructure, smartphones, and electronics, refer Figure 4 (right).[34] Copper upholds a unique position as an important factor to modernisation but also plays an important role in the transition of society to a zero-carbon future.

Figure 4 - Copper uses by end use sector.
(Source ICSG The World Copper Fact Book, 2019)



Around half of the world's refined copper is used in China, with remaining key markets in the US, Europe, Japan and South Korea. Major copper use markets are outlined in Figure 5 below:[35]

Figure 5 - Key Copper Use Markets (kt) – (Source OCE - Resources and Energy Quarterly, December 2019)



While copper use is sensitive to general world economic growth, international trade factors, and industrial activity dynamics, it is not surprising that copper demand is affected by short-term factors. However, the important and broad role that copper plays in modern society including the transition to a lower carbon future indicates ongoing demand growth well beyond the short-term.[36]

34 International Copper Study Group (ICSG). World Copper Factbook. 2019.
35 Australian Government Department of Industry, Innovation and Science, 2019. *Office of the Chief Economist (OCE) Resources and Energy Quarterly - December 2019.*
36 Ibid

5.2. OVERVIEW OF COPPER MINING LANDSCAPE - FUTURE DEMAND AND SUPPLY

DEMAND

The world used more than 23.5 million tonnes of copper in 2018. As the world's leading economies continue to urbanise and industrialise, copper use is expected to increase to more than 25 million tonnes in 2021.

There is an increasing number of foundational demand side drivers, including:

- country urbanisation – China up from 19.4% in 1980 to 59.2% in 2018[37]
- onset of mobile laptop computers and smart phone units per capita since iPhone release in 2007
- low cost electrical goods and appliances – televisions, white goods
- roll out and expansion of copper-based data infrastructure networks
- technology drivers facilitating automation, data recording and storage shift to electrical vehicle (EV) production and supporting infrastructure
- a structural change towards renewable energy generation

These demand drivers are in part offset in the short term by:

- Sino – USA trade disputes
- impacts to copper end use supply chains through global 'black swan' events
- gross copper stockpile inventory and movements, and
- real changes in manufacturing use vs apparent use (goods warehouse stockpile) in China

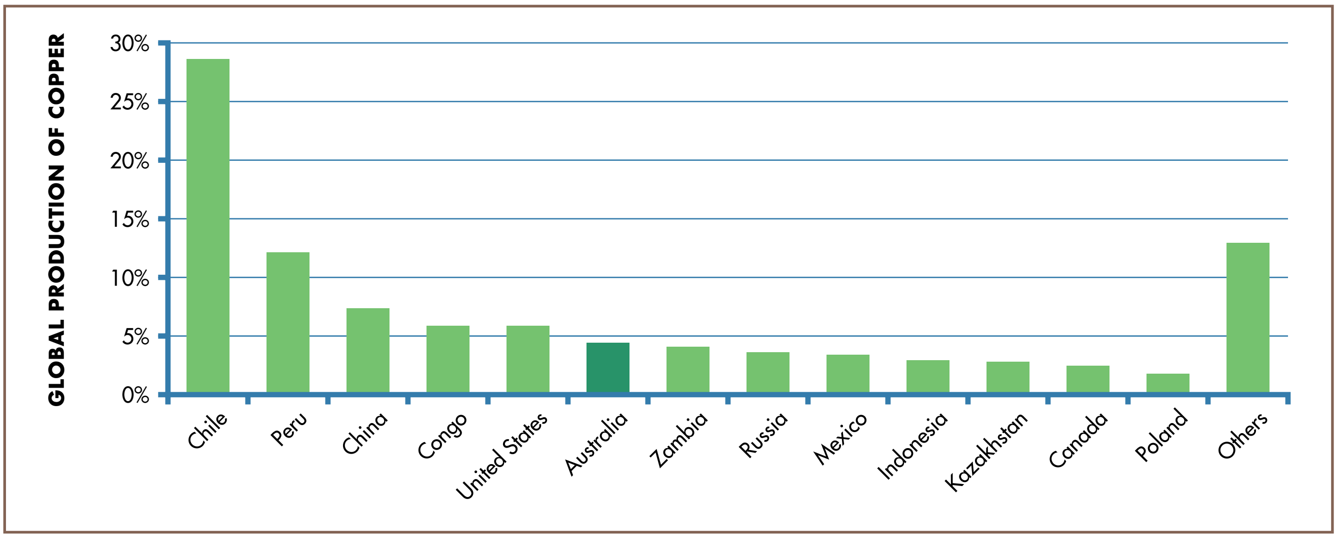
Base metals including copper, silver, aluminium (bauxite), nickel, zinc, and possibly platinum, among others, are expected to benefit from these drivers, particularly the evolution to a low carbon energy transition. It is clear that meeting the long-term Paris Agreement goal of keeping global temperature increases to well below 2°C will require:

- a change in the supply energy matrix,
- a sustained supply of the metals required to enable the clean energy shift
- increased efficiency in the mineral intensity to manufacture clean energy infrastructure
- supply side industry advancements to decrease reliance on fossil-fuel-based energy supply systems to facilitate the extraction and production of these key base metals.[38]

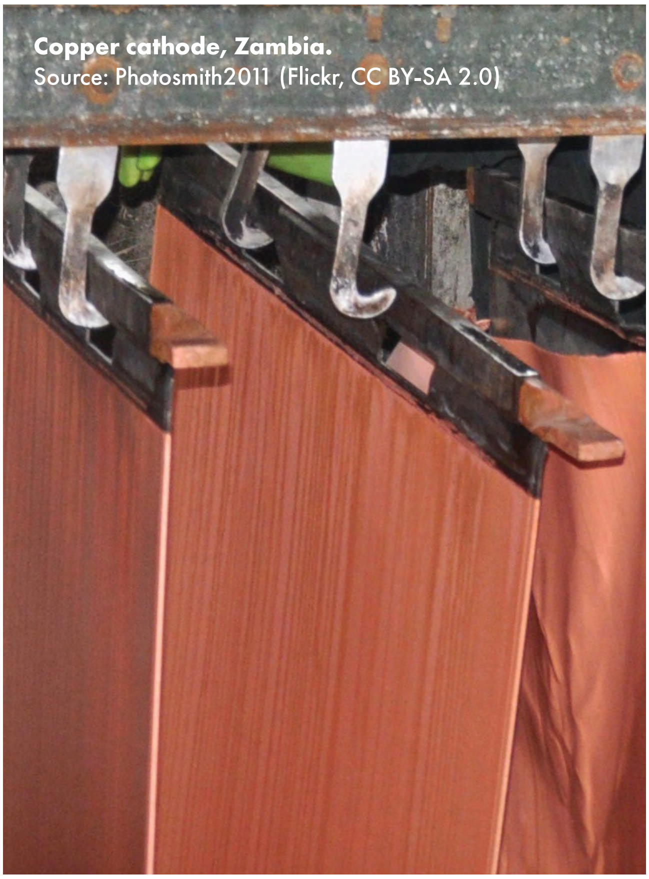
SUPPLY

Australia is one of the world's major copper mining countries, behind Chile, Peru, China, the Democratic Republic of Congo and the United States. Chile alone represents more than one-quarter of global mined copper output as indicated in Figure 6.[39]

Figure 6 - Copper Production by Country – (Source: World Bank Group Data)



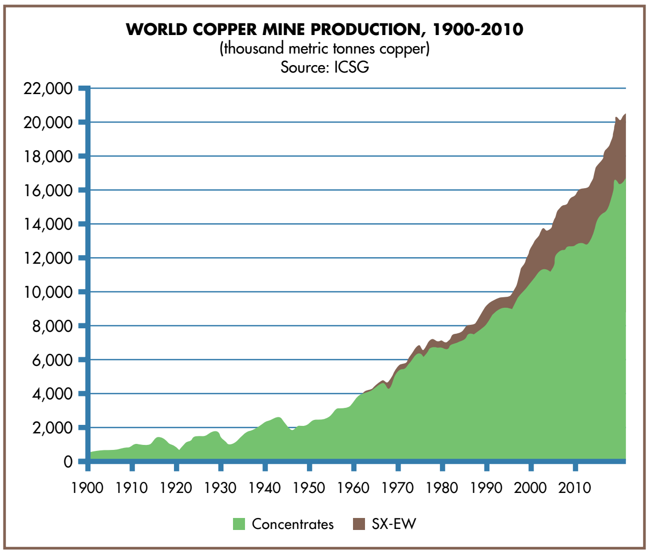
37 www.worldbank.org, 2020. *Worldbank data - Urban population (% of total population) – China*
38 World Bank Group, 2017. *The Growing Role of Minerals and Metals to a Low Carbon Future*
39 www.worldbank.org, 2020. *World Bank Data*



Copper cathode, Zambia.
Source: Photosmith2011 (Flickr, CC BY-SA 2.0)

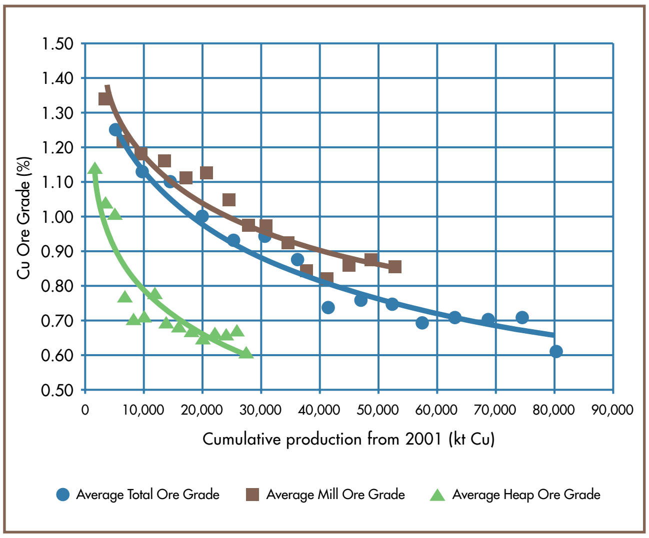
Copper is primarily produced as either an intermediary product known as a 'concentrate' or as finished plated product known as a 'cathode' from a combined solvent extraction and electrowinning ("SX-EW") process, or via electrorefining. Copper concentrates comprise the largest form of copper production, with the relative amount of copper produced via these two methods shown in Figure 7.[40]

Figure 7 - Copper mine production by product type (Source ICSG, 2019)



To meet future demand drivers, an ageing copper producing industry needs to consider a number of factors including ore grade decline (as indicated in Figure 8), resource depletion, fixed and variable input costs, cost of capital (debt and equity), availability of energy and water, permitting requirements, social support, and the availability of high–quality future development opportunities. [41]

Figure 8 - Average copper ore grades for mill plants, for Heap Leach/SX/EW processes and for Chile copper production versus cumulative production from 2001 to 2015. (Source: Lagos, 2017)



These factors are likely to require higher copper prices to attract the necessary investment in new projects to balance the market. These diverse considerations will also be contributing factors toward identifying the most feasible prospective pipeline of new projects, where the next marginal tonne of primary copper will originate, and at what production cost.

Neither the SX-EW nor concentrate source of copper production is likely to come cheaply.

40 (ICSG), *World Copper Factbook, op. cit.*
41 Lagos, The effect of mine aging on the evolution of environmental footprint indicators in the Chilean copper mining industry 2001 – 2015. *Journal of Cleaner Production*, Volume 174, pp. 389 - 400.

5.3. COPPER MINING – A BRIEF SUMMARY OF THE PROCESS

Copper production is a capital-intensive process, and the industry is facing increasing operating costs due to declining grades. As the industry faces tighter margins, the challenge to existing mine site operations is to maximise efficiencies in the extraction, comminution and metallurgical processes so as to remain profitable and sustainable.[42]

MINING

The two primarily methods of copper mining are open pit (surface mining) and underground mining. Copper ore is extracted from either oxide or sulphide orebodies, and each type of orebody requires different processing methods.

Open pit mining refers to the development of a large excavation through the use of blasting and large earthmoving equipment. Surface vegetation and waste rock are removed to reach the location of the metal ore body. Benches are carved into the walls of the excavation to provide geophysical stability as the excavation progressively deepens.

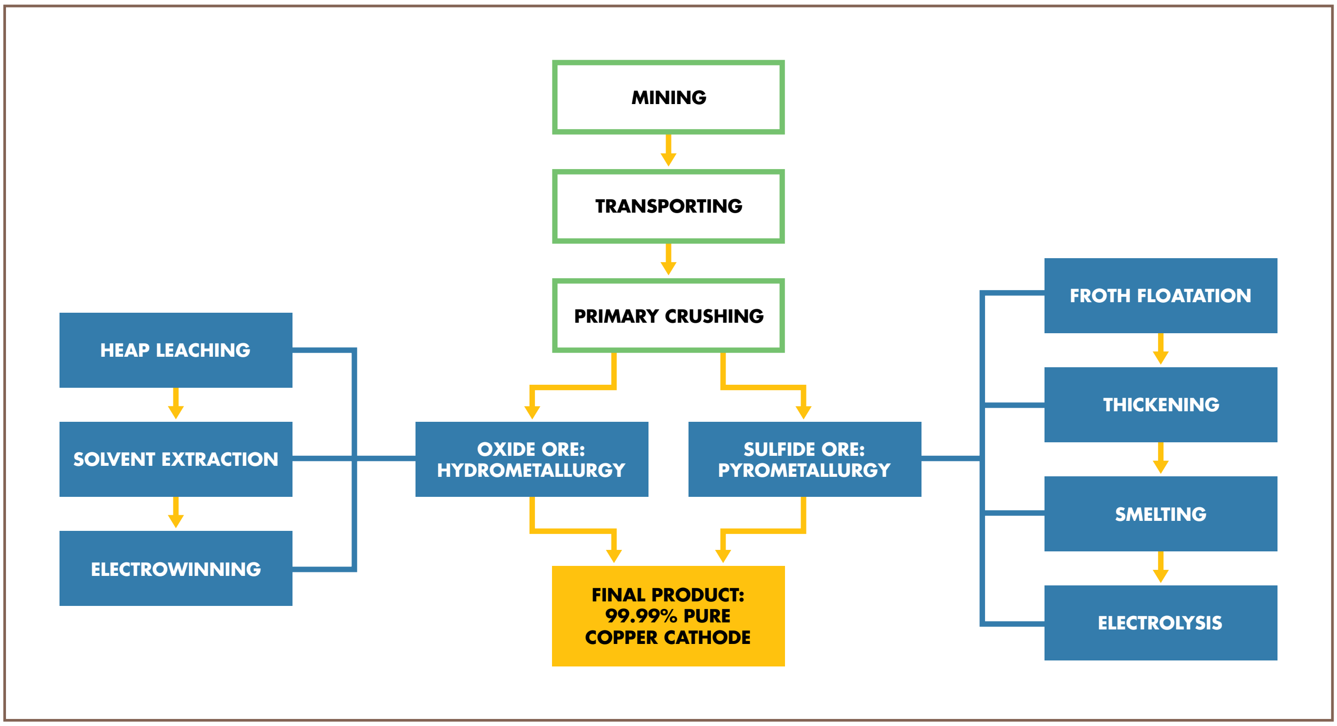
Mining is sequenced to maximise the recovery of metal ore in the orebody, with the excavation progressing deeper as the upper levels of the orebody become depleted. The metal ore is then hauled and transported elsewhere for processing and refining. Open pit mining has been criticised due to the volume of ore and waste rock removal and environmental impact. Extensive remediation processes are required to return the mining operation back to its original greenfield state.[43]

Underground mining involves the construction of a shaft or tunnel that declines under the surface and leads to the metal ore deposit. Passages are then required to be cut from the shaft at different levels to access different parts of the metal ore body. Once the ore is recovered and undergoes primary crushing, it is then hoisted or hauled to the surface for beneficiation. Underground mining leaves a lesser environmental impact on the surface compared to open pit methods, and some waste rock must still be brought to the surface for separation.[44]

BENEFICIATION

The copper beneficiation process is determined by the chemistry or nature of the host rock, be it derived from a copper oxide orebody or a copper sulphide orebody, as shown in Figure 9.[45]

Figure 9 - Copper Mining and Processing: Processing of Copper Ores – (Source: University of Arizona)



42 Ibid
43 U.S. Department of Energy, 2002. *ITP Mining: Energy and Environmental Profile of the U.S. Mining Industry.*
44 Ibid
45 University of Arizona, 2020. *Copper Mining and Processing of Copper Ores.* [Online]. Available at: https://superfund.arizona.edu/learning-modules/tribal-modules/copper/processing

The copper beneficiation process requires a high level of energy input as the ore is crushed and ground into particle sizes small enough to maximise the recovery of copper. Lago (2015) identified that 87% of the electric energy consumption in Chilean copper mining in 2015 occurred in mill plant concentrators and Leach/ SX/ EW processes.[46]

5.4. FUTURE COPPER SUPPLY SCENARIOS

Mudd and Jowitt (2018) assessed 2,301 copper deposits globally collating resources and reserves (as stated in 2015). The findings to delineate likely global copper supply are contained and align relative to "Copper Production by Country" geographies as outlined in Figure 6 and indicate that the major copper resources are primarily located in the current major copper producing regions.

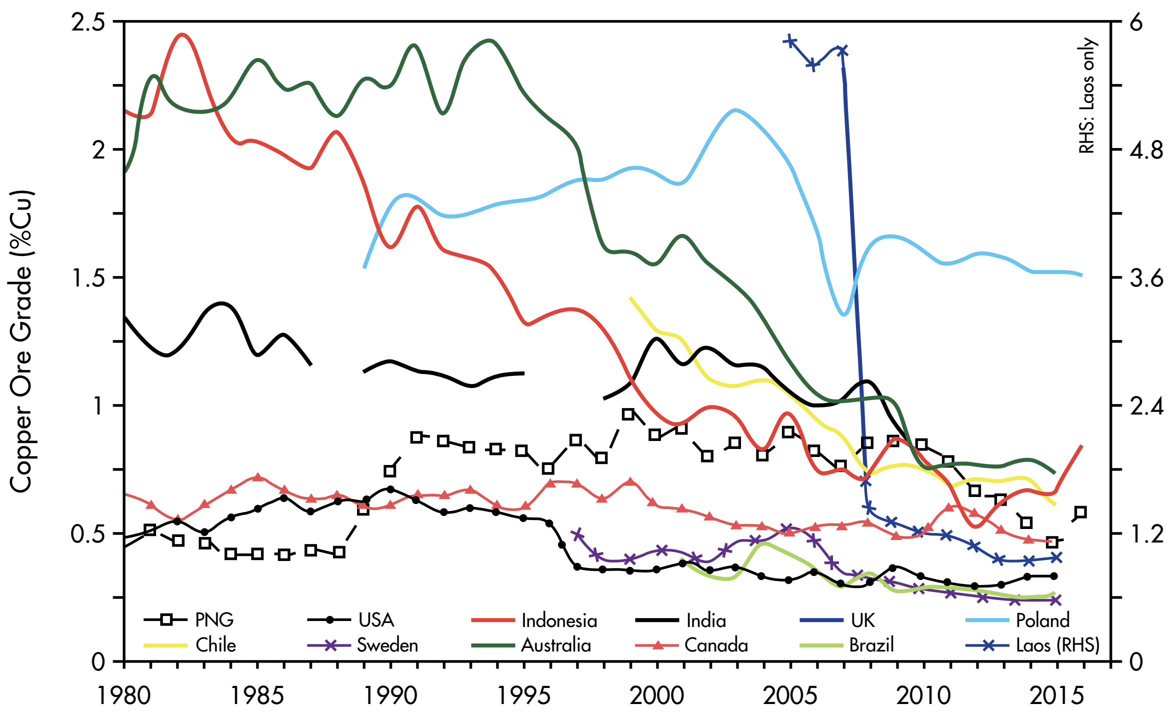
Mudd identified that approximately 75% of the contained copper in the resource database were reported in copper porphyry deposits.[47]

Both Mudd and Lagos agree that the average ore grade in copper production has been declining over time, albeit Mudd has considered the global copper trends whereas Lagos only considered Chile.[48]

Drawing from these findings, a likely outcome is that, in the absence of new high-grade discoveries, new projects will need to contend with lower grade deposits in current extractive jurisdictions.

Of note these deposits will also need to contend with the cost of mine site inputs such as water and power. In the absence of innovation and technological development, these cost inputs will likely drive up the unit cost of production and hence the price of copper in a demand driven copper market.

Figure 10 - Declining copper grades over time – (Source: Mudd and Jowid, 2018).



46 Lagos, The effect of mine aging on the evolution of environmental footprint indicators in the Chilean copper mining industry 2001 – 2015, op. cit.
47 Mudd, G. & Jowitt, S., 2018. "Growing Global Copper Resources, Reserves and Production: Discovery Is Not the Only Control on Supply". Economic Geology, 113(6), p. 1235–1267.
48 Lagos, The effect of mine aging on the evolution of environmental footprint indicators in the Chilean copper mining industry 2001 – 2015, op. cit.

5.5. THE COPPER MINING COST STRUCTURE COMPOSITION

New copper supply needs to consider costs beyond immediate site based operating costs. The investment attraction for the development of new operations takes into account where an operation is most likely placed within the global cost curve. Chile currently produces greater than 25% of the global copper supply and hence has a large influence on the current and future cost structure of the copper industry. Any new supply would need to demonstrate a favourable position against the world's largest supply region. The cost structure of new copper supply needs to consider factors including but not limited to:

- Regulation and permitting requirements at a local, national and global level
- Health, safety and environmental considerations
- Deposit grade
- Proportion of fixed and variable input costs
- Cost of capital (debt and equity)
- Availability of energy and water
- Energy consumption and emissions
- Social licence to operate
- Technology adoption
- Skills and training

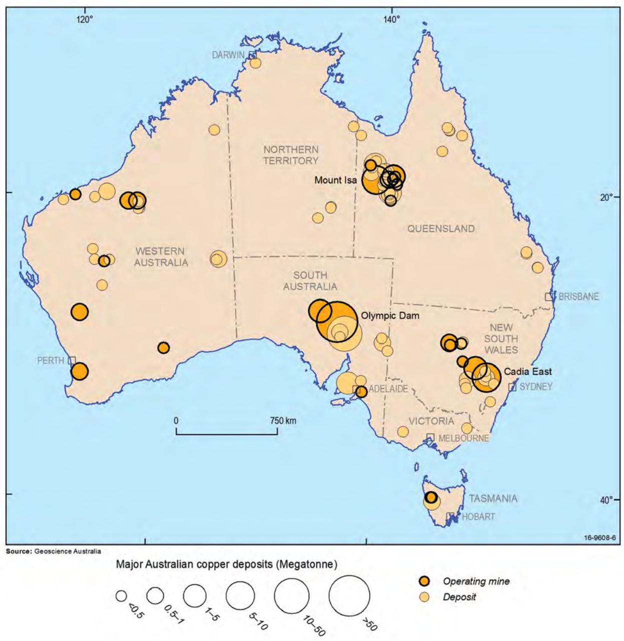
5.6. AUSTRALIA'S CONTRIBUTION TO CURRENT AND FUTURE SUPPLY

Australia is likely to play an important role in the future global copper mining landscape and is ranked second in the world for economic resource potential.[49] It is currently is the seventh largest producer of copper globally, and the second largest exporter in primarily copper ores and concentrates.

A number of new projects and expansions are underway, which are expected to underpin export growth in line with production output from 932kt in 2018-19 to 1.0Mt in 2020-21.[50]

Figure 11 shows Australia's major copper deposits and mines indicating the breadth of distribution in deposit size.[51]

Figure 11 - Australia's Major Copper Deposits and Mines (2016)



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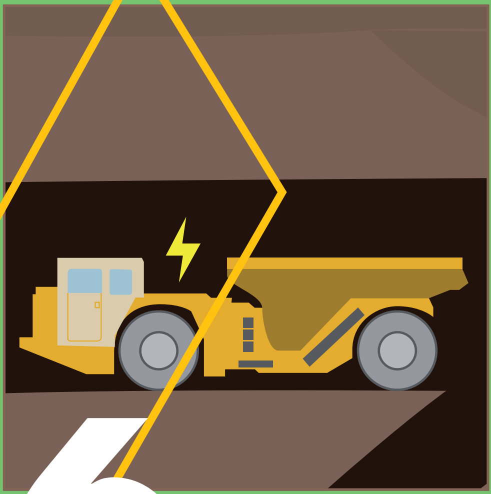
49 Australian Government - Geoscience Australia, 2020. *Copper.* [Online]. Available at: https://www.ga.gov.au/data-pubs/data- and-publications-search/publications/australian-minerals-resource-assessment/copper

50 Australian Government Department of Industry, Innovation and Science, 2019. *Office of the Chief Economist (OCE) Resources and Energy Quarterly - December 2019.*

51 Australian Government - Geoscience Australia, 2020. *Copper.* [Online]. Available at: https://www.ga.gov.au/data-pubs/data- and-publications-search/publications/australian-minerals-resource-assessment/copper



6. Emission contribution in primary copper production

6.1. EXPLORING THE EMISSIONS FROM A TYPICAL COPPER OPERATION

Greenhouse gas (GHG) emissions through the copper production process are typically associated with the consumption of fuel in the mining and materials transport process, and indirect emissions from electrical energy use in extractive and beneficiation processes.[52]

Northey et. al. assessed a wide variety of copper producing mines to determine the average energy intensity and GHG intensity with an average of 2.6 t CO_2-eq per tonne of copper produced, as shown in Table 1 below. Energy intensity was categorised into direct and indirect energy categories, aligned with the recommendations from the Global Reporting Initiative (GRI) guidelines. GHG emissions were calculated as the sum of Scope 1 and Scope 2 emissions.

52 Australian Government: Australian Renewable Energy Agency (ARENA), 2017. *SunSHIFT: Renewable Energy in the Australian Mining Sector.* [Online].

Table 1: Summary of greenhouse gas emissions and energy intensity of a typical copper process, obtained by an assessment of sustainability reports of several copper producing mines around the globe. [53]

		RANGE	AVERAGE
ENERGY INTENSITY (GJ / t Cu produced)	TOTAL	10 – 70	22.2
	DIRECT	2 – 51	13
	INDIRECT	1 – 23	12
GREENHOUSE GAS EMISSIONS (t CO_2-eq / t Cu produced)		1 – 9	2.6

These findings indicate that while there is a broad range of emission intensity within the industry, the average is skewed toward the lower end of the range.

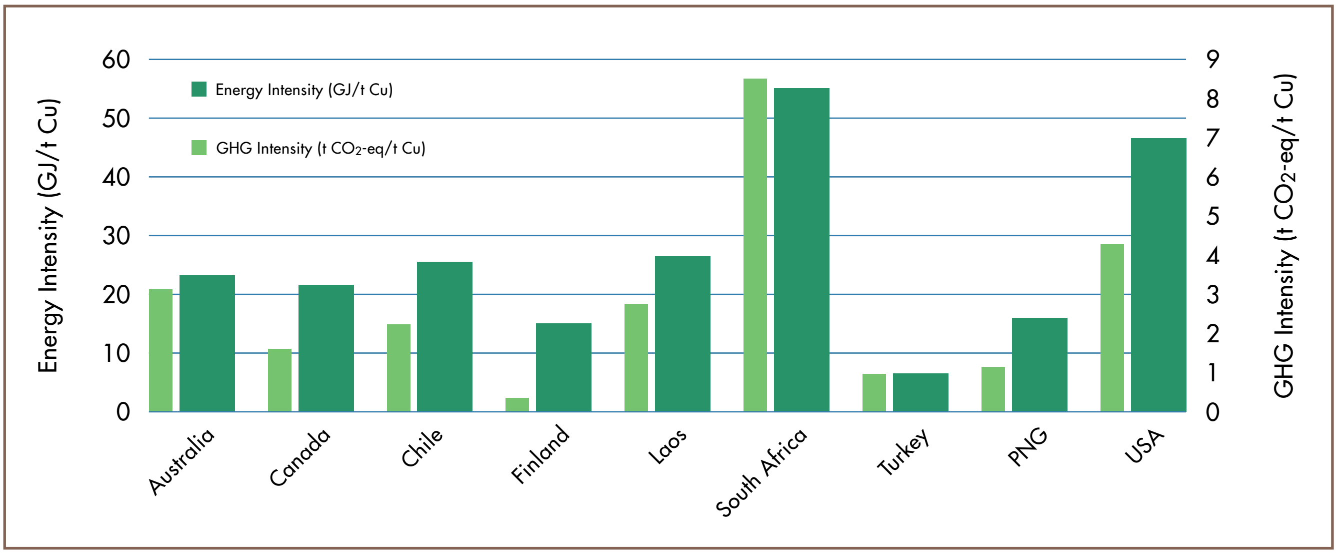
6.2. A NOTE ON SULPHUR DIOXIDE

Of note, in addition to managing CO_2 emissions, the copper industry also addresses emissions from sulphur dioxide (SO_2). Sulphur dioxide (gas) is typically produced in smelting, leaching, and electro-refining. The smelting-converting process produces 2t SO_2/ t Cu produced (energy and process emissions).[54] These emissions are typically captured and reused for sulfuric acid production on site. The copper industry has established processing pathways to manage other gas pollutants such as SO_2 as a product within the copper extraction process.

6.3. DIVISION BY COUNTRIES

Additional data from Northey et. al. is summarised in the Figure 12 below, showing the energy intensity and GHG emissions intensity of primary copper production by country. It should be noted that for all countries except Australia, Canada and Chile, only a single mine was in the data set.

Figure 12

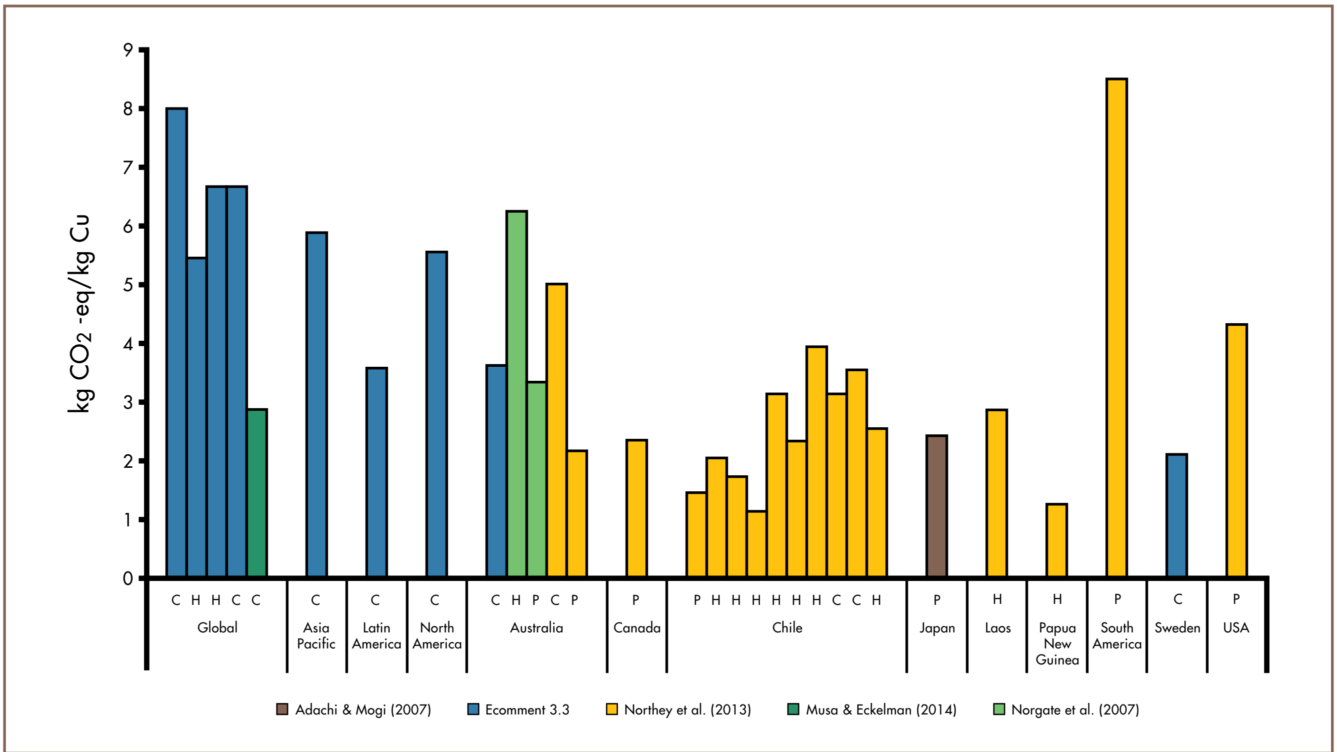


The relationship between the energy intensity and GHG intensity correlates to the primary energy source used in production.

53 Ibid.
54 Alvarado, S., 2002. Long term energy-related environmental issues of copper production. *Energy*, 27(2), pp. 183 - 196.

A review of the carbon footprint of copper mines by country and metallurgical process was carried out by Nilsson et. al. (2017)[55], as shown in Figure 13 below.

Figure 13 - Overview of carbon footprints (CFs) of copper (Cu) production (Cradle-to-gate) from primary sources by geographic region and metallurgical process - Pyrometallurgy, Hydrometallurgy, and Combined. (Source Nilsson et. al. (2017)




Copper cathode.
Source: Rolinator, CC BY-SA 3.0.

It is indicated that energy intensity of the primary copper production process will vary greatly, as most likely a result of factors such as:

- Variation in deposit type, ore grade and composition
- Geographic location and number of operating days per year
- Mining method and equipment requirements
- Material movement methods
- Waste to ore ratios
- Type of copper produced
- Processing method and output (concentrate or cathode),

Whereas the GHG intensity is linked to the available energy sources.[56,57,58]

55 Nilsson, A. E. et al., 2017. A Review of the Carbon Footprint of Cu and Zn Production from Primary and Secondary Sources. *Minerals,* 168(7).
56 *Ibid.*.
57 Northey, S., Haque, N. & Mudd, G., 2013. Using sustainability reporting to assess the environmental footprint of copper mining. *Journal of Cleaner Energy*, Volume 40, pp. 118 - 128
58 US Department of Interior, US Geological Survey, 2011. Estimates of Electricity Requirements for the Recovery of Mineral Commodities, with Examples Applied to Sub-Saharan Africa. *Open File Report 2011-1253*, pp. 36 - 38..

6.4. THE IMPACT OF DECLINING ORE GRADE

The trend towards declining orebody grades and continued development of the pursuit of existing operation to exploit lower grade deposits is likely to continue, in the absence of high-grade project discovery. A decline in ore grade results in higher operating cost due primarily to the amount and depth of material required to be mined and processed to produce the same amount of copper product. It is no surprise that both GHG emission intensity, refer Figure 14, and energy intensity, refer Figure 15, increase as ore grade decreases. There is a point of inflection, where below an ore grade of around 0.5% Cu the intensity of both metrics rises sharply.

Figure 14 - GHG Intensity as a function of ore grade for 28 copper operations, with each data point representing a year of production. (Source: Northey et. al.) [59]

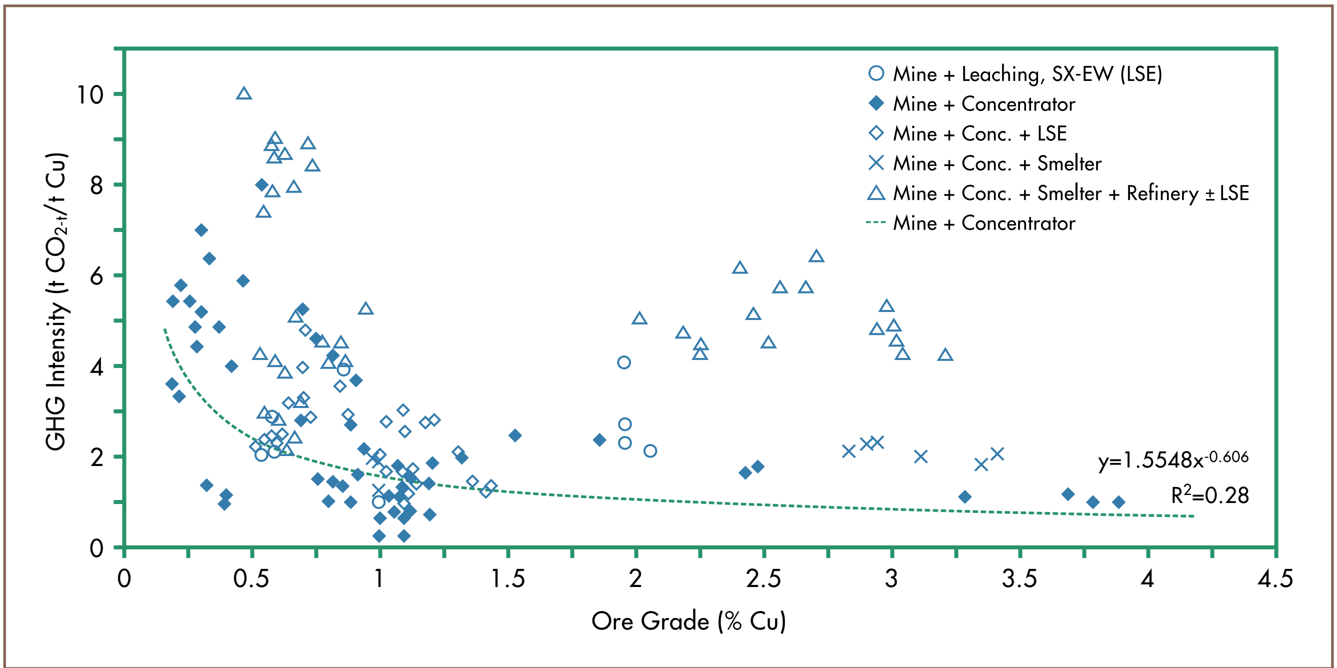
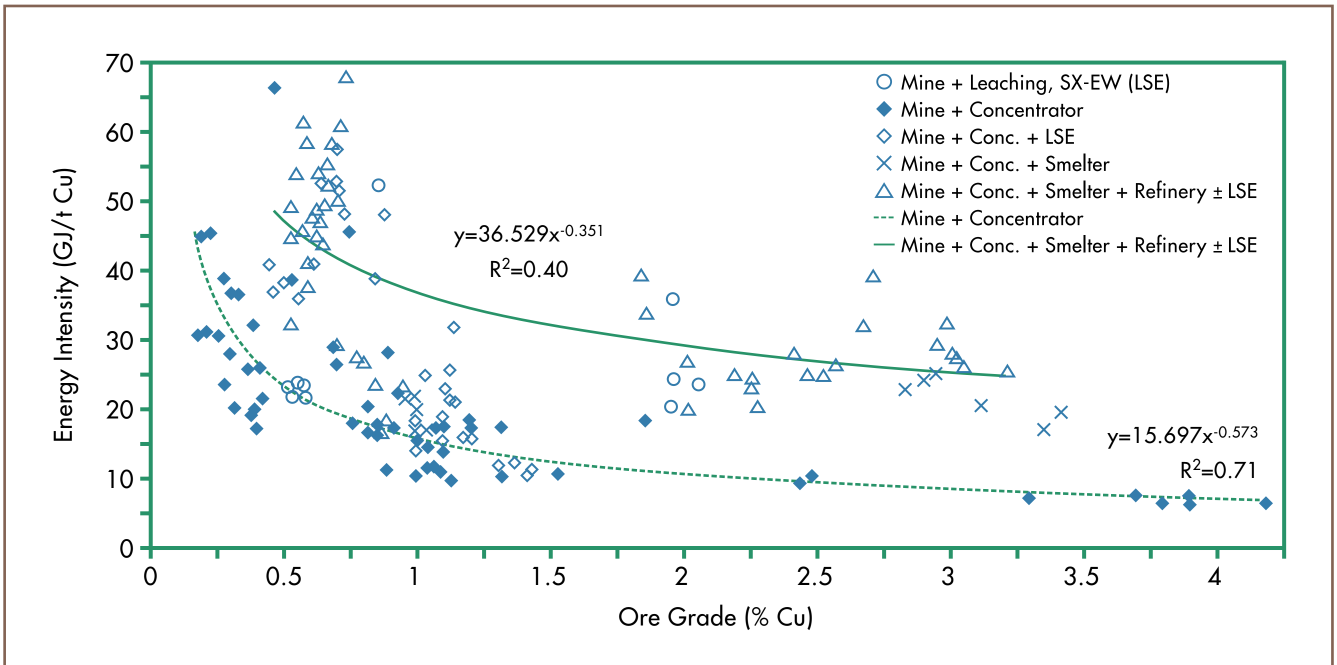


Figure 15 - Energy Intensity as a function or ore grade for 31 copper operations, with each data point representing a year of production. Source: Northey et. al.[60]



59 Northey, S., Haque, N. & Mudd, G., Using sustainability reporting to assess the environmental footprint of copper mining. *Journal of Cleaner Energy*, op. cit.

60 Ibid.

6.5. WHERE ARE THE EMISSIONS FROM A TYPICAL COPPER OPERATION?

There are a number of factors that drive and influence the energy and emission intensity of the copper mining process. The ore grade and geochemical composition will determine the extraction methodology that will influence both the intensity and quantity of emissions from the mining and mineral processing stages of production.

> ***In general, the energy consumption in the primary copper process is dominated by the earlier stages of beneficiation. This is due to the high energy demand requirement to crush and grind ore. Within the mining process loading and hauling, blasting, and ventilation (in the case of underground mining) all consume a higher proportion of energy to other aspects of the mining process.***

GHG emissions are in general comparable for underground operations versus open cut mines when viewed in a global context. There are differing opinions as to whether pyrometallurgical processes have a higher energy intensity than electrowinning and waste heat recovery.[61] There is however consensus that the extractive processes are the most energy intensive stage of the entire copper production process.

While not extensive, several journal articles and government reports have estimated the distribution of emissions in the process chain. These estimations have been summarised schematically below, noting the variation between sources related to process assumptions and ore grade variability.

6.6. EMISSION COMPARISON BETWEEN UNDERGROUND AND OPEN CUT MINING

The average emissions and energy intensity for underground, open cut, and combined mines have been compared (data obtained from Northey et al.) It can be seen that open cut mining methods have a higher energy intensity, underground mining produces a comparable emissions per tonne of copper produced.

The increased energy requirement of a combined mine is due to integrating the operating parameters of an underground operation. In addition to hauling and ore transportation that is required energy in an open-cut mine, underground mining is often at depth and requires significant energy demand for hauling in addition to ventilation, lighting, water pumping, increased transfer points for materials handling and other necessary activities.[62]

As the industry seeks to exploit lower grade and deeper deposits, the incorporation of underground operations to existing open cut operations could result in an increased number of combined operations. The outcome is that GHG emissions are approximately 35% greater when an underground mine is combined with an open cut site.

Table 2 - Summary of greenhouse gas emissions and energy intensity of underground, open cut and combined mines, obtained by an assessment of sustainability reports of several copper producing mines across the globe.[63]

		UNDERGROUND	OPEN CUT	COMBINED
ENERGY INTENSITY (GJ / t Cu produced)	TOTAL	21.9	26.8	28.3
	DIRECT	9.3	16.1	12.8
	INDIRECT	12.6	9.1	17.5
GREENHOUSE GAS EMISSIONS (t CO_2-eq / t Cu produced)		2.47	2.52	3.42

61 Nilsson, A Review of the Carbon Footprint of Cu and Zn Production from Primary and Secondary Sources. *Minerals, op. cit.*

62 U.S. Department of Energy, 2007. *Mining Industry Energy Bandwith*

63 Northey, S., Haque, N. & Mudd, G., Using sustainability reporting to assess the environmental footprint of copper mining. *Journal of Cleaner Energy*, op. cit.

6.7. ENERGY DISTRIBUTION WITHIN THE MINING PROCESS CHAIN

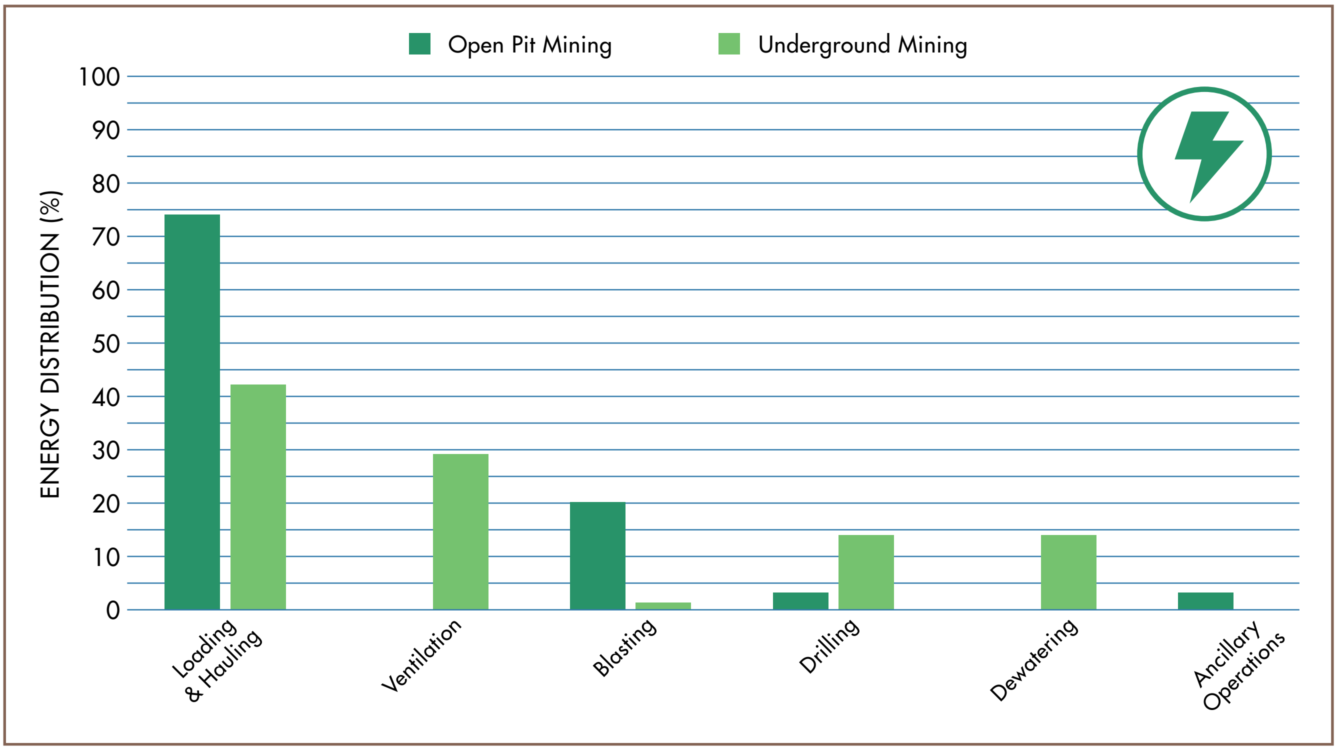
The energy distribution for underground and open cut mining extraction processes are represented in Figure 16 below, which was adapted from information sourced from Norgate and Hague (2010). It assumes an ore grade of 1.8 % and the production of concentrate, grade 27.3%.

Within the mining process, loading and hauling account for a greater proportion of energy consumption due to heavy reliance on diesel operated vehicles. Diesel is required to transport large quantities of waste rock from an operation to ensure only copper bearing ore of grade is sent to the mill for processing.

Underground mining also requires ventilation, lighting and water as essential services. The confinement of underground mines creates a potentially toxic and explosive environment that needs to be mitigated to provide a safe working environment for mine site operations personnel. Ventilation is required to remove and dilute airborne contaminants with the use of underground fans which justifies the high energy demands. [64, 65]

Water and lighting are essential services to ensure efficient drilling practices. Water is used in drilling, water spray is used to minimise airborne particles, and water is used as a coolant in deep operations. Water generated through underground mining operations as well as water inflow from operations below the water table is pumped to the surface as part of dewatering activity to ensure a safe working environment.

Figure 16 - Percentage distribution of energy within the copper production process for open cut and underground mining operations

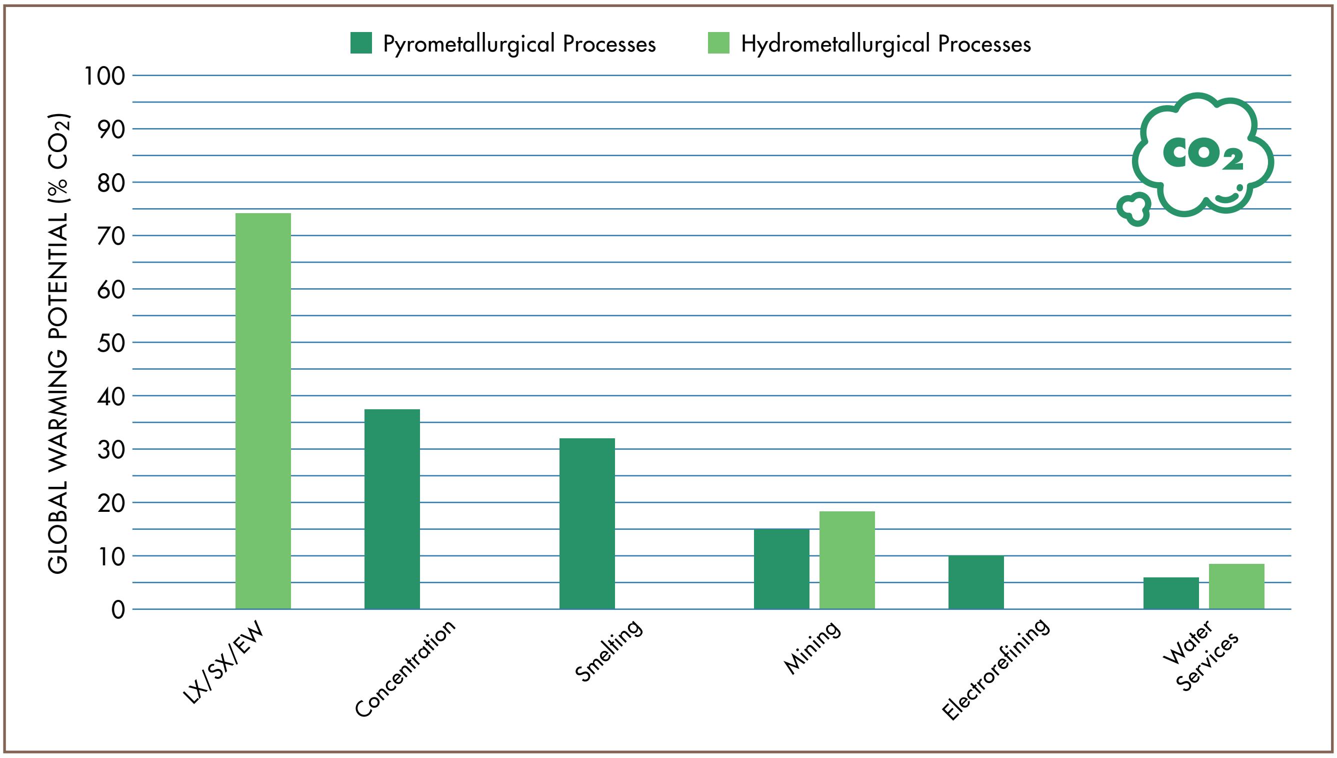


64 Norgate, T. & Haque, N., 2010. Energy and greenhouse gas impacts of mining and mineral processing operations. *Journal of Cleaner Production*.
65 Pitt, C. & Wadsworth, M., 1981. Current Energy Requirements in the Copper Producing Industries. *JOM*, 33(6), pp. 25 - 34.

6.8. ENERGY DISTRIBUTION IN THE BENEFICIATION PROCESSES

Moreno-Leiva et. al. determined the comparative emissions (global warming potential) for pyrometallurgical and hydrometallurgical processes.[66] The distribution of these emissions in the process chain are shown in the Figure 17. Norgate et. al. (2007), determined converse results between the two processes, and therefore it is difficult to conclude a comparative advantage of one process over the other, except to conclude that the overall processing phase, regardless of method, holds the greatest global warming potential when compared to other aspects of the mining process.[67]

Figure 17 - Percentage of GHG emissions between pyrometallurgical and hydrometallurgical operations including mining and processing



66 Moreno Leiva, S. et al., 2017. Towards solar power supply for copper production in Chile: Assessment of global warming potential using a life-cycle approach. *Journal of Cleaner Production*, Volume 164, pp. 242-249.

67 Norgate, T. E., Jahanshahi, S. & Rankin, W. J., 2007. Assessing the environmental impact of metal production processes. *Journal of Cleaner Production*, Volume 15, pp. 838 - 848

7.

The Pathway to a Zero-Emission Copper Mine of the Future

THE PATHWAY TO ACHIEVING A ZERO-EMISSION COPPER MINE OF THE FUTURE CAN BE DELIVERED THROUGH A NUMBER OF SCENARIOS. THE SOLUTION IS EMBEDDED IN A MULTI LAYERED FRAMEWORK WHERE PRODUCERS IDENTIFY AN OPTIMAL PATHWAY TO ADDRESS THESE SIGNIFICANT CHALLENGES BALANCED AGAINST THE OPERATING NEEDS AND CONSTRAINTS OF A BUSINESS.

The copper mining process is complex and nuanced when taking into account various ore types, geographic settings, and the extractive and processing technologies to produce economically sustainable products. To achieve this objective the development of a zero-emission strategy will require a combination of actions from a diverse group of actors including producers, suppliers, governments, investors, not for profit organisations and researchers.

A number of these innovative technologies have been identified, deployed and positioned for scale. Many innovators and suppliers however are not yet clear on the specific value proposition and role they could play toward a lower emission future, and the opportunity to partner and leverage with complementary solutions to provide an integrated and whole-of-systems thinking approach along the mining value chain.

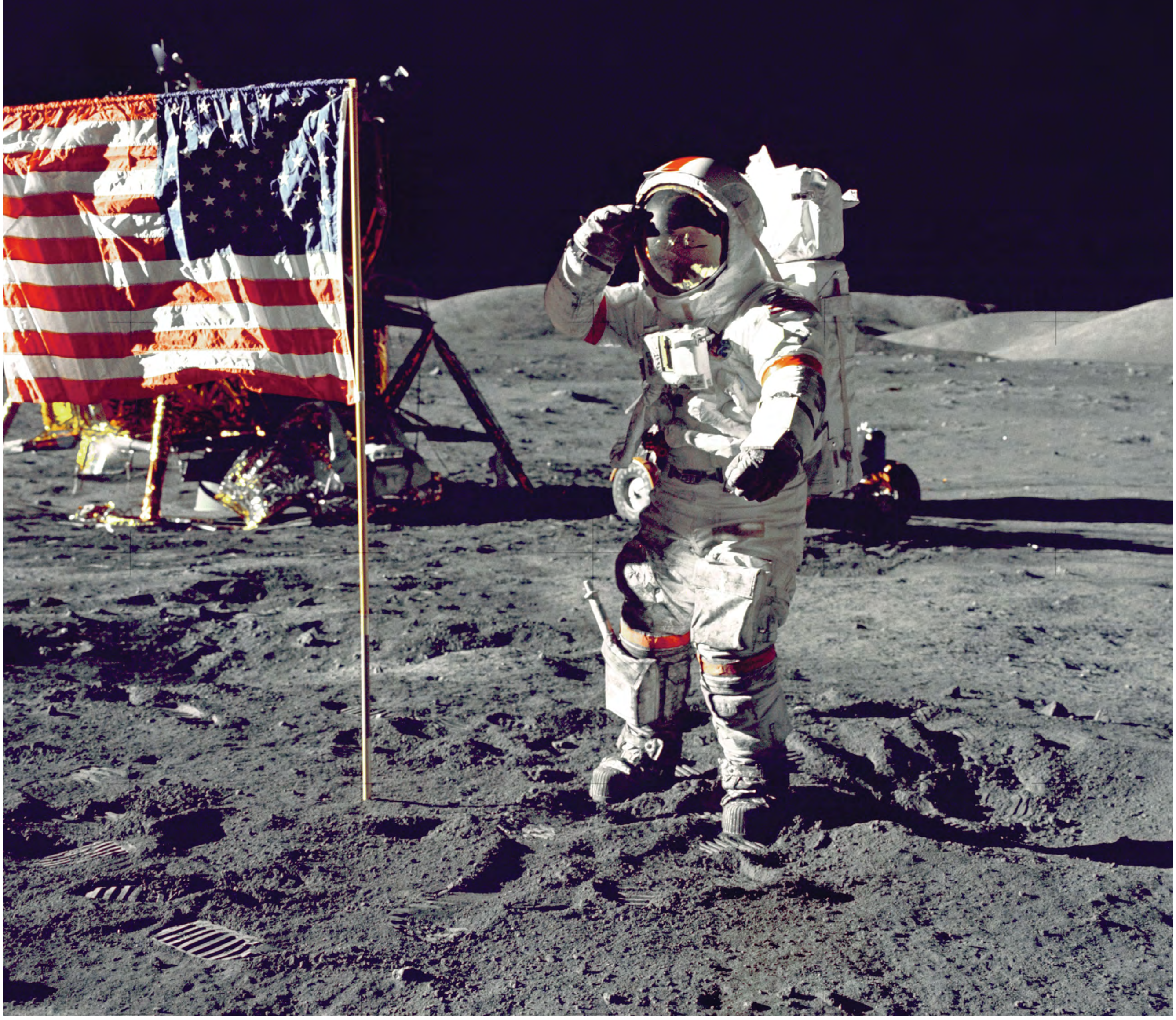
From both the producer and supplier perspective, an understanding of a range of risks relating to technology, commercial, social and stakeholder risks should also be reviewed in consideration of a wider deployment across the industry.

There are a number of technologies under research and development that are not yet market-ready, nor have the commercial capacity to be deployed at scale. It is also anticipated that future 'breakthrough' technologies and innovations from within and outside the sector will almost certainly play a role in future copper mining decarbonisation scenarios.

In anticipation of increased industry demand for innovative technologies that could contribute to a decarbonisation pathway, a coordinated partnership approach must be enacted to realise future opportunities. A partnership approach is needed also to optimise the opportunity for success to support technology transition and manage risk in a complex and variable operating environment.

A collaborative vision coupled with an underlying framework to activate and enable innovation is essential to achieve impactful decarbonisation scenarios and pathways. A strategic vision and framework will influence and drive policy, programs, research, capital, knowledge and skills across the copper mining value chain. Such a vision optimises the likelihood of success to achieve a zero-emission future balanced by industry needs, cost structure and productivity considerations.

The Apollo Moon Landing inspired generations of engineers and scientists.
Source: NASA, public domain.



John F. Kennedy, Rice University, Houston, 1963.
Public domain.

Moonshot Thinking - Is the road to a zero-emission copper mine of the future a fast-track or long-term vision?

More than 50 years ago, U.S. President John F. Kennedy captured the world's imagination when he said, "This nation should commit itself to achieving the goal, before the decade is out, of landing a man on the moon and returning him safely to the Earth." Thus, the term 'moonshot' entered the lexicon as shorthand for "a difficult or expensive task, the outcome of which is expected to have great significance."[68]

At the time, the world redefined possibility and changed the parameters of what seemed impossible through the activation of the space race. The speed at which technology was created and improved in order to complete the seemingly 'impossible task' was progressing at an accelerated rate and ultimately resulted in reaching a level of technology that surpassed any previous expectations.

This type of thinking has since then been applied successfully in other industries and is more commonly known as 'moonshot thinking'. Moonshot thinking brings a thought process to propose a radical technology or vision that can have a global impact for some of the world's most difficult problems. It aims to provide a solution that not only brings small improvements to a specific field but also solutions that can give ten times improvements and completely solve the issue at hand.[69] A blueprint of 'moonshot' thinking is presented below which describes three key components.

In strategy development moonshot thinking takes a "future back" approach to strategy which requires a consensus view of a desired future state. A good "future back" strategy goes well beyond a three- year planning horizon and has three aspects to success:

- It inspires
- Is credible
- Is imaginative

A Zero-Emission Copper Mine of the Future is such a moonshot aspiration, as the success elements to build a future back strategy requires the foundation of clear short, long term, and multi staged frameworks. Despite appearing impossible, previous experiences throughout history teach that these heights can be reached with a consensus vision and correct pathways in place.

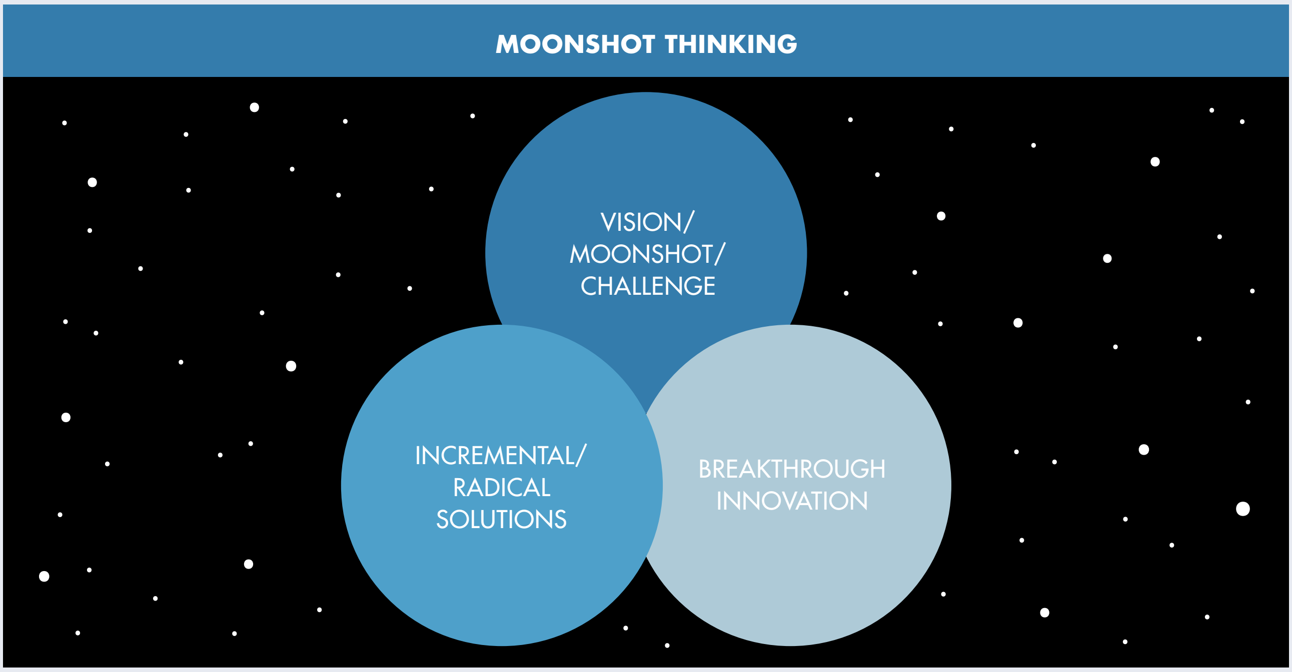
68 Anthony, S. D. & Johnson, M., 2013. *What a Good Moonshot is Really For.* [Online]. Available at: https://hbr.org/2013/05/what-a-good-moonshot-is-really-2

69 Alayon, D., 2019. *Understanding Moonshot Thinking.* [Online]. Available at: https://medium.com/future-today/understanding-moonshot-thinking-783e3399c611

Moonshot Thinking - Is the road to a zero-emission copper mine of the future a fast-track or long-term vision? *(continued)*

In the case of a decarbonised future for copper mining, significant breakthrough technology takes time, and this needs to be balanced with incremental short-term goals.

Figure 18 - An adapted Blueprint of Moonshot Thinking[70]



SpaceX is leading the new generation of 'moonshot' imagination.
Source: SpaceX, CC-BY.

70 Ibid

Vertical rocket landing was believed to be impossible until 2015.
Source: SpaceX, CC-BY.

Moonshot Thinking - Is the road to a zero-emission copper mine of the future a fast-track or long-term vision? *(continued)*

A challenge to the application of moonshot thinking in the copper industry is to leverage the level of public knowledge on the value copper offers to society now and into the future, as well as where copper originates. In comparison with the space race, where these advancements were trending worldwide at the time and sparked a global interest, copper is far from this level of interest to the general public. Multiple experts who were interviewed in the process of making of this report answered that the public has some understanding of mining but little to no knowledge at all with regards to copper, where copper comes from, how it is produced, what is it used for, how it impacts daily lives.

> ***I call it a broad understanding, that is there is quite a number of people in our community who have a fairly good understanding of the mining process at the 30,000 foot level. It's not that we're an entirely ignorant society when it comes to mining and its processes.***
>
> *Adrian Beer, CEO METS Ignited Australia Ltdor*

> ***I don't think so, I think it's like an aircraft black box, copper is invisible in society, yet it plays such a crucial role. People don't have an understanding of the technological, societal, and regulatory complexity and the social aspects of extracting copper from the Earth.***
>
> *Hal Stillman Global, International Copper Association ICA, USA.*

Following from this however, Stillman also emphasised that the current generation of people are also limited in their understanding of not even just copper, but how everyday products are produced.

> ***"We don't even know where our food comes from. And we consume it every day."*** *Hal Stillman Global, International Copper Association ICA, USA*

Decarbonisation in industry however is a significant and rapidly evolving global trend. Aligning moonshot thinking of a Zero-Emission Copper Mine of the Future will be an essential component to achieve this objective and could positively contribute toward society's knowledge and perception of copper production and its wider contribution to society.

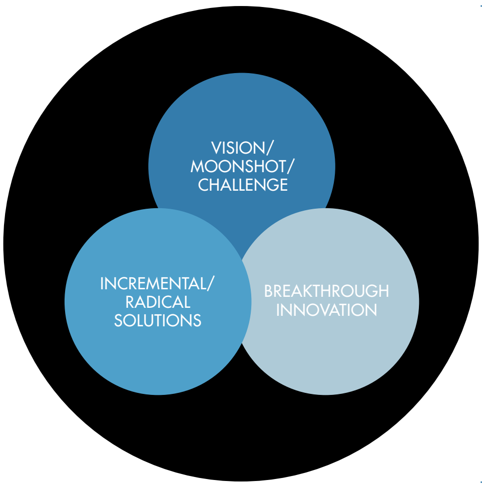
7.1. HORIZONS OF OPPORTUNITY FOR A LOW EMISSION FUTURE

There are numerous pathways for copper producers to realise a lower emission future. Guidance and alignment of innovative opportunities in addition to well identified horizons for adoption are essential to address energy efficiency and productivity opportunities along the identified emission intensive points of the current copper mining value chain.

Existing innovative mining equipment, technology and services (METS) businesses can be an important source of new ideas for producers to address emission reduction pathways in the short and medium term. Raising the profile and awareness of innovative new technologies that offer pragmatic solutions, including a risk matrix of adoption, will act to complement and enable accelerated roadmap efforts for individual and consortium stakeholders.

> ***The METS sector plays an absolutely critical role in technology development and implementation. A mining company's business is primarily focussed on safety, product quality, reducing cost and minimising the environmental footprint. Miners are predominantly technology users and not technology developers. METS companies can be the drivers, and by working in close partnership with (mining) companies and research providers, effectively deliver technology solutions into the field.***
>
> *Dr Chris Goodes, University of Melbourne*

Looking beyond the mining industry to advancements made in other sectors offers an additional opportunity for the cross-pollination of information, ideas and technology between industries. This requires a new approach in which all players that contribute to the copper supply chain could actively engage and participate in open communication and collaboration.



Create the setting and foundation for industry to ***navigate choice*** *on alternate technologies that could meet operational needs, coupled with opportunity to reduce emission in the short, medium, and longer-term horizons.*

A raised awareness technology and innovation will create positive industry perception, and the ***momentum to test, pilot, measure, and ultimately increase the uptake of innovative solutions.***

Numerous operational economic drivers influence a copper producer's appetite for innovation uptake. Operational cost drivers, alongside the balance of push and pull mechanisms, are required to drive the uptake of emission reduction technologies.

> ***Where you get synergy is when there is opportunity to reduce both cost and reduce emissions. That's when it starts to become economic and to be proactive in reducing emissions, and what will motivate people to change.***
>
> *Jacqui McGill AO, C-Suite Executive and Non-Executive Director*

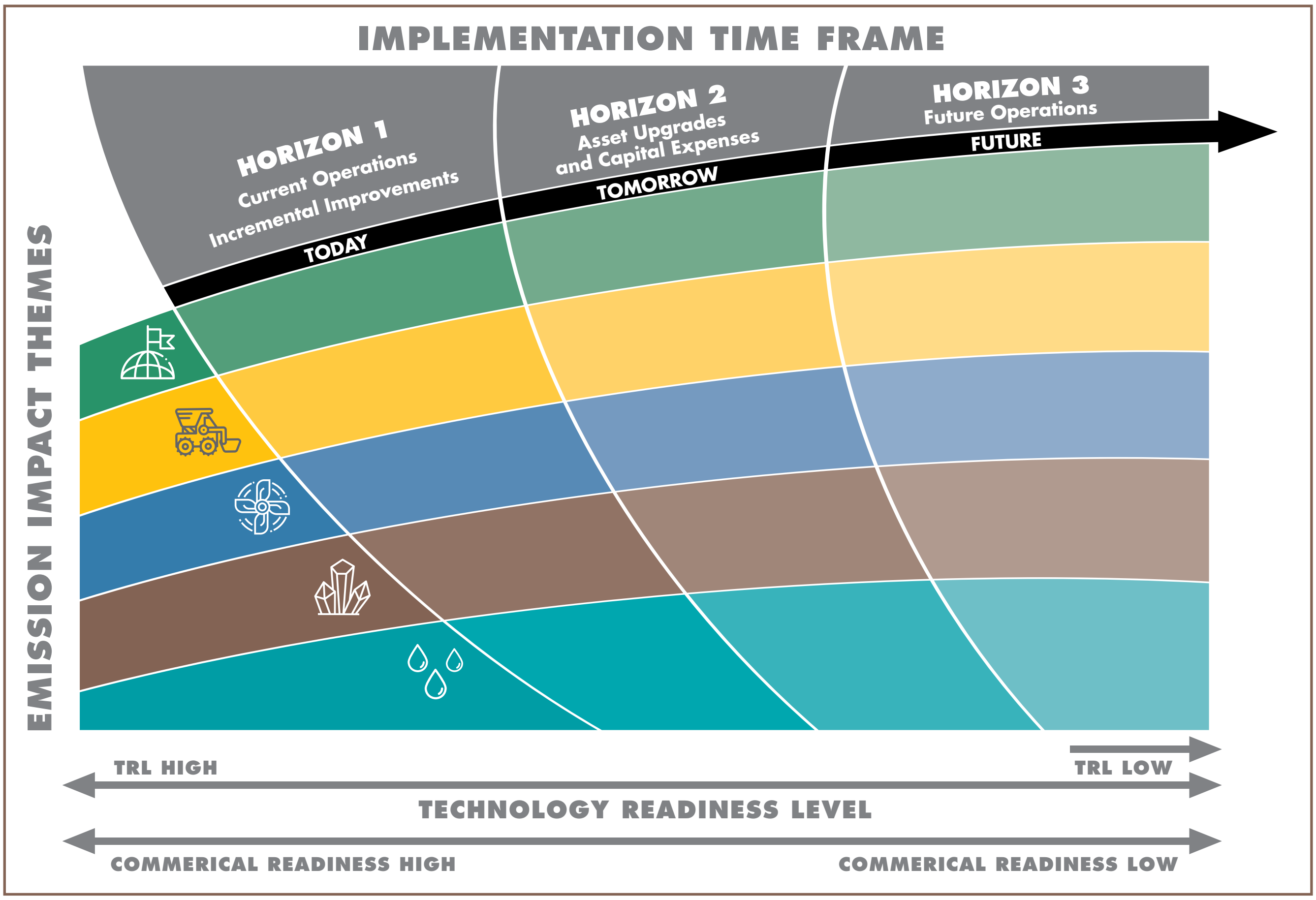
In the shorter-term, emission reduction opportunity pathways exist at a number of points along the development and operating mining chain, and uptake should be linked to points of project development, capital acquisition, maintenance cycles, and overhauls to optimise likelihood of success.

> ***There is a window of opportunity in any particular mine when they can adapt and adopt to a new technology, and a technology reviewer will take it at that time, in that domain.***
>
> *Prof Alan Broadfoot – Director Newcastle Institute of Energy & Resources*

The mining industry is by nature risk averse for a number of factors including market dynamics, impacts to continuity of supply and the capital-intensive nature of project development. Recognising these points and overcoming the trust hurdle to enable the flexibility to test and adopt technologies aligned to operating programs, while balancing longer term investment and research to advance horizon 2 and 3 technologies is required to minimise the complexity and costs and ultimately resolve risks associated with innovation adoption.

> ***Industry knowledge is generally quite deep and thorough, but those who have that insight rarely have the opportunity to apply it to address challenges during construction, or at the capital investment phase when converting an ore body from development to production.***
>
> *Adrian Beer, CEO METS Ignited Australia Ltd*

Figure 19 - A Schematic Representation of Emission Reduction Horizons of Opportunity



7.2. STRATEGIC COORDINATION – ENABLE THE LEVERS TO UNITE AND TRANSFORM

Working toward a Zero-Emission Copper Mine of the Future requires the coordinated effort of a number of actors to enhance policy settings, producer-supplier collaboration, capital, skills development and open innovation mindset.

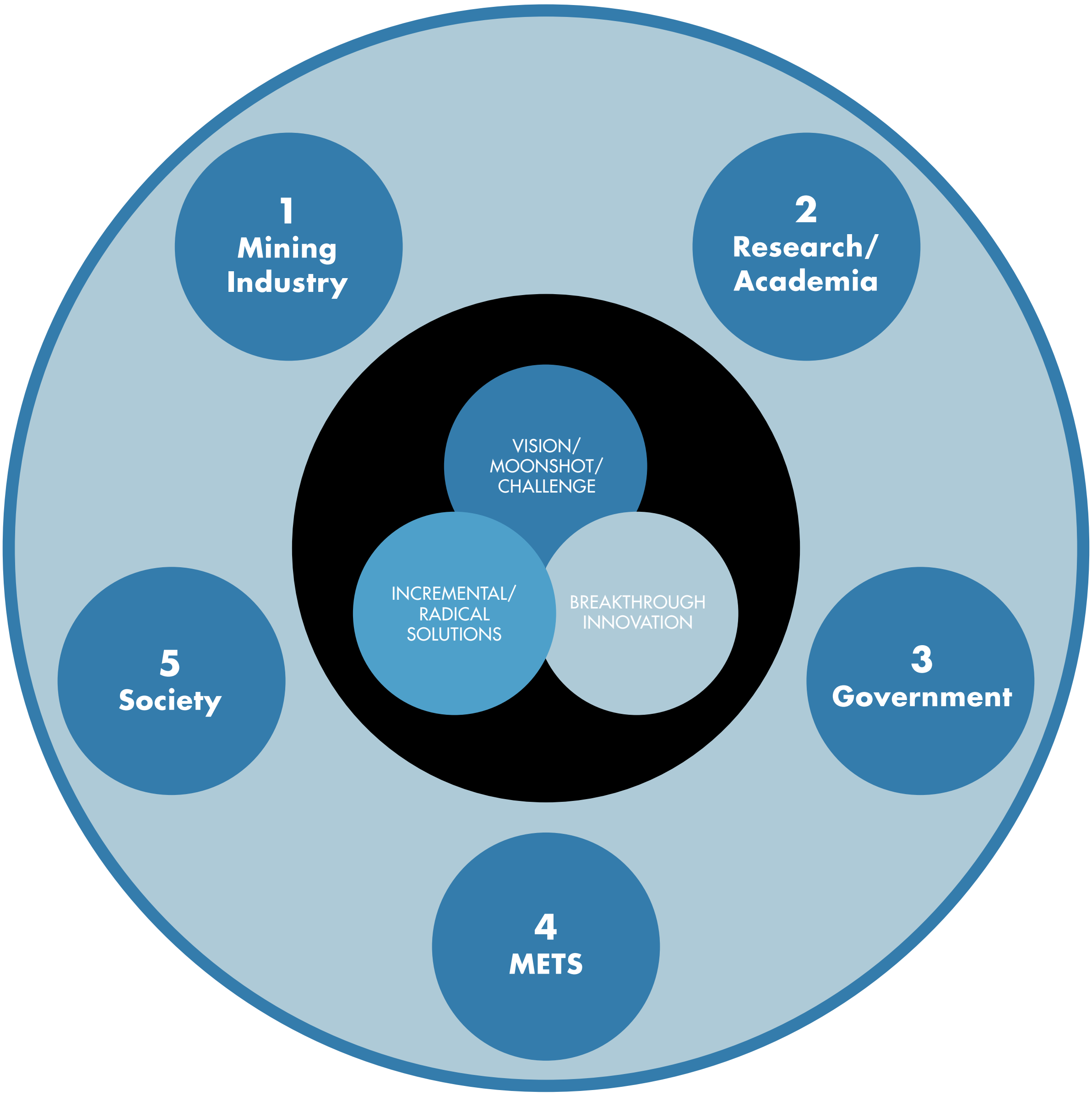
The magnitude of the challenge to achieve a zero-emission copper mine of the future and to unite this transformation across the industry is beyond the resources of a single producer, any one solution provider, and indeed any one government.

As recognised by METS Ignited Australia Ltd (2015) the traditional elements of a triple helix collaboration among industry, research and government is required to advance a knowledge-based economy. A quadruple helix includes Mining, METS, Research and Government to advance industrial innovation and uptake in the sector.[71] The Warren Centre's consultation with industry revealed that the social attitudes toward sustainability should be recognised to stimulate the decarbonisation imperative. Therefore, the need to shift thinking to include society is recommended across a network of actors to advance interaction and knowledge exchange, build trust and attract future skills.

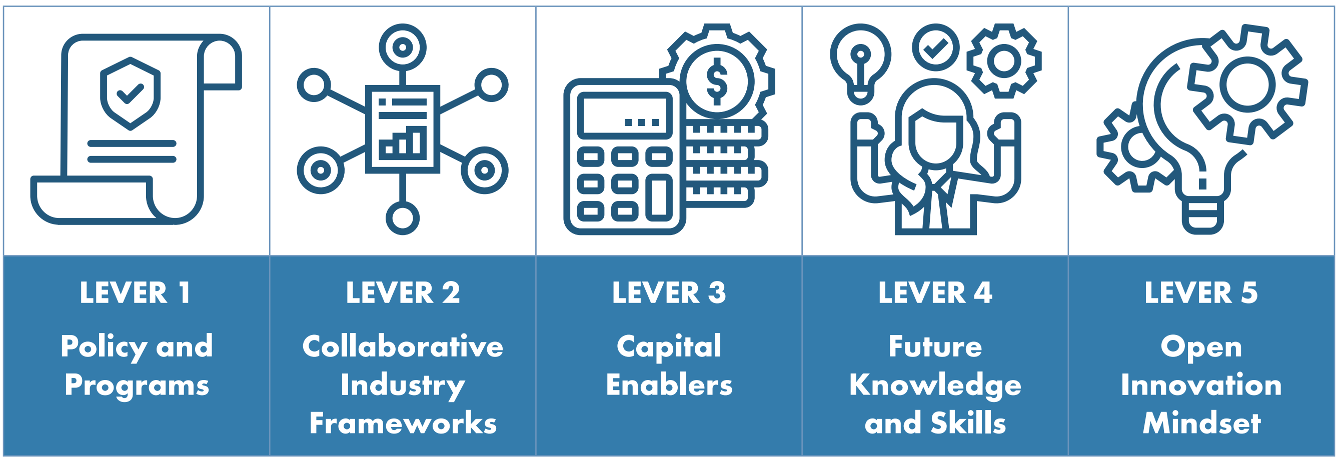
> ***Currently mining executives have a good understanding of how a given technology, a given methodology or a given device can improve the performance of mining operations in terms of emission, productivity, safety, water efficiency or any other performance indicator used. Mining companies are very good on that. But, as important as understanding the potential of a technology and how to use it to improve the operational performance, is to understand the social impact it can generate and how to support delivering the full social value it can create. However, how to assess the social angle is less advanced compared to the operational one. Closing this gap, is probably one of the main challenges for a successful adoption of new technologies and innovations. Viable business will be those able to integrate social impact as well as economic impact of business decision.***
>
> *Dr Ozvaldo Urzua, Independent Expert*

Consumers want transportation and energy systems that are clean, and copper is the means to deliver that consumer desire. Society's aspiration for reduced CO_2 emissions are both a market-demand opportunity and also a call for an industry response that maintains integrity to the original intent that drives growth.

71 Australian Government Department of Industry Innovation and Science, 2015. *Industry Growth Centres. In: Mining Equipment, Technology and Services 10 Year Sector Competitiveness Plan*. pp. 42 - 43.

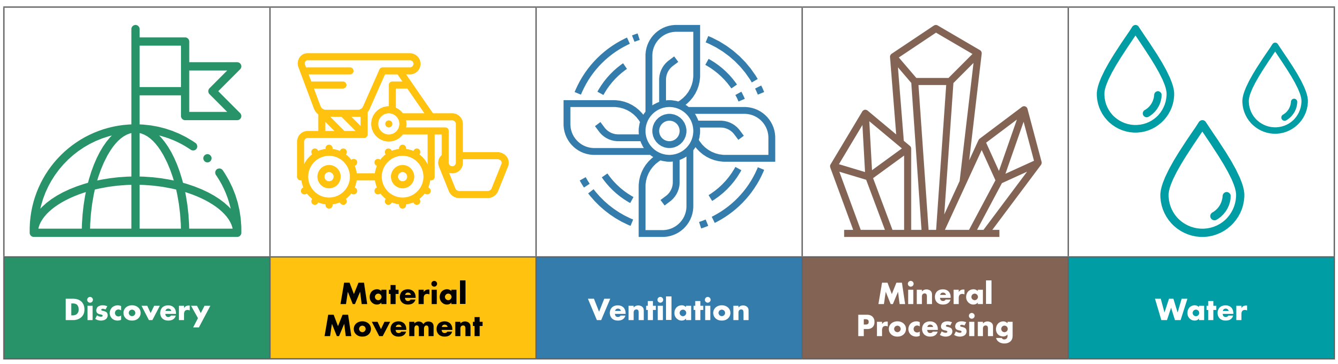


The Warren Centre present a series of actions to achieve a Zero-Emission Copper Mine of the Future concept under five distinct emission impact levers. These enabling levers for success are explored further in Chapter 9.



8. Emission Impact Themes

To present this concept further the Warren Centre conducted a desktop study on a sample set of potential innovations and design concepts under the following emission impact themes. Further identification and analysis, including quantifying direct emission impacts, and economic considerations could be broadened via partnership with key industry associations, producers and experts, or crowd sourcing means.



8.1. DISCOVERY

Applying advanced technologies at the discovery and exploration stage of the mining cycle will enable the development of robust ore-deposit identification and exploration models to improve the likelihood of detection of high-grade deposits in greenfield and brownfield sites Advanced technologies can optimise attractive host rock settings and subsequent future ore recovery..

Spectral geology image, Arizona, USA.
Credits: NASA/GSFC/METI/ERSDAC/JAROS and U.S./Japan ASTER Science Team (CC BY 2.0).

The better we can understand what is in the ground the more energy efficient the mining activity will be. If nothing else, if you mine, handle and process less waste, then surely this will be more energy efficient in terms of tonnes of product produced. *Dr Chris Goodes, University of Melbourne*

EMISSION IMPACT THEME - DISCOVERY			RISK CONSIDERATION MATRIX				
Segment of Opportunity	**What challenge could the Innovation solve?**	**Horizon of Opportunity**	TECHNOLOGY	SAFETY/COMMERCIAL	MARKET	SOCIAL	STAKEHOLDER/REGULATORY
Economic scenario modelling systems	The integration of geological and mine planning inputs to analyse scenario options	1					
GPS positioning systems	The use of satellite systems to optimise positioning, exploration and prospecting, and mapping of minerals	1					
Drill alignment systems	Increased accuracy of drill hole alignment to optimise ore recovery and ore body detection	1					
Geological information and exploration modelling systems	Increased accuracy of resource detection of orebodies in greenfield and brownfield sites	1,2					
Advanced gravity gradiometer systems	To assist direct detection and geological mapping capabilities for a large variety of mineral commodities and deposit styles	1,2					
LiDAR (Light Detection And Ranging capabilities)	Rapid turnaround of exploration data and images in the cloud, with wide ranging surveillance applications	1,2					
Mine Plan Optimisation	Integrated orebody models to optimise mine design with aim to reduce future hauling distances and material movement	1,2					
Digital twin exploration technologies	Provide virtual simulation capabilities to model orebody systems	1,2					
Autonomous drone technologies	Complemented with IOT technologies provides ability to optimise exploration surveillance and remote operations	1,2					

EMISSION IMPACT THEME - DISCOVERY			RISK CONSIDERATION MATRIX				
Segment of Opportunity	**What challenge could the Innovation solve?**	**Horizon of Opportunity**	**TECHNOLOGY**	**SAFETY/COMMERCIAL**	**MARKET**	**SOCIAL**	**STAKEHOLDER/REGULATORY**
Autonomous drilling technologies	Exploration drilling utilising on-board guidance systems to provide precise drill hole locations, dips and angles, and enable greater depth	1,2					
AI and Machine Learning for exploration applications	Utilise Artificial Intelligence expertise and Machine Learning to improve the rate of success to find mineral deposits	1,2					
Satellite-Based Augmentation Systems (SBAS)	More accurate satellite positioning capability by augmenting Global Navigation Satellite System (GNSS) signals	2					
Core scan technologies	Hyperspectral logging technology that accurately characterises minerals in drill core samples	2					
Predictive Sampling Technologies	Machine learning technologies to enable optimised orebody detection of mineral boundaries and guide sample detection	2,3					
Quantum Sensing technologies	Apply quantum gravity sensors to create a significantly higher degree of sensitivity to detect mineral ore, complementing other mineral exploration applications	3					
Minerals 4D Modelling	Better predict the distribution and understanding of orebody. Holistically integrate sensors and specialised imaging techniques tied with data analysis and machine learning	3					

8.2. MATERIAL MOVEMENT

The practice of mining consumes two principal sources of energy, namely diesel or electricity for mobile machinery and equipment – depending on equipment type. Diesel combustion produces more than three tonnes of CO_2 for every tonne of diesel consumed, and emissions from electricity generation vary according to the grid generation mix.[72] Emissions are also generated from the detonation of explosives. The reduction in diesel consumption, improved equipment reliability and efficiency, optimised haulage distances, the degree of rock fragmentation, and the overall level of electrification are all factors that impact an operation's emission intensity and GHG output.

In recent times there has been a significant shift to advances in the electrification of mining systems and the transition to automation in all aspects of the mining and material movement process. There are numerous examples of incremental technologies to deliver technical efficiencies with improved asset availability, reduced maintenance requirements, extended mine life, enhanced productivity and reduced emission outcomes.

An important driver for any sort of change is cost reduction. We have expanded our material movement over the last couple of years so we have ongoing cost pressures when it comes to … the actual transport of material around the pit…. When we introduce a new process, we have to understand the impact of that change and how we're going to roll that change across the workforce.

David Thurstun – Manager Business Strategy, Ok Tedi Mining

Caterpillar 795 AC Trolley Assist Electric Drive mining truck.
Source: Caterpillar press release 54PR20, Feb 2020.

72 Brent, G. & Goswami, T., 2016. *AusIMM Bulletin: Blasting approaches to decrease greenhouse gas emissions in mining.* [Online]. Available at: https://www.ausimmbulletin.com/feature/blasting-approaches-to-decrease-greenhouse-gas-emissions-in- mining/

EMISSION IMPACT THEME - MATERIAL MOVEMENT			RISK CONSIDERATION MATRIX				
Segment of Opportunity	**What challenge could the Innovation solve?**	**Horizon of Opportunity**	TECHNOLOGY	SAFETY/COMMERCIAL	MARKET	SOCIAL	STAKEHOLDER/REGULATORY
Ultra-high intensity blasting systems	Finer rock particles, improved fragmentation distribution and improved comminution outcomes	1					
Haulage fleet – payload management and optimisation systems	Optimised payload, improved efficiency in equipment usage and associated fuel use	1					
Integrated mine planning and optimisation systems	Data analytics and simulation solutions to improve productivity, scenario planning, efficiency and safety, including interoperability between equipment types	1					
Diesel fuel efficiency intelligent management technologies	Improved engine life, loading capacity and reduced downtime due to fuel filling and maintenance	1					
Improved mine site communication and tagging and alert systems using sensor and other technologies	Decreased downtime and health and safety outcomes	1					
Precision and automated drill rigs	Improved outcomes in drill alignment and accuracy. Minimise waste rock movement and blasting dilution	1,2					
Conveyor technologies including conveyor distributed drive technologies, vertical systems, and sensor based integrated ore sorting	Reduction in overall power consumption and size of required extraction openings to accommodate traditional conveyor drive-heads	1,2					
Autonomous haul trucks	Robotic command and control technologies to manage movement of haulage fleet offering safety, fuel consumption and productivity and maintenance benefits	1,2					

EMISSION IMPACT THEME - MATERIAL MOVEMENT

Segment of Opportunity	What challenge could the Innovation solve?	Horizon of Opportunity	TECHNOLOGY	SAFETY/COMMERCIAL	MARKET	SOCIAL	STAKEHOLDER/REGULATORY
Autonomous and advanced ancillary equipment	Drones and cameras to improve visual inspection. Optimise road maintenance and surveying	1,2					
Virtual reality technologies. Machine testing and data analytics prior to deployment	Pre-testing of mining equipment to de-risk damage and cost and analyse efficiency	1,2					
Augmented reality - overlay of a digital visualisation onto a real-world environment	Improve the quality of training prior to deployment of equipment. Reduce equipment maintenance costs and improve safety	1,2					
Mining and material movement battery electric vehicles	Lower maintenance costs, manoeuvrability, optimise automation opportunities	1,2					
Improved mobile communication infrastructures e.g. 5G networks	Optimise and validate new mining technology, more efficiently connect data systems applications and business models between equipment networks	1,2					
Advanced haul road design technologies	Compaction and material design to improve haul road quality and maintenance outcomes utilising waste rock materials	2					
Material sorting technologies using sensor technology	The ability to intelligently direct material movement – to sort valuable ore from waste	2					
Hybrid diesel electric trucks and trolley systems	Improved fuel economy and productivity to direct electric power from a trolley system to truck during peak load haulage	2					

EMISSION IMPACT THEME - MATERIAL MOVEMENT			**RISK CONSIDERATION MATRIX**				
Segment of Opportunity	**What challenge could the Innovation solve?**	**Horizon of Opportunity**	**TECHNOLOGY**	**SAFETY/COMMERCIAL**	**MARKET**	**SOCIAL**	**STAKEHOLDER/REGULATORY**
Hydro-Hoisting	Only material of value is transported to the surface	2,3					
Ore tracking with Artificial Intelligence, blockchain, distributed ledger and other supply chain tracking technologies algorithms to track ore from the pit to the processing plant	Optimise material value and volume movement across whole of supply chains	2,3					
Hybrid electric vehicles	Improved fuel economy by combining combustion engine to battery energy and storage systems	2,3					
Quantum sensing technologies	Apply quantum gravity sensors to create a significantly higher degree of sensitivity to detect ore and waste intersections in block caving, and lower waste recovery. Geotechnical applications to optimise rock stability applications	3					
Hybrid hydrogen electric vehicles	Installed hydrogen fuel cells convert compressed hydrogen to power battery technology electric motors	3					

8.3. VENTILATION

An essential requirement for underground mining, ventilation provides fresh air underground whilst removing stale and contaminated air produced from activities within the mine.[73] Underground mining ventilation, as a primary system, has remained essentially unchanged for a number of years. The requirements are met by large surface fans that drive the air requirements underground. Shifts in technology are responding to the transition to autonomy including a reduction in personnel underground. This includes ventilation on demand systems and technologies to optimise power requirements. Underground cooling is also a key requirement.

> ***We are starting to see a lot of the engineers that come through our business looking at ways to capture the energy generated from our mining activities and reuse it to reduce our consumption of electricity. Refrigeration is an area where we have a number of processes that generate heat as a result of the smelting process. So instead of just reducing, rejecting that heat to atmosphere through cooling towers and the like, the discussion is around the use of absorption refrigeration where you convert that heat to drive the refrigeration process.***
>
> *Matt O'Neill – Chief Operating Officer, Mt Isa Mines, Glencore*

Molten copper transfer has opportunities for waste heat recovery.

73 U.S. Department of Energy, 2002. *ITP Mining: Energy and Environmental Profile of the U.S. Mining Industry.*, op.cit.

EMISSION IMPACT THEME - VENTILATION			RISK CONSIDERATION MATRIX				
Segment of Opportunity	**What challenge could the Innovation solve?**	**Horizon of Opportunity**	**TECHNOLOGY**	**SAFETY/COMMERCIAL**	**MARKET**	**SOCIAL**	**STAKEHOLDER/REGULATORY**
Energy systems to optimise mains fans	Real-time adjustments of main fan systems according to required airflow demands	1					
Sensor technologies, IoT enabled devices	Optimise ventilation measurements and requirements in real time to plan lower power requirements and improve air supply	1					
Modular refrigeration technologies	Air cooling systems that are modularised to accommodate increases in demand during hot climate or increased or reduced capacity requirements	1					
Secondary ventilation control systems	Enables a secondary ventilation requirement beyond main fan to accommodate particular areas / demands	1,2					
Optimising whole of ventilation systems parallel to equipment electrification scenarios	Reduced ventilation energy requirements due to reduced diesel particulate and heat transfer and personnel	1,2					
Wearable technologies and measurement controls	Safer and more productive mines with increased worker thermal comfort. Reduced ventilation and temperature demands	1,2					
Ventilation on Demand Systems – including control and monitoring systems	Ability to direct the right quality and quantity of air to the area that requires it	2					
Natural refrigeration technologies	Air cooling systems using ambient air and previously mined stopes	2,3					

8.4. MINERAL PROCESSING

Mineral processing is the largest consumer of energy in the copper production system. Targeted innovation efforts include technologies to improve crushing and grinding efficiencies, separation and concentrate drying, optimisation of processing performance, in addition to measurement technologies to inter-connect systems across the whole of plant operations, and dry processing technologies.

In-situ recovery refers to the recovery of valuable metals from ore deposits by the circulation of fluid underground and the recovery of the valuable metal from the fluid at the surface for further processing. It has the potential to be a low-impact and selective mining option.[74]

EMISSION IMPACT THEME - MINERAL PROCESSING			RISK CONSIDERATION MATRIX				
Segment of Opportunity	**What challenge could the Innovation solve?**	**Horizon of Opportunity**	TECHNOLOGY	SAFETY/COMMERCIAL	MARKET	SOCIAL	STAKEHOLDER/REGULATORY
Grinding mill technologies to optimise mill performance	Optimising electric motor use and circuit design	1					
Data science, predictive analytics, sensor technologies and analytics to optimise plant performance	Takes a whole of systems approach to optimise inputs (such as ore grade, feed size, product size and other material factors) and overall circuit efficiencies	1,2					
High Pressure Grinding Rollers HPGR	A high-pressure comminution process can result in micro-cracks in the particles, resulting in higher fines production. This solution also addresses water scarcity solutions	1,2					
Drying and dewatering opportunities to reduce energy consumption of drying circuits	Recycle waste heat for drying circuits and solar opportunities	1,2					
Underground Processing Systems	Processing systems are designed for flexible underground application to enable material of value only to be transported to the surface	2,3					

74 Robinson, D. & Kuhar, L., 2018. *In-situ recovery—a move towards 'keyhole mining'.* [Online] Available at: https://www.mining3.com/situ-recovery-move-towards-keyhole-mining/

EMISSION IMPACT THEME - MINERAL PROCESSING			RISK CONSIDERATION MATRIX				
Segment of Opportunity	**What challenge could the Innovation solve?**	**Horizon of Opportunity**	**TECHNOLOGY**	**SAFETY/COMMERCIAL**	**MARKET**	**SOCIAL**	**STAKEHOLDER/REGULATORY**
Biotechnology and genomics applications	Use of microorganisms and genomes to enhance the recovery of base and precious metals, and optimise tailings recovery	3					
Optimising the development of in-situ recovery techniques for copper oxide deposits, and the potential for copper sulphide ores	Avoids the physical impacts of mining extraction, comminution costs and storage/disposal of tailings. Could allow for currently sub- economic ores to become more attractive	3					
Alternate methods such as the MIT Process to replace traditional smelting, converting and electro-refining	Replace emission intensive and costly aspects of the copper production process	3					
Novel leaching process such as the Galvanox method	Replace traditional leaching processes providing a new method that can accommodate larger sized ores, and hence reduced comminution requirements	3					

8.5. WATER

Water use in mining is essential to the extractive process as well as a precious resource that needs to be managed carefully as part of a company's social licence to operate. The use of water in mining was identified as one of the seven mega trends by the World Economic Forum[75] and is a key component to transitioning to a "low carbon economy". In many locations water has reach in the social acceptance of mine production and development.

Water is present throughout the lifecycle of a mining operation, ranging from:

- The dewatering processes to remove and manage ground water to levels below where mining is to occur,
- Within the operation, including as a
  - transport medium for slurry conveying,
  - an additive to sulphur to generate sulphuric acid via an exothermic reaction,
  - in hydrometallurgical flotation processes,
  - potable water for human consumption,
  - Water and dust suppression in operations, and finally
- At the end of mine life in the remediation of acid mine drainage or tailings remediation.

EMISSION IMPACT THEME - WATER			RISK CONSIDERATION MATRIX				
Segment of Opportunity	**What challenge could the Innovation solve?**	**Horizon of Opportunity**	TECHNOLOGY	SAFETY/COMMERCIAL	MARKET	SOCIAL	STAKEHOLDER/REGULATORY
Optimised dewatering of mine workings	Mass water balancing between bore field and localised water tables	1					
Data analysis, water analysis, sensor and hydro pump technologies to optimise water use sourcing and consumption, pipe leakage, and scaling impacts	Optimising water flow and quality and infrastructure use to ensure efficiency gains and energy recovery can be achieved throughout the pipe network	1					
Site storm water capture, treatment and discharge	Maximise whole of site water use, minimise new influent sources and losses	1					
Acid Mine Drainage	Improved metals recovery	1,2					

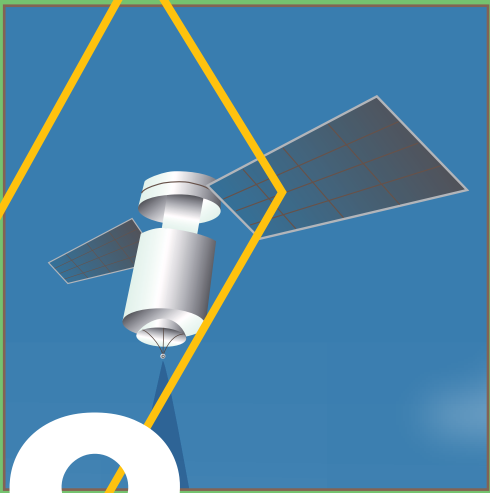
75 Maennling, N. & Toledano, P., 2019. *Seven trends shaping the mining and metals industry*. [Online]. Available at: https://www.weforum.org/agenda/2019/03/seven-trends-shaping-the-future-of-the-mining-and-metals-sector/

EMISSION IMPACT THEME - WATER			RISK CONSIDERATION MATRIX				
Segment of Opportunity	**What challenge could the Innovation solve?**	**Horizon of Opportunity**	**TECHNOLOGY**	**SAFETY/COMMERCIAL**	**MARKET**	**SOCIAL**	**STAKEHOLDER/REGULATORY**
Desalination technologies	Lowering the capital requirements of desalination technologies and energy requirements	2					
Transportation of ore through slurry pipelines	Offset the use of diesel operated machinery to transport material with high efficiency slurry pumps	2					
Creation of sulphuric acid for leaching processes	Treating and recycling water and or sulphuric acid to lower the mass water balance and decrease contaminated discharge	2					
Water use in hydrometallurgy including flotation process	Conditioning water to maximise the recovery of copper in process with the ability to selectively remove other metals and potentially offer saleable product streams	2,3					
Tailings water discharge for recycle and potential reuse	Recycle water from tailings dams for reuse in process, minimising the footprint of a tailings dam	2					

Industrial scale desalination (reverse osmosis) or the use of membrane technology is a process used to remove salts (cations and anions) and other contaminants from water. Mining operations often require salt and contaminant free water in hydro and pyro-metallurgical processes to achieve optimum resource recovery. In the absence of a localised water source, desalination may present a viable option subject to proximity to a salt water body and an associated transportation pathway.

The advantage of desalination is the ready access to free feedstock (seawater). This advantage is somewhat offset by a number of practical challenges such as the capital-intensity of building new supply, economies of scale required to develop new capacity, high energy consumption, the production and disposal of concentrated brine waste streams, and the costs associated with transportation if the operation is distal from the coast or salt water body.

Due to the critical nature of water in minerals processing, desalination and other membrane technologies have proven to be effective in geographies such as northern Chile that suffer from significant water scarcity. Its application however impacts the overall Scope 2 energy balance of a copper operation due to the energy input requirements. The growth in renewable technology is proving to be an effective offset mechanism to the high energy intensive operations of a desalination plant. In certain geographies that experience water scarcity, desalination demonstrates the challenges and variability in emission reduction pathways when working toward a Zero Emission Copper Mine of the Future.



9. Strategic Coordination

- Enabling Levers for Success

PROGRESSING MULTIPLE INNOVATION PATHWAYS AND BALANCING ENABLING LEVERS WILL ALLOW THE COPPER INDUSTRY TO REDUCE THE RISKS ASSOCIATED WITH TECHNOLOGY ADOPTION AND ACCELERATE THE UPTAKE OF INNOVATION AND TECHNOLOGY.

Simultaneous and multi-faceted pathways are likely required to enact decarbonisation in a complex and variable copper mining systems, and a network of partnerships and actors will work to de-risk the transition while maintaining security of ongoing production and economic viability.

Supporting levers are required to overcome trust hurdles and the typical barriers associated with mining innovation adoption, to maximise the likelihood of success of incremental innovation, and also to provide the opportunity for significant breakthroughs, which are likely to take more time.

Solutions come from a number of sources, and all require strategic coordination to balance the push and pull mechanisms evidenced by suppliers, miners, government, public and private research and development, and society.

> ***I see that some solutions come from creative thinkers who have been in the industry for a while and have recognised and understood it at its most complex and detailed level, and then have thought differently about it. The other solutions come from entrepreneurial companies that have developed a technology and they're seeking another market application. A third type are very experienced technical innovators, and they deliberately seek out an industry problem that's within their skill set. Finding it may take them a while, and once they find it, they don't let go. They get access to capital, time, talent, and they prove out their technology. Then they introduce it to industry.***
>
> *Hal Stillman – Director International Copper Association ICA, USA*

THE ENABLING LEVERS TO INNOVATION HAVE BEEN OUTLINED BY THE WARREN CENTRE UNDER FIVE KEY THEMES:

LEVER 1	**LEVER 2**	**LEVER 3**	**LEVER 4**	**LEVER 5**
Policy and Programs	**Collaborative Industry Frameworks**	**Capital Enablers**	**Future Knowledge and Skills**	**Open Innovation Mindset**

9.1. LEVER 1 – POLICY AND PROGRAMS

There are numerous public and policy-enabled programs and initiatives that can be leveraged to promote and sustain decarbonisation pathways and to encourage the uptake of innovation in the copper mining process.

According to the Australian Department of Industry Innovation and Science (DIIS) domestic and international evidence shows that government, industry and research collaboration is increasingly important to drive business and economic growth, and to deliver impact.[76]

Understanding and leveraging the programs that target collaborative efforts in copper technology innovation, and in particular linking research, government and industry is essential to providing the foundations to advance and accelerate both incremental and longer-term copper technology opportunities.

The Australian Industry Growth Centre initiative is one example where the Australian Government has established programs to support a national industry led approach to innovation, productivity and competitiveness in sectors of national importance. The government has established six growth centres to advance the competitiveness of these key sectors over a 6-year time horizon, including Australia's $90Bn Mining Equipment, Technology and Services (METS) sector. Each Growth Centre is mandated to increase connections between industry and research, improve workforce skills and capabilities for the future, advance export growth into global supply chains, and address regulatory barriers.

From an international perspective, other examples include the Chilean Alta Ley National Mining Program, a public-private initiative created in 2015 linking the mining industry, its suppliers, government, research and development with the objective to address the challenges of productivity, safety and environmental aspects of the copper mining industry, and to create, strengthen and energise the mining innovation ecosystem. This highly successful program has published the Chile Copper Technology Roadmap to 2035. The program identifies pathways to support the industry in its competitiveness, including the growth of 250 world class suppliers targeting services and technology applicable to mining.

> ***There is the opportunity to effectively build and leverage specific successful programs and ecosystems to refine a broader copper technology roadmap specific to decarbonisation pathways and use the strength of the participating actors to advance its delivery.***

9.2. LEVER 2 – COLLABORATIVE INDUSTRY FRAMEWORKS

Collaboration across networks enables a mechanism for important elements of knowledge sharing between copper producers, suppliers and research. Industry-led collaboration could also provide a mechanism to delineate best practice and identify efficiency opportunities. A Zero-Emission Copper Mine of the Future concept presents an exciting opportunity for the industry to work together to navigate best practice and opportunity over short and long-term time horizons.

Furthermore, targeted collaboration facilitated by an agnostic or representative entity provides an opportunity to aggregate both the pipeline of opportunity and demand through non-competitive means and increase the likelihood of commitment by parties to work together for the advancement of the objectives as a whole.

An initial focus on short-term incremental opportunities targeted at emission intensive aspects of the copper mining process could provide the opportunity to demonstrate early success. There are numerous benefits to be derived for producers to test a collaborative process which builds confidence to drive longer term objectives and further commitment.

76 Australian Government Department of Industry Innovation and Science, 2020. *Industry Growth Centres.* [Online] Available at: https://www.industry.gov.au/strategies-for-the-future/industry-growth-centres

Case Study: Amira Global

Amira Global is an independent not for profit organisation representing members from the resources industry seeking to enhance, sustain and deliver transformation research and development, innovation and implementation to the benefit of society. Established over 60 years ago Amira Global enjoys a well-respected brand in the industry to work on behalf of its members to:

- Identify challenges and leverage R&D,
- Serve society's future resource needs,
- Add value to the resource sector ecosystem, and - Enhance networking and education[77]

In 2004 Amira led an international effort to identify and prioritise technology related research and development priorities for the copper industry to address some of the some of the most important technical, economic, and social challenges of the coming decade and beyond, and published the Copper Technology Roadmap.

The nine-month effort coordinated collaboration with nine copper companies and associate sponsors, resulting in over 100 identified R&D needs, many of which overlapped to form larger technology pathways and programs.

Importantly Amira recognised the technology road mapping activities of other organisations relevant to copper mining. Resulting activities included the formation of the Copper Technology Working Group to progress the Research and Development high priority needs.

... our remit is to help our members find some solutions to mega challenges through collaboration and finding the best brains to work on problems. And that's across the spectrum of the mine value chain, and looking at R&D, innovation, implementation, and finding pathways for commercialization, not doing the commercialization ourselves, but encouraging the R&D, to the outputs, to find a way to deliver them.

Dr Jacqui Coombes, Managing Director and CEO, Amira

Case Study: Austmine

Austmine is the peak industry body for Australia's $90Bn Mining Equipment, Technology and Services (METS) sector. It exists to develop the METS sector and provide growth opportunities and value to its members to achieve greater success. It currently hosts over 600 members, reflecting the impressive diversity of METS companies, from major OEMs, contractors and EPCMs, through to SME software, equipment manufacturers, consultancies, technology and support services.

Austmine recognises the strategic challenge of mining industry decarbonisation that could impact economic prosperity, including industry sustainability and social licence to operate.

In working to preserve Australia's METS sector's leading position as global innovators in the resources industry, the organisation recently held national workshops to explore what can be collectively done to slow climate change and to make a difference to secure a sustainable future.

Specific topics included how the METS community can lead by collaborating to reduce carbon emissions, lessen industry footprint and provide solutions to help in the worldwide effort to address climate change.

The forums were structured to enable open discussion on topics such as:

- Practices for reducing the footprint of businesses;
- New approaches to tackling climate change across the value chain;
- External assistance and support needed to take action;
- Technologies, expertise and processes currently in place.

This foundational work demonstrates an excellent opportunity to contribute to innovative solutions pathways and could be further expanded to include direct collaboration with copper producers to share findings, understand specific challenges, and develop targeted strategies and solutions.[78]

77 Amira Global, 2020. *Amira Global*. [Online]. Available at: https://amira.global/
78 Austmine, 2020. *Austmine*. [Online]. Available at: http://www.austmine.com.au/

9.3. LEVER 3 – CAPITAL ENABLERS

Overcoming barriers to the commercialisation of innovation is essential to foster widespread adoption and growth of incremental innovation, foster next generation solutions, and to stimulate R&D and commercial activity.

There are a number of mechanisms and programs in public and private sectors that facilitate the commercialisation of innovation, from seed capital to strategic investment. These require support and intervention from all actors to unlock funds and ensure a healthy pipeline of industry uptake.

A coordinated network of investment partners and advocates is required to raise the visibility of impactful and value-accretive innovation. To stimulate investment in innovation that is aligned to emission intensive and operational needs across the entire mining value chain needs to overcome challenges related to intellectual property frameworks.

In the future innovative funding models can be explored that are specifically linked to upstream copper decarbonisation pathways. In the first instance understanding existing and new models is the first step to supporting this opportunity.

Case Study: The Aurus III copper venture fund[79]

The copper centric Aurus III Copper Venture Fund was established in Santiago, Chile in 2013 to fund start-ups and new tech companies focused on the development of technologies that would benefit the copper industry in upstream processes, competitiveness and sustainability. The US$65m fund (which includes approximately $40m contribution from the Chilean Government) aims to provide the bridge between ideas and the implementation of those ideas in partnerships aligned to the challenges faced by mining companies.

The primary qualifications for start-ups and ventures that seek funding include:

- finding new applications and uses for copper that will help sustain demand and hence copper mining,
- the development of important services and supplies for copper mining operations, and
- innovative solutions that will improve processes, sustainability, and competitiveness in the industry

The ICA participates in the activities of the fund via the initial fund creation and capital raising, participation in the investment committee, providing connections, and the support of due diligence activities.

Case Study: BHP – US$400m Climate Investment Program

In July 2019 BHP announced a five-year, US$400m Climate Investment Program to develop technologies to reduce emissions from its own operations as well as those generated from the use of its resources.

Over the next five years the program aims to scale up low carbon technologies that are critical to the decarbonisation of its operations. It aims to drive investment in nature-based solutions and encourage further collective action on scope three emissions.

BHP CEO Andrew Mackenzie said, "Commercial success of these investments will breed ambition and create more innovative partnerships to respond collectively to the climate challenge."[80]

79 Stillman, H., 2018. *South Australia Copper to the World Conference: Presentation.*
80 BHP, 2019. *BHP to Invest US400m to Adress Climate Change.* [Online]. Available at: https://www.bhp.com/media- and-insights/news-releases/2019/07/bhp-to-invest-us400m-to-address-climate-change/

9.4. LEVER 4 – FUTURE KNOWLEDGE AND SKILLS

A pathway to a Zero-Emission Copper Mine of the Future will reveal the emergence of new technologies and innovations applied to and replacing or enhancing existing aspects of the copper mining process. Many of these innovations require new skills and capabilities to achieve this ambition. Emerging technologies in electrification, hydrogen generation, renewable energy systems, automation, data analytics, machine learning, artificial intelligence, quantum computing, sustainable development and circular economy thinking will all take shape in the creation of jobs of the future.

> ***The industry is shifting, and innovation will come from the (interface between) technologies and human beings and their actions and activities with regards to the work of mining. I see data engineering, machine learning, artificial intelligence being applied (to) all professional sectors within the supply chain of a mine.***
>
> *Jacqui McGill AO, C-Suite Executive and Non-executive Director*

Both innovation and the daily methods of work are changing at a rapid pace. A zero-emission copper mine of the future will not only require next-generation skills and capabilities, but successful implementation requires the ability to augment the existing skillset and knowledge at mine operations. This could present particular challenges and unique opportunities for mining in regional and remote areas, where copper operations are located.

> ***The (implementation of innovation) requires the next generation of hands on, enthusiastic, bright people in our regional communities that can work with our world class operators; who have the practical skills, but also bring an understanding of the latest in modern technology .... Some of the latest technology coming from international vendors or being developed within our own world leading METS sector here in Australia, and integrating that technology into an interoperable, safe and sustainable operating environment at the local level.***
>
> *Adrian Beer, CEO METS Ignited Australia Ltd*

Case Study: Warren Centre and ICAA Support University of Sydney Advanced Engineering Students

In 2019 The Warren Centre with the support of the ICAA created a research project experience for a select team of exceptionally talented final year engineering students at the University of Sydney to stimulate and challenge them beyond the ordinary engineering coursework. The final year 'Jacaranda' module engaged the group to act as 'consultants' for clients on projects. The ICAA challenged the students to find potential solutions for a zero-footprint copper mining site revolving around the construction and development of a mine, its processing methods and a novel underground surface transportation system. The module was supported by CMOC North Parkes and concluded with a visit to the North Parkes operation to discuss, test and review the student findings in a practical mine-site setting.

The ability to test, experiment, demonstrate and deploy innovative technologies will also be critical if industry is to implement decarbonisation pathways rapidly in the shorter term. Providing the framework to attract and develop relevant skills from innovative thinkers and to develop new business and operating models is critical to drive investment and innovation uptake.

Case Study – Tonsley Innovation District

Tonsley Innovation District, based in South Australia, is designed to unite individuals, businesses and researchers seeking to collaborate, test, build and grow in a flexible and supportive environment. Tonsley's masterplan incorporates collaborative meeting and working spaces providing world-class facilities to help take new ideas from concept to market.

The model for achieving the Tonsley vision is based around a triple helix partnership among government, university and industry. This model incorporates the development of high amenity, mixed-use urban development (physical assets), populated with anchor businesses as well as research and training institutions (economic assets) in an environment that supports entrepreneurial activity and a culture of innovation (networking assets) to create this unique innovation district.

Tonsley Innovation District attracts companies seeking to develop, launch and test innovative new mining technologies in addition to automation, software and simulation technologies. The South Australia Drill Core Reference Library is based at Tonsley. Not located on the Tonsley site, but in the broader region, BHP Billiton, BP, OZ Minerals, and Santos are just some of the many mining and energy companies with a strong presence in the region, and other key industry sectors such as manufacturing, defence, energy, health, building and construction are also represented.

Tonsley aims to link major mining and energy project development with local companies and capabilities. The district includes education facilities focused on skills and training, as well as companies who service the mining sector.[81]

9.5. LEVER 5 – OPEN INNOVATION MINDSET

Mining companies are increasingly aware that innovation can be driven from within the company and from adopting innovation developed outside the company. By opening their doors to the external ecosystems and inviting start-ups, small and medium sized enterprises in collaboration with universities, established companies can build an effective method to bring in fresh, new ideas to resolve some of their biggest challenges.

> ***The mining industry need to address a very complex set of interconnected risks, which include market risk, price risk, geological risks, socio-political risk among others. Integrating technological risk is very challenging. This does not mean that mining shouldn't invest in innovation. On the contrary, nowadays technology and innovation is a key value driver. Tackling technological risk in collaboration with suppliers is emerging as a strategic enabler that supports addressing technological risk and speeds up innovation. Mining can provide a fantastic platform to drive, to create, to foster innovation in their supply chains, and probably one of the biggest contributions in terms of innovation that the mining industry can do is to embrace an open innovation approach and enhance the related ecosystem of innovation.***
>
> *Dr Ozvaldo Urzua, Independent Expert*

For example, Chile's Antofagasta Minerals has been implementing for some time an open innovation platform titled Innovaminerals, which serves as an entry for suppliers to showcase their solutions to solve the defined operational challenges of the company.[82]

81 Tonsley Innovation District, 2019. *Tonsley Innovation District: Promotional Brochure.* [Online]. Available at: www.tonsley.com.au

82 Bnamericas, 2019. *Open Innovation in Copper Mining is the Name of the Game.* [Online] Available at: https://www.bnamericas.com/en/news/open-innovaEon-in-copper-mining-is-the-name-of-the-game

In another example, Chile based Expande is an open innovation program of a public-private nature, which promotes the development of high potential solutions from technology-based companies and connects them with the challenges that copper mining companies face. The Expande program assists producers in the preselection of candidates that later the company could choose to advance to the next stage. Chilean copper producers such as BHP and Codelco have partnered with Expande on a series of pre-defined incremental challenge-based innovation programs. The commitment from the producers is evident in a significant multi-year challenge-based programs recently launched by BHP, the US$10m Global Tailings Challenge.[83]

Other innovation and impact organisations that have not traditionally engaged with the resources sector are becoming increasingly active and proving to bring a fresh mindset to a traditionally siloed and conservative industry.

Case Study: XPRIZE Zero Waste Mining Prize

XPRIZE operates as platform for impact. It designs and operates multi- million-dollar, global open innovation competitions to incentivise the development of technological breakthroughs that accelerate humanity towards a better future. The Foundation's mission is to inspire and empower a global community of problem-solvers to create positive impact in the world. They believe solutions to the world's problems can come from anyone, anywhere.

The first-ever XPRIZE competition, the US$10m Ansari XPRIZE for sub-orbital spaceflight, captured the world's imagination and catalysed a multi- billion-dollar commercial space industry. Since then, the program has launched seventeen competitions in the areas of Energy, the Environment, Civil Society, Human Health & Longevity, Exploration, and mobility.

XPRIZE develops competitions in areas where system failures have limited progress or exhausted resources. XPRIZE's Prize Design process is anchored in an open collaboration model, encouraging input from sponsors, innovators, industry leaders, academia, government, non- governmental organisations and the general public.

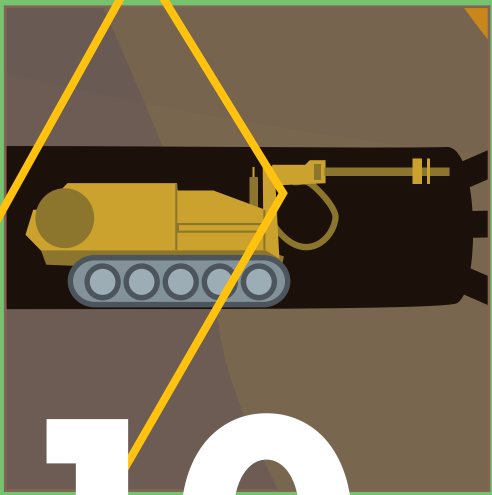
XPRIZE and its sponsors aim to revolutionise mining to sustainably meet the resource needs of the planet. XPRIZE is exploring the feasibility of prize designs that use innovative and scalable technologies to catalyse true zero-waste mining.

The Zero-Waste Mining XPRIZE was first presented at the 2017 XPRIZE Visioneering summit and selected as a candidate for a prize design by more than 280 industry leaders, tech experts, and representatives from NGOs. It is the first XPRIZE to address mining on a global level, recognising the urgent need for Moonshot Thinking and an incentivised global mining competition.

This initiative is sponsored by the Chilean Mining Consortium (ChMC), a partnership between Anglo American, Antofagasta Minerals, and BHP.

Scaled Composites won the Ansari X Prize with its experimental SpaceShipOne.
Source: D. Miller, Flickr, CC BY 2.0.

83 Expande Mineria, 2020. [Online]. Available at: https://expandemineria.cl/desafio/10m-4-tailings/



10.

Realise the opportunity for a Zero-Emission Copper Mine of the Future – a call to action

THE DECARBONISATION OF THE COPPER PRODUCTION PROCESS IS RAPIDLY SHIFTING IN IMPORTANCE. THIS POSITIVE TRANSITION TO A ZERO EMISSION MINE OF THE FUTURE PRESENTS AN ECONOMIC OPPORTUNITY FOR PRODUCERS AND INNOVATORS TO WORK COLLABORATIVELY IN THE IMPLEMENTATION OF ENABLING TECHNOLOGIES.

The industry interviews conducted with subject matter experts across producers, suppliers, researchers, and government consistently highlight the imperative to bring a new narrative to the sector for zero-emission innovation and progress. The opportunity is there for industry to embrace a zero-emission copper mine of the future as a shared and inspiring 'moonshot' vision and introduce multi-faceted pathways for innovation and impact.

> ***I think everyone has to do their part, and if the mining industry can demonstrate that it has a clear plan on how … it will achieve a zero- emission outcome then this will contribute positively to the sector. I think it is important not just for the industry and not just for the public but also for government….it is a very important step forward and if mining can do it – anyone can do it.*** *Chris Gibb-Stewart, CEO Austmine*

It is clear that the value of a zero-emission copper mine of the future will only be realised by connecting innovators to producers and establishing a framework that enables trust so as to deliver success. Driving an outcome toward a zero-emission copper mine of the future will require collaboration from a diverse set of actors across the upstream copper mining landscape including producers, suppliers, investors, government, research, not for profit and membership organisations. This collaboration will create opportunities for the wider community to transition and unlock the future skills required to support this objective.

Developing a clear and consensus long-term vision will drive the imagination of what is achievable over a series of time horizons.

> ***A shared vision can activate numerous incremental scenarios and pathways, ensuring that innovative solutions are aligned to the needs of an individual producer, the unique settings and operating phase evident in the industry, and structured to target emission intensive aspects of the process.***

A coordinated vision will also prioritise research efforts to enable breakthrough and holistic solutions to flourish and that ultimately yield support from capital markets to engage in the zero-emission economy with appropriate funding mechanisms and confidence.

The opportunity for the ICAA is to drive the conversation forward, to convene and establish concise and practical results-driven strategic roadmaps and pathways, and leverage the work by numerous bodies including existing ICAA member activities, the South Australian Government, the Warren Centre, AMIRA, Austmine, METS Ignited and others including those hosted outside Australia.

While a definition of a broad zero-emission copper mine of the future concept requires further refinement on key priority areas and associated levers, an immediate opportunity exists to activate a short-term roadmap for Scope 1 emission reduction priorities, opportunities and solutions. A drive toward short-term incremental solutions targeted at the known emission intensive segments of the copper mining process will not only identify innovative opportunities for immediate deployment but will work to foster and enhance partnership between suppliers and producers, enable pilot testing and operational demonstration, and ultimately progress alignment toward longer term goals.

> ***In the immediate future this could be delivered via a series of workshops between producers and suppliers, or priority working groups to ensure ongoing progress and consultation. The delivery of a short-term roadmap will also importantly demonstrate that the pathway toward a Zero-Emission Copper Mine of the Future is both technically and economically feasible.***

A pathway to a zero-emission copper mine of the future will promote discussions so as to address questions such as:

- What should be the expected contribution from all participants and stakeholders in the ecosystem?
- What role could each participant play in driving the transition to a zero- emission operation? and,
- How can existing and future operations be sustained and continuously improve so as to be more productive and efficient beyond that transition?

The copper mining process is a complex system, and there are many barriers for innovation uptake. Many of barriers to innovation adoption fit within common themes across the whole of mining sector. A zero-emission copper mine of the future is a global challenge. However, it is one that requires a coordinated and collaborative response. This report sets out a pathway from the Warren Centre perspective that is based on technical research and guided from the practical insights of industry experts with many decades of experience at front-facing mining operations. The findings recognise the magnitude of the challenge, and hence this milestone is the start of the conversation.

Recognising that a zero-emission pathway requires effort in direct Scope 1 emission intensive segments is an important factor, and indeed Scope 1 has been a primary focus of this report. A zero-emission copper mine of the future requires aligned and parallel programs in Scope 2 and abatement measures. There are many recognised achievements in the Scope 2 indirect power generation areas of technology, however a zero-emission copper mine of the future cannot be sustained by progress in the Scope 2 area alone.

The report has emphasised that raising the profile and awareness of innovation in concert with developing a pathway to adoption sets the foundation for industry to actively pursue a zero-carbon emission future. A raised awareness of technology and innovation will support positive industry perception, and gather the momentum to test, pilot, measure, and ultimately increase the uptake of innovative solutions.

Recognising strategic support levers is required to overcome trust hurdles and the typical barriers associated with mining innovation adoption. Working to connect industries outside of mining and to prioritise technologies that could fulfil economic and technical feasibility criteria or emissions reduction potential in the short or long term will all bring transformational benefits.

The findings from the industry interviews indicate that action on zero-emission reduction will likely be achieved through multiple pathways and that a diverse set of actors are required to achieve success. It is through a network of actors with a shared vision that collective capacity will be harnessed to drive knowledge exchange, build trust and attract future skills. This network can advance foundational work in the measurement and reporting framework and can establish consensus targets where a coordinated effort is required.

> ***There is a significant and rapidly evolving global trend toward a lower- carbon economy, and the favourable properties offered by copper will ensure it will play an essential and fundamental role to achieve this objective.***

Community and government expectations are challenging industries, including copper to achieve carbon neutrality in the short to medium term. Industry is responding to this challenge and acknowledges the significant benefits that are emerging through renewable energy emission offsets and abatement measures. To this end there is a compelling need for industry to take an even greater role in the application of innovation in the upstream segment of the copper mining process to achieve a zero-emission copper mine of the future. These are necessary steps to ensure the sustainability of the copper industry as primary sourced copper is expected to continue well into the future.

Moving forward, the challenge the copper industry faces is to implement a structural shift towards improving and transforming the emission intensive stages within the whole-of-cycle copper production process, and the Warren Centre believes this is possible with an appropriately framed vision and imagination. Future efforts should recognise and implement incremental solutions through a coordinated framework to drive breakthrough technologies in the longer term.

11.

What the Warren Centre will do

The Warren Centre is committed to promote the advancement of technology and innovation for good and ethical engineering through diverse collaboration and thought leadership. The Warren Centre continues to drive and deliver projects and initiatives that will create positive change.

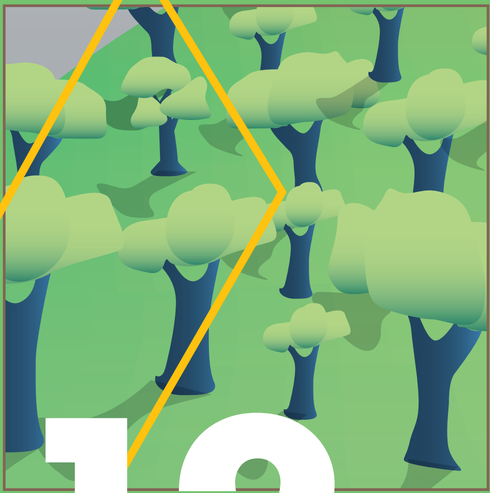
The Warren Centre remains committed to the translation of research and to the work of the centre with industry and representative bodies to advance innovation capacity, maximise impact and tackle important challenges that will face the copper industry of the future.

The Warren Centre recognises that the copper mining process is complex, and there are many barriers to the implementation of innovation. The Warren Centre promotes a strong commitment to the objectives of the ICAA and the Zero Emission Copper Mine of the Future.

The Warren Centre will continue to play a role in supporting the establishment of a framework to identify and enable new technologies for the copper mining industry. This includes services that assist in shaping priorities that are commercially relevant and deliver significant results in the first instance.

The Warren Centre will continue to support the ICAA to activate stakeholders toward cohesive action. Other initiatives could include programs that explore the Copper Mark to include a zero emission mine of the future as a multi-stakeholder standard or explore certification initiatives for the copper sector to include the emissions generation from the copper mining process itself.

The Warren Centre will work to facilitate and promote industry objectives, support delivery frameworks, support specific areas of research to promote business activity and capital frameworks, as well as inform the public to engage in the concept.



12.

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wc4975-21 • September 2020

Cover Design by Markus Verwey - www.dilectite.com.au
Layout by CreativeHQ

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