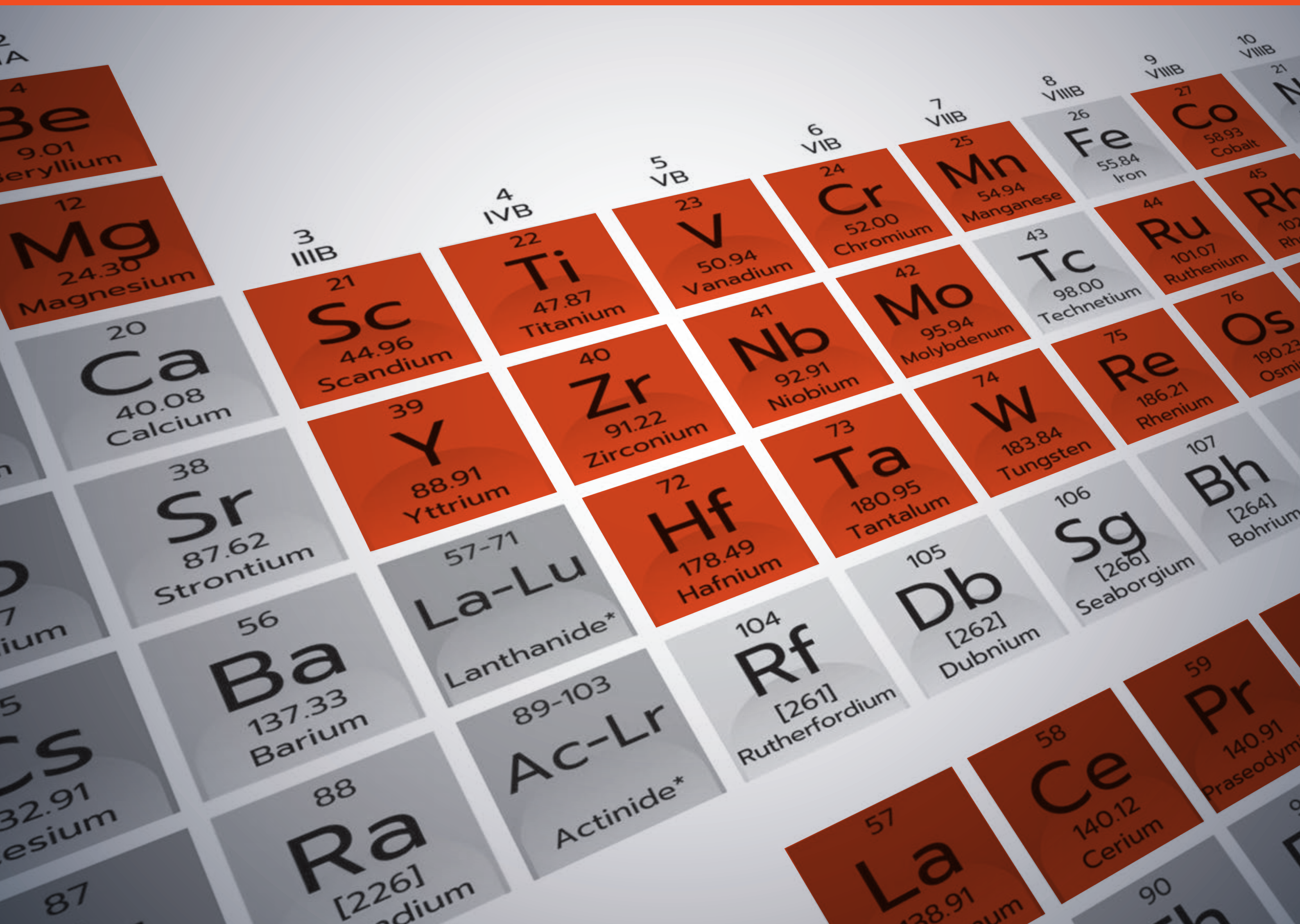
THE UNIVERSITY OF SYDNEY

Critical Minerals *and Materials*

The sustainable supply of materials for the clean energy transition

A white paper from the Net Zero Institute based on its multidisciplinary research



Acknowledgement of Country

We recognise and pay respect to the Elders and communities – past and present – of the lands that the University of Sydney's campuses stand on. For thousands of years, they have shared and exchanged knowledges across innumerable generations for the benefit of all.

Preface

Tackling the transition to net zero emissions presents a universal challenge that transcends national borders and demands a unified response. As the coordinator of global efforts, the United Nations emphasises that "climate change is the defining issue of our time, and we are at a defining moment."[1]

The world must transform to a net zero emissions future by around the middle of this century to avoid irrevocable damage to the planet's ecosystems and human societies. On September 6th 2024, the Climate Change Authority, an independent statutory body established by the Australian Government, released a highly anticipated report titled *Targets, Pathways and Progress*. The report outlines sectoral roadmaps for Australia's transition to net zero emissions by 2050.[2] Critical minerals and materials are integral to the transition. They underpin renewable energy technologies, electric vehicles, and various advanced manufacturing applications.

During its first months, the Net Zero Institute has embarked on its own road-mapping to understand the portfolio of multidisciplinary research underway across the University's community. Recognising the central role of critical minerals in the transition, the Net Zero Institute presents this paper as a viewpoint from its Critical Minerals and Materials research pillar – a team of more than 40 colleagues across the University with collective expertise spanning the sciences and engineering disciplines, business, social sciences and humanities. Research case studies from the Net Zero Institute and its international Scientific Advisory Board are highlighted throughout the paper as practical examples of a pipeline of innovations.

The net zero challenge presents a unique opportunity to drive innovation, develop environmentally sustainable solutions, and build a more resilient society and economy.

The Net Zero Institute aims to support the transformative change outlined in the Climate Change Authority's 2024 roadmaps for Australia's transition to net zero emissions. This challenge presents a unique opportunity to drive innovation, develop environmentally sustainable solutions, and build a more resilient society and economy.

About the Net Zero Institute
The Net Zero Institute is a multidisciplinary research cluster at the University of Sydney with 180 researchers dedicated to helping government, industry and communities develop, adopt, deploy, and manufacture cost-effective, low and zero emissions solutions at scale.

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The Net Zero Institute gratefully acknowledges the following contributors to the critical minerals and materials road-mapping process, and to this white paper (asterisks indicate workshop participants and case study contributors).

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THE UNIVERSITY OF SYDNEY
Net Zero Institute

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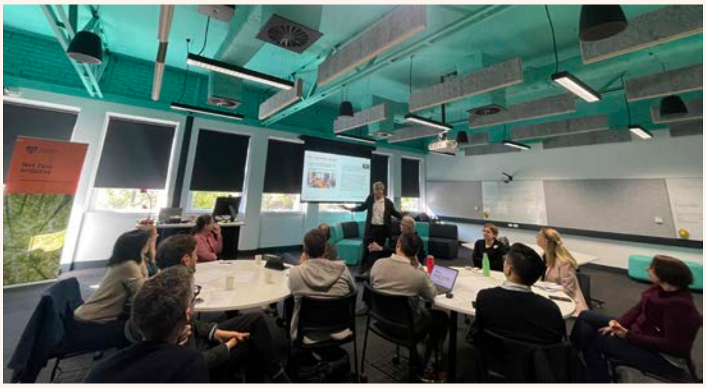

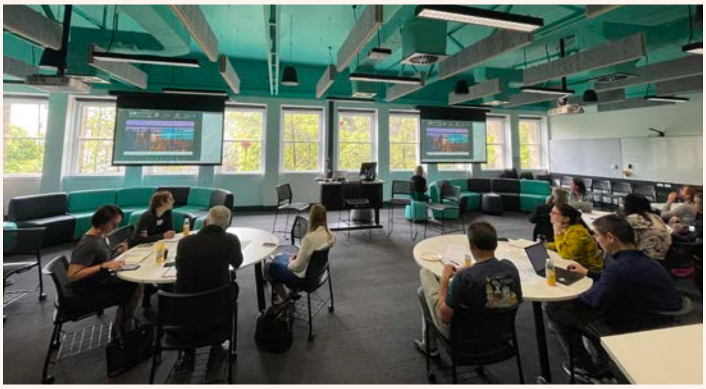

The Net Zero Institute Critical Minerals and Materials Pillar held three workshops at the University of Sydney's Knowledge Hub on May 27th, June 24th, and September 5th, 2024.
Top left: Dr Gordon Weiss (Engineering) facilitating Workshop 1, May 27th 2024. Top right and bottom left: A/Prof. Amanda Tattersall (Science) facilitating Workshop 2, June 24th 2024 and Workshop 3, September 5th 2024.
Bottom right: A/Prof. Amanda Tattersall (Science) facilitating panel discussion, left to right: Prof Dietmar Müller (Science), Dr Danielle Kent (University of Sydney Business School) and Prof. Susan Park (Arts & Social Sciences).

Executive Summary

The Net Zero Institute (NZI) was launched at the University of Sydney in mid-2024, and this white paper specifically focuses on one of its key pillars: Critical Minerals and Materials. The white paper has been developed with contributions and case studies from more than 40 researchers across the University and from the Net Zero Institute's advisory Scientific Board, who collectively shared their expertise through three workshops and associated working groups.

The transition to a net zero future depends on technologies that require significantly more mineral resources than traditionally used. Ensuring a reliable supply of critical materials is essential for achieving this transition, safeguarding energy security, and addressing national security concerns. Additionally, it is essential to meet the demands of a growing human population while ensuring the resilience of our planetary ecosystems for future generations.

This paper highlights Australia's potential by examining the exploration, extraction, and processing of these essential resources. The Net Zero Institute's research recognises that simply increasing production is insufficient. A holistic approach to sustainability must also consider the potential depletion of non-renewable resources.

Researchers are exploring not only the extraction and processing of critical minerals, but also innovative recycling technologies and alternative materials to reduce our reliance on primary resources. Case studies from the University and its international Scientific Board members highlight impactful outcomes and good practices across various sectors. Recognising that technical innovations are only one aspect, the Net Zero Institute's holistic approach tackles technological, environmental, social, governance, and financial challenges associated with critical minerals.

By showcasing the University of Sydney's – and the Net Zero Institute's – contributions at both the national and international levels, this paper highlights the importance of collaborative, multidisciplinary and cross-sector efforts in driving sustainable solutions.

The transition to a net zero future depends on technologies that require significantly more mineral resources than traditionally used.

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Introduction

The age of critical materials

Much has been written about critical materials, critical minerals, and "the age of critical materials".

This white paper does not need to contribute in detail to this overview work, as governments, international agencies, and the scientific literature have covered the topic well. For example, the International Energy Agency[3] (IEA) has provided an excellent summary. However, some additional background material is helpful.

Critical minerals are gaining widespread attention due to their essential role in modern technologies and their strategic importance in the global economy.

The Australian Government defines a critical mineral as "a metallic or non-metallic element that is essential for modern technologies, economies or national security, and has a supply chain at risk of disruption".[4] Other national governments adopt similar definitions.

And the list of critical minerals is long. In 2022, the U.S. Geological Survey[5] nominated more than 50 elements in its list of critical minerals – more than half the naturally occurring elements. Australia lists 32 critical minerals, although it lumps the 17 rare-earth elements and the six platinum group elements into single categories.

We see from the definition of 'critical material' that nations focus on these materials for several reasons:

- **National security:** critical minerals are found in advanced defence systems
- **Living standards:** the technologies that underpin modern life all use critical minerals, and
- **Energy supply:** the clean energy transition will use large volumes of these critical minerals.

The Net Zero Institute's focus is on this third aspect: meeting the needs of the net zero transition in energy supply.

The IEA focuses on the critical minerals supporting the clean energy transition. It notes that an electric vehicle requires six times the mineral inputs of a conventional car, and an onshore wind farm requires nine times more mineral resources than a gas-fired power station. The move to renewable generation has resulted in a 50% increase in the average amount of minerals needed for a new unit of power generation capacity since 2010.[6]

The anticipated growth in the demand for certain critical minerals driven by the clean energy transition can be seen in Figure 1.

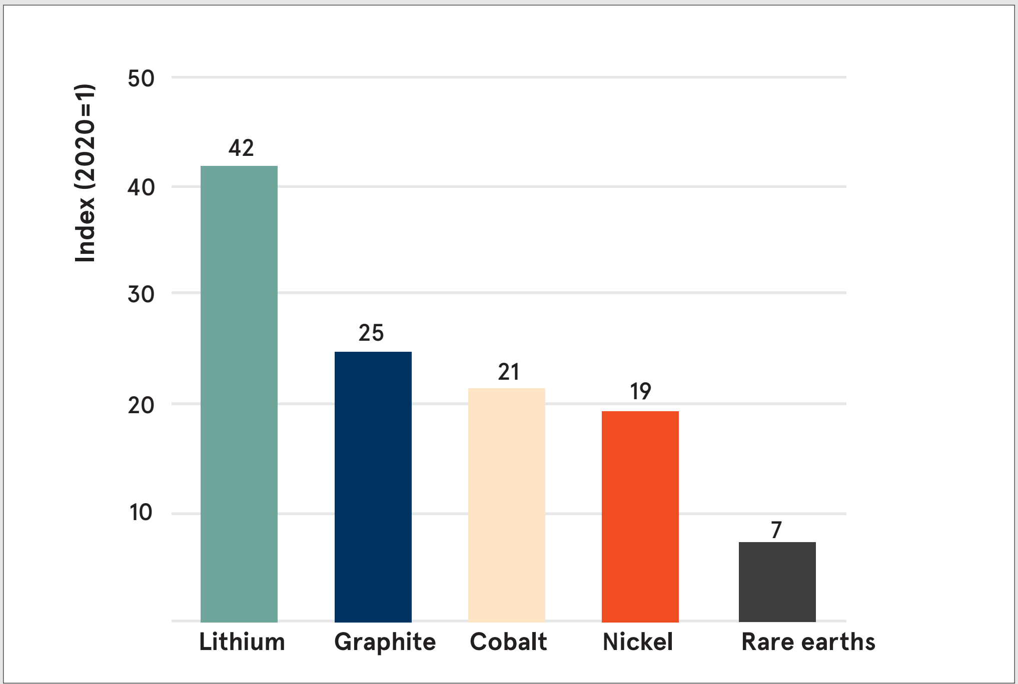


Figure 1: Growth in the demand for selected minerals in the IEA Sustainable Development Scenario, 2040 relative to 2020[7]

Figure 2 below shows the anticipated growth in the demand for lithium. The increase is driven by the demand for technologies that underpin the transition to net zero emissions. In the case of lithium, the driver is the growing uptake of electric vehicles and batteries. The demand for lithium starts from a low base, and the anticipated growth under the net zero scenario is dramatic. The demand for other critical minerals such as copper, nickel and cobalt is expected to grow significantly in the period to 2050, but from a larger base.

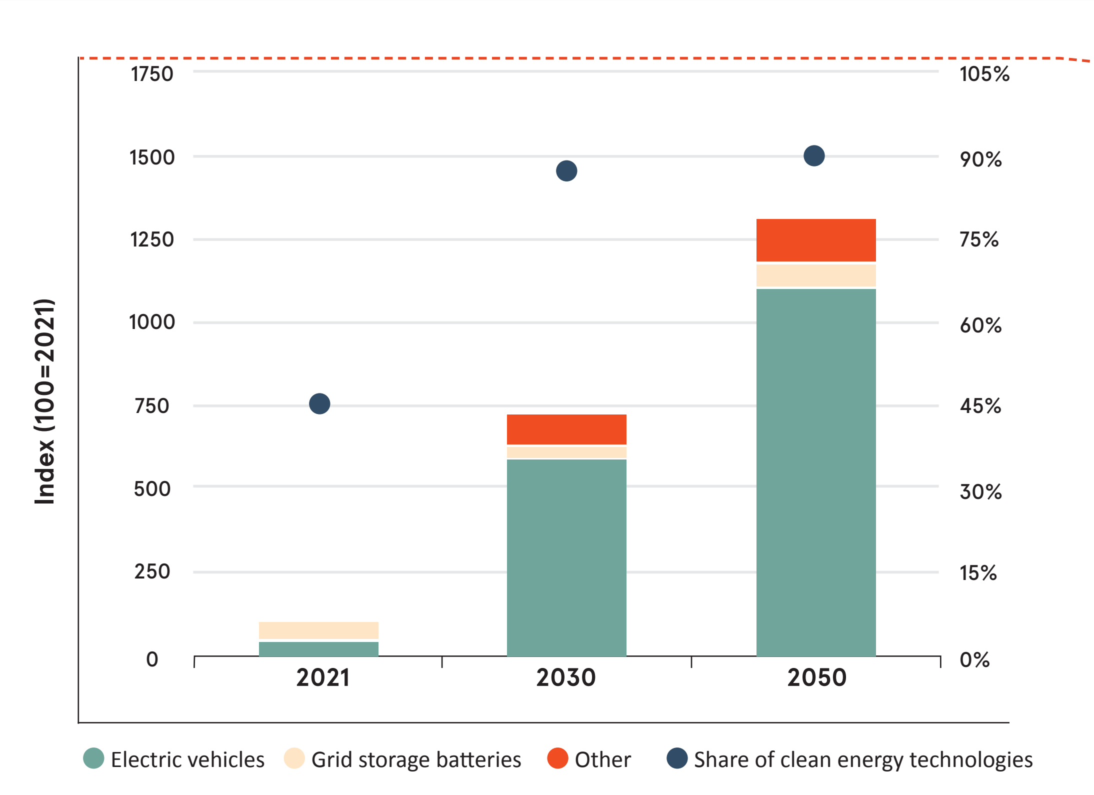


Figure 2: Total demand for lithium by end-use in the Net Zero Scenario, 2021-2050[8]

We see a similar trend in the growth of the demand for neodymium, which is one of the rare-earth elements.

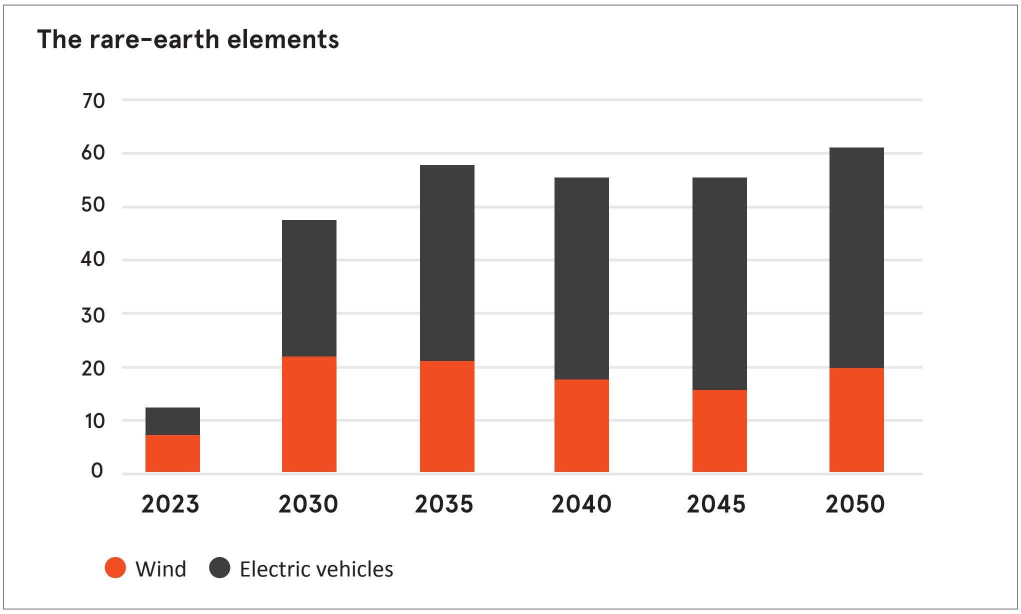


Figure 3: Total demand for neodymium by end-use in the Net Zero Scenario, 2021-2050[9]

This white paper will argue that it is impossible to research the future of the net zero transition without considering the role of critical minerals, how disruptions to the supply chain for critical minerals will impact the transition, and what can be done to mitigate the impacts.

When examining the role of critical materials, it is important to keep in mind that the average person is interested largely in the products and devices that contain them, such as electric vehicles, laptops, and mobile phones. They aren't, for example, interested in the mineral bastnäsite or the neodymium it contains, which is used in the magnets found in these products and devices.

This is important because it underlines that expanding existing supply chains isn't the only task. Innovating to reduce, or eliminate, the need for certain critical materials in various products and devices is also crucial.

It is easy to focus on the existing supply chains and seek to expand them, make them more secure, and more efficient. This is especially true for a raw material supplier like Australia. However, advances don't come from incremental improvements. They come from disruptions. No matter how efficient we made the telegraph, it was no match for the telephone. Similarly, the telephone's day in the sun ended with the rise of the Internet and smart devices.
So, the answer to the challenge of critical materials may be to make them less critical by developing alternate technologies or services that do not require as much of the critical material, or that use a different material entirely.

This white paper explores the broader question: What can be done to make critical minerals less critical? In this context, the Net Zero Institute will pursue a "sustainable supply of materials for the clean energy transition." This is our vision.

The document begins by examining the scope of sustainable supply. We then discuss the supply chain of critical materials and how its structure can be used as a pointer to future research programs. We end by discussing the approach of the Net Zero Institute.

The answer to the challenge of critical materials may be to make them less critical by developing alternate technologies or services that do not require as much of the critical material, or that use a different material entirely.

Copper, cobalt and nickel ore.

The Australian Government maintains two lists of minerals – a critical minerals list and a strategic materials list. The critical minerals list contains minerals essential to modern technologies, economies, and national security. Furthermore, these critical minerals are available from Australia, are in demand from our strategic international partners, and are vulnerable to supply chain disruption.

The Australian Government's strategic materials list comprises materials essential to modern technologies, economies, and national security, but whose supply chains are not sufficiently vulnerable to justify their inclusion on the critical minerals list.

The IEA focuses on minerals critical to the clean energy transition, which is expected to increase demand for some minerals. Five minerals receive particular attention in the IEA's 2021 paper on the role of critical minerals in the clean energy transition: lithium, graphite, cobalt, nickel, and rare earths.

It is interesting to note that these five minerals aren't minerals but *materials* (mainly metals). Further, the reason they are flagged as 'critical' requires an assumption that existing technologies will be deployed at scale to realise the clean energy transition. However, if alternative technologies are developed that are cost-effective and do not require the materials currently deemed as critical to the same extent, then the challenge of critical minerals is lessened.

Moving from critical minerals to critical materials

The vision of the Net Zero Institute is the "sustainable supply of materials for the clean energy transition". This vision moves the focus from critical minerals to critical materials. The United States Energy Act of 2020 defines a "critical material" as:

1. Any non-fuel mineral, element, substance, or material that the Secretary of Energy determines: (i) has a high risk of supply chain disruption; and (ii) serves an essential function in one or more energy technologies, including technologies that produce, transmit, store, and conserve energy; or
2. A critical mineral, as defined by the Secretary of the Interior.

The Act goes on to define a "critical mineral" as:

- Any mineral, element, substance, or material designated as critical by the Secretary of the Interior, acting through the director of the U.S. Geological Survey.

The definition of a critical material above is much broader than just referring to a critical mineral. However, the definition makes it clear that critical minerals are a subset of critical materials.

Ramifications for the Net Zero Institute

There are two important ramifications for the Net Zero Institute.

First, the term "critical minerals" is misleading. The real concern is over certain materials expected to be central to the clean energy transition. We focus on minerals because the current approach to supplying these materials is to mine the source minerals and then process them into the desired material. However, the Net Zero Institute should explore ways to reduce the pressure on supplying critical minerals by sourcing the materials derived from them through different routes, or by making existing supply chains more efficient.

Second, projections of the demand for these materials are based on current commercial or near-commercial technologies. While it might seem courageous to assume that emerging technologies will reduce the demand for the current suite of critical minerals, it is not impossible that ways will be found to do so. The Net Zero Institute should develop new technologies that do not require critical materials. An example of this is the Chinese battery manufacturer Contemporary Amperex Technology (CATL), whose work on deploying sodium-ion batteries at scale would reduce the demand for lithium.[10]

An uncertain future?

Before we examine the details of the Net Zero Institute's work on critical minerals, we should consider a couple of issues that cloud the view of the future.

It is important to do so because the net zero transition will happen in an uncertain context. The transition hinges on developing and deploying low-emissions technologies that are still in their early stages or are not fully realised. Additionally, the urgency of achieving net zero emissions is being weighed against other pressing global challenges, such as economic inequality, energy security, and geopolitical tensions.

McKinsey & Company has estimated that the global economy's transformation to achieve net-zero emissions by 2050 will require annual average spending of US$9.2 trillion on physical assets, which is US$3.5 trillion more than current spending.[11] This increase is equivalent to one-quarter of the total United States tax revenue in 2020. At this level, funding the net zero transition through public expenditure alone will not be feasible. Substantial private-sector investment will also be necessary.

However, the increase is also equivalent to half of global corporate profits, and businesses will need confidence in the value of investments in the net zero transition to commit funds of that magnitude. Government policy alone won't be enough because as governments change, so do priorities and policies.

In addition, unforeseen market conditions make it difficult for organisations (or governments) to make informed decisions about investments, expansions, or other strategic moves. Decisions can be based on initial, inflated expectations of technology, only to be undermined when reality hits.

Australia's efforts to reach both its emissions reduction and renewable energy targets demonstrate these sorts of challenges.[12] Targets established by extrapolating early successes in rolling out renewable generation are proving more difficult now that the easy opportunities have been exhausted.

Relying solely on the ongoing needs of the net zero transition to justify investments that meet the anticipated demand would be risky. However, the net zero transition, while undoubtedly important, is not the only factor driving the focus on critical materials. Critical materials are essential to much of modern life. They also underpin many modern defence systems. Therefore, a range of reasons can be used to make the case for urgently strengthening the value chains of critical materials by locating more resources, finding better ways to extract the minerals, recycling more, and developing substitutes.

What is meant by 'sustainable'

The Net Zero Institute seeks the "sustainable supply of materials for the clean energy transition". But what is meant by 'sustainable'? In 1987, the United Nations Brundtland Commission[13] defined sustainability as "meeting the needs of the present without compromising the ability of future generations to meet their own needs."

Many have tried to interpret this definition. Kuhlman and Farrington[14] argue that since the time of the Brundtland Commission, the concept of sustainability has been re-interpreted to encompass three dimensions: social, economic, and environmental. The authors believe that this change in meaning obscures the real contradiction between the aims of welfare for all and environmental conservation, and risks diminishing the importance of the environmental dimension.

Furthermore, it suggests a separation between the social and economic dimensions, which some argue is not true. Kuhlman and Farrington advocate for a return to the original meaning of sustainability, which is concerned with the well-being of future generations, and particularly with irreplaceable natural resources, as opposed to the immediate gratification of present needs that we refer to as well-being.

As Robert Solow[15] has pointed out, we cannot avoid using up some non-renewable natural resources, but this does not mean that these will necessarily become completely exhausted. In Solow's view, natural resources (whether renewable or non-renewable) can always be substituted by capital, taking the form of new materials, or smaller amounts of the natural resource for the same amount of end product. New natural resources are harnessed, while others become obsolete before they are depleted.

Considering the well-being of future generations presents significant challenges when it comes to critical materials. Many papers emphasise the need to increase production of critical materials for the transition to net zero. However, it's important to understand that the goal isn't just to reach net zero by 2050, but to maintain it every year after that.

Exhaustion or near-exhaustion of non-renewable resources, such as key ore bodies, could jeopardise the future unless alternatives are developed. This becomes even more critical considering the limited lifespan of components like solar panels or batteries in the net zero transition. The solution to this challenge involves recycling critical materials from end-of-life products and substituting critical materials.

In view of this conclusion, the medium- to long-term focus of the Net Zero Institute must be on recycling critical materials in end-of-life products and substituting critical materials in new products.

It is important to understand that the goal isn't just to reach net zero by 2050, but to maintain it every year after that.

Sustainable supply of materials
for the energy transition

Make the value chain more effective

The current value chain is a great starting point for realising the "sustainable supply of materials for the clean energy transition". Technological advances may see the substitution of current critical materials with materials that have more secure supply chains. However, this will take time to be deployed at scale, and in the meantime, the world is stuck with today's clean energy technologies (as well as other products that require critical materials). So, improving the current supply chain is still essential. Figure 4 shows Net Zero Institute's view of the critical minerals value chain.

Other value chain elements, which span the environmental, social, and governance space, are not included in the figure but are addressed in subsequent sections.

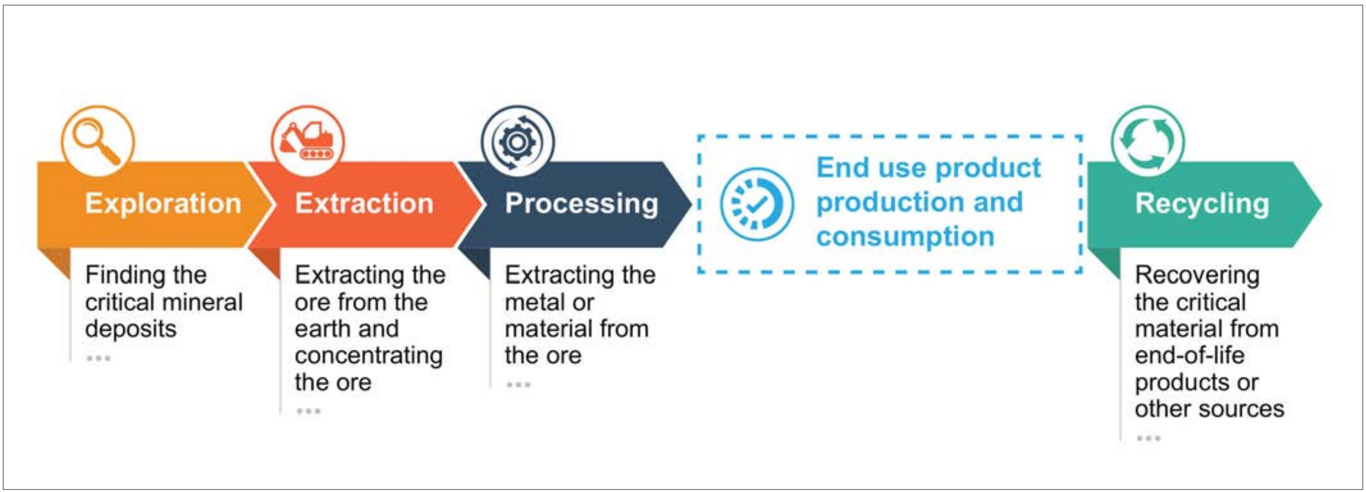


Figure 4: The critical minerals value chain

Exploration

What it is, and why it's important

As the global demand for critical minerals continues to rise due to GDP growth and technology transformation, such as the net zero transition, the mining industry faces the challenge of finding more resources in the Earth's crust to meet the increasing need for metals and raw materials. However, the discovery of new ore deposits – especially through greenfield exploration – has declined due to difficult conditions such as thick overburden, remote locations, declining ore grades, and social and environmental challenges. Consequently, there is now a greater need for technological innovation in mineral exploration to ensure the sustainability of non-renewable resources.

What the Net Zero Institute is doing

The team at the School of Geosciences, led by Prof Dietmar Muller, is working to develop open-source software for paleogeographic information systems and global digital datasets through the EarthByte research group. One of the main goals of the EarthByte Group is to synthesise geological data over space and time, incorporating various geological and geophysical data into comprehensive Earth models. This work involves using machine learning techniques to address challenges related to complex and limited geological data.

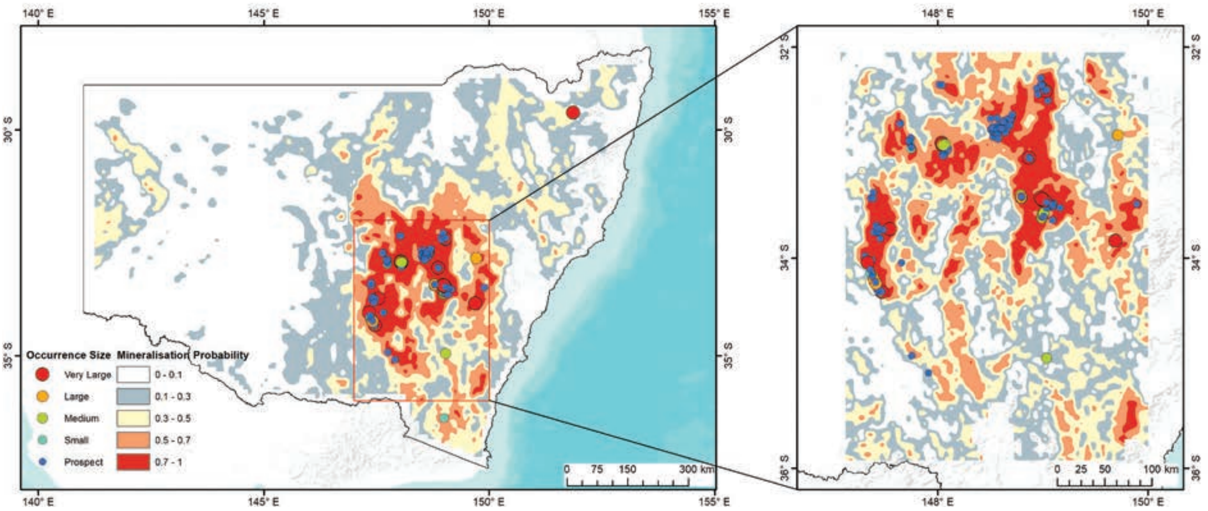
Prof Budiman Minasny, from the School of Life and Environmental Sciences, has developed innovative approaches to digital soil mapping research. His work, which has sparked global interest among soil scientists, explores new methods for generating soil information to address today's pressing global issues.

This has resulted in the initiation of GlobalSoilMap, a worldwide project that provides vital soil information to tackle global challenges such as food security, water security, energy security, and sustainable responses to climate change. Prof Minasny and his research team have explored various new technologies, including near-infrared and portable x-ray fluorescent spectroscopies, which allow for the rapid collection of soil information. Additionally, the group has utilised deep learning AI methods, which have significantly enhanced the prediction of soil properties from extensive soil spectral databases and the incorporation of spectral data from multiple instruments.

Case study:

AI-Powered Prospectivity Mapping

by Prof Dietmar Müller and Dr Ehsan Farahbakhsh



Prospectivity Map of Poryphyry Mineralisation in NSW.

Prospectivity Map of Poryphyry Mineralisation in the Lachlan Orogen.

Discovering new sources of critical minerals is getting harder, with new deposits often located deeper underground. The increased demand for critical minerals means we need better ways to explore for them.

In this research by Elnaz Heidari, Ehsan Farahbakhsh, Hojat Shirmard, Fabian Kohlman, and Dietmar Müller from the EarthByte Group at the University of Sydney and Lithodat Pty Ltd, a machine learning-based framework was used to create predictive models that produced prospectivity maps showing where porphyry deposits are likely to be found.

The study used three types of data: geological (like faults and rock units), geophysical (magnetic, gravity, radiometric, and seismic imaging), and alteration maps created by remote sensing. These were used to create a reliable model for predicting where porphyry deposits might be found in the Macquarie Arc in eastern NSW – known for its important porphyry copper-gold deposits.

The predictive models enabled the identification of key features that can help distinguish between mineralised and non-mineralised areas. The prospectivity map of likely mineralisation shows a clear connection between high probabilities and known mineral occurrences and predicts several new potential areas for exploration, as shown in the figure above.

The discovery of new ore deposits has declined … there is now a greater need for technological innovation in mineral exploration to ensure the sustainability of non-renewable resources.

Geologists collect samples in the Pilbara, Western Australia.

How this aligns with government priorities

The Australian Government's Exploring for the Future program, led by Geoscience Australia, aims to enhance the understanding of the nation's mineral and energy potential as well as its groundwater resources. As part of this program, studies focusing on critical minerals were conducted. One example is the National Mine Waste Assessment, which sought to facilitate the sustainable and economically viable recovery of critical minerals from secondary sources. This involved a nationwide assessment of mine waste to uncover new opportunities for the supply of critical minerals.

The US Department of Energy seeks to diversify and expand critical mineral and material supply from varying sources while minimising waste and increasing the techno-economic coproduction of materials in order to ensure material availability.

Guidance from the literature

We highlight two papers. One describes how advanced instrumentation and data processing is leading to new approaches to exploration. The second builds on the theme of data and discusses how clever data management can highlight likely mineral resources.

Discovering new sources of critical minerals is getting harder, with new deposits often located deeper underground. The increased demand for critical minerals means we need better ways to explore for them.

In a significant review article, Kazuya Okada[16] looked at breakthrough technologies for mineral exploration. Breakthrough technologies in exploration include induced polarisation, airborne electromagnetics, airborne gravity gradiometry, spectroscopic methods, global navigation satellite systems, unmanned survey platforms, and utilising AI neural networks and deep learning. Some challenges for the future were highlighted, such as improving the economic efficiency of exploration through unmanned operation or improving various airborne exploration techniques. Okada also highlighted the importance of extracting key information needed to identify mineral deposits, such as the induced polarisation of certain key classes of minerals. The effects of the surface layer can be removed using advanced technologies, giving a view of underlying minerals.

The role of information acquisition and management was explored by Partington et al.[17] They looked at how to rank mineral exploration targets by creating an exploration information system, or EIS. An EIS is a way of creating and managing exploration targets, with its main goal being the provision of information to help find new mineral deposits that are economical to mine and process under current financial conditions.

We also highlight a paper by Jillian Ash[18] to foreshadow a section below that discusses the broader social context of the critical minerals. Ash explains how demand for critical minerals will intensify exploration on First Nations peoples' lands. The existing literature on the social impacts of mining is extensive, but few studies focus on the exploration phase. Nickel exploration in the Solomon Islands, which is used as a case study, generates more negative social impacts than positive.

Extraction

What it is, and why it's important
Mineral extraction refers to removing valuable minerals and metals from the Earth. This white paper focuses on mining, as other parts of the process are considered separately. The extraction of critical minerals is essential to meet the rising demand, but it comes at a high cost in terms of its environmental impact (habitat destruction, water pollution, soil degradation, greenhouse gas emissions, and waste generation). It also has a social impact through, among other things, the displacement of communities and health risks.

What the Net Zero Institute is doing
The Rio Tinto Centre for Mine Automation at the University of Sydney conducts applied research in autonomous systems, orebody modelling and systems optimisation towards the realisation of fully autonomous integrated mining operations. Well-designed autonomous vehicles can benefit the industry by operating more consistently and reliably than human-operated vehicles, thus increasing efficiency and safety. Fleets of autonomous vehicles can provide additional benefits by optimising their actions to reduce congestion and redundant work, which lowers fossil fuel consumption and carbon emissions. Dr Andrew Hill, the Centre's lead, is developing robust planning and control algorithms to manage fleets of autonomous mining vehicles.

Researchers in the centre are also developing novel algorithms to improve geological estimations, fusing together dense and sparse data from different sources. A better understanding of a mine's mineral resources leads to more efficient ore extraction, increasing the volume of ore extracted while improving the quality of the extracted material.

The Sydney Centre in Geomechanics and Mining Materials, led by Prof Itai Einav, is conducting cutting-edge research in geomechanics and granular physics. The centre aims to further enhance its world-leading position in mining geomechanics. Improvements in handling bulk and granular solids in mining are expected to increase yields and reduce costs.

Case study: Regional development and global production networks in Central West NSW

by Prof Neil Coe and Dr Lian Sinclair

Newmont Mining's Cadia Gold-Copper-Molybdenum Mine surrounded by prime agricultural land near Orange in Central West NSW.

With 10 critical mineral mines and facilities already operating or proposed – including for rare earths, nickel, cobalt, scandium and copper – Central West NSW is an emerging centre in the new mining boom.

However, rural and agrarian communities and Traditional Owners do not always welcome the dramatic changes brought by renewable energy projects, let alone critical mineral mining. Water rights, pollution and land rights are already contentious issues for regional communities. The mining industry, governments and researchers must tread carefully to avoid stoking tensions.

The work of Prof Neil Coe and Dr Lian Sinclair from the School of Geosciences seeks to explore these regional development contestations through using the framework of global production networks, or GPNs. This understands mining regions such as Central West NSW as starting points for long, complex and often global webs of relationships that connect the mined minerals to their ultimate uses in renewable energy and other technologies. The decisions taken by 'lead firms' in those client industries – such as Tesla or Volkswagen that use these minerals in electric vehicles – propagate back along the network and shape both its configuration and operation. Of course, critical mineral GPNs are also heavily shaped by government policies and international agreements in times of geopolitical tension, as governments attempt to 'de-risk' investment.

The decisions made in distant board rooms and government offices will thus determine the local environmental and social impacts, the contribution to regional and national economic prosperity, and the global contribution to the decarbonisation of critical mineral mining in NSW. Economic geographical research of this kind helps us understand both the decision-making structures and power relations inherent to GPNs, and their interplay with the local contestations that surround critical mineral developments in regions like Central West NSW.

How this aligns with government priorities
Australia's National Science and Research Priorities include research into new and innovative ways of extracting, refining and processing critical minerals while minimising environmental impact.

The International Energy Agency has recommended a series of actions for governments to create conditions conducive to diversified investment in the mineral supply chain.

Guidance from the literature
We look at two papers that offer pointers to future research into extracting critical minerals. The first paper focuses mainly on productivity enhancements. The second paper looks at the environmental challenges linked to rare earth metal extraction, which are a significant barrier to the onshoring of rare earth metal extraction and processing in the developed world.

In the first paper, Elisabeth Clausen and Aarti Sörensen[19] discuss the advancements needed to modernise mineral and metal extraction. The industry aims to enhance the productivity of mineral extraction while improving its environmental, social, and governance performance. To achieve this, a growing focus is on adopting automation and digitalisation technologies, such as electrifying equipment and implementing sustainable energy solutions. The authors emphasise that the mining industry still has work to do to fully embrace automation, digitalisation, and low-emission drive systems. They believe that, from a technological standpoint, the vision of a digitally connected, autonomous, and carbon-free mine is achievable. However, they stress that the key breakthroughs will come from successfully developing, implementing, and integrating a full range of automation and digitalisation technologies across entire mining operations and moving towards fully integrated, autonomous systems. Clausen and Sörensen also highlight the importance of mining companies reevaluating their role in the economic, social, and environmental ecosystems they operate within, going beyond technological aspects to contribute positively to these areas.

Rare earth elements are a special case. They play an ever-more-important role in modern society and are essential to several technologies at the centre of the net zero transition. While not all that rare, rare earth elements are tough to extract in pure form as they have very similar physical and chemical properties. In the second paper, Deniz Talan and Qingqing Huang[20] reviewed the environmental impacts of rare earth element extraction processes and solution purification techniques. They pointed out limitations in examining the environmental implications of rare earth mining. Their main focus was on toxic radionuclides found in the same mineral deposits as rare earths, irrespective of whether they come from primary or secondary sources. The concentration of these harmful trace elements might increase due to extraction and beneficiation processes. Failure to properly separate and dispose of these radionuclides can result in their accumulation on the soil surface or integration into aquatic systems, leading to elevated environmental and health concerns.

Wang et al.[21] proposed a new approach to the extraction of rare earth elements highlighting the potential for technological breakthroughs to reduce the pressure of critical material value chains.

From a technological standpoint, the vision of a digitally connected, autonomous, and carbon-free mine is achievable.

The hybrid Gullen Solar Farm and Gullen Range Wind Farm at Bannister in the Upper Lachlan Shire, NSW.

Processing

What it is, and why it's important
While extraction focuses on removing the critical mineral from the earth and some degree of simple processing at the mine site, the intermediate processing is about converting the material obtained from the mine into a form suitable for end-use applications.

What the Net Zero Institute is doing
A/Prof Alejandro Montoya has developed an advanced electro-metallurgical technology that provides a sustainable and efficient alternative to traditional extraction methods. This innovative process allows for the selective recovery of valuable metals such as copper, nickel, cobalt, and vanadium from various sources under atmospheric conditions. Currently approaching Technology Readiness Level 5 (TRL5) for the extraction of metals from electronic waste, the process operates in the liquid phase, producing a stream of soluble metals and a solid byproduct rich in transition metals, liberated from the plastic and silica components of electronic waste. This approach can be readily adapted to the extraction of critical minerals from end-of-life products, as described below.

Prof Yuan Chen is seeking alternate routes to producing critical materials used in future batteries. Carbon materials, including graphite and carbon conductive additives, are critical battery components. Prof Chen's group developed novel methane pyrolysis processes to produce high-purity carbon materials as byproducts of clean hydrogen production. These processes can help meet lithium-ion and emerging sodium-ion battery requirements, and offset hydrogen production costs to make the process economically competitive. The production of these carbon materials often involves using fossil fuel precursors, energy-intensive processes, and large amounts of chemicals, resulting in a high carbon footprint. Their production is also currently dominated by a few countries. The new methane pyrolysis approach, a partnership with Hazer Group in Perth, offers a more sustainable solution. Furthermore, the production plant can be built at various locations due to the wide availability of methane sources (natural gas and biogas).

Prof Yuan Chen (University of Sydney) and Dr Benjamin Chivers (Senior Research Scientist) at Hazer's hydrogen production demonstration plant in Perth (credit: Y. Chen).

How this aligns with government priorities

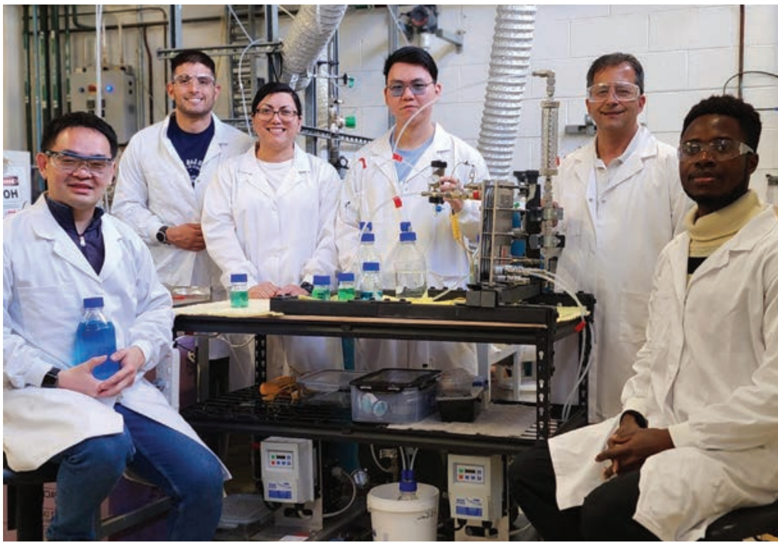
The Australian Critical Minerals Research and Development Hub (ANSTO, Geoscience Australia, and CSIRO) seeks to scale up and commercialise critical minerals research and development by undertaking priority projects and identifying research and development priorities, gaps, and technical obstacles in supply chains of strategic significance. The hub will also leverage Australia's resource potential to support onshore processing and create opportunities in downstream high-value industries.

The Minerals Research Institute of Western Australia operates a Critical Minerals Advanced Processing Common User Facility with the support of the Australian Government. The CMAP will focus on upstream (recycling of mining waste and tailings) and midstream (minerals processing activities, high purity metal refining and advanced material manufacturing) activities. It aims to provide common use pilot plant equipment to support the growth and diversification of Western Australia's resources and related industries and to create a critical mass in research and training.

Guidance from the literature

A common theme in the literature is the need to address the environmental and social impact of the processing of critical minerals. We see this, for example, with the Thacker Pass Lithium mine in the USA[22] and the proposed lithium mine in Jadar, Serbia.[23]

Rare earth elements warrant special attention because separating the various metals from the concentrated ores is challenging. Chen et al.. provide a good discussion of the issue.[24] They reviewed recent advances in selective separation technologies of rare earth elements and highlighted the challenges the current rare earth separation technologies face. The separation technologies include chemical precipitation, ion exchange, solvent extraction, membrane separation, and adsorption, all of which carry significant environmental costs. In the future, developing green and high-quality rare earth separation technology should focus on reducing environmental problems, seeking separation technologies with higher selectivity, stability and cost-effectiveness, and further developing process technology with low energy consumption, high efficiency, low cost and large processing capacity. The authors also emphasised recycling resources and treating suitable secondary resources containing rare earths. This last point aligns with work done by Geoscience Australia.[25]



A/Prof Alejandro Montoya and team, working on the new advanced electro-metallurgical technology (Credit: I. Kristianto).

Case study:
Improved recovery of critical metals

by A/Prof Alejandro Montoya

The team, led by A/Prof Alejandro Montoya from the School of Chemical and Biomolecular Engineering, in partnership with EcometalX Pty Ltd, is developing and implementing an advanced electrometallurgical process for the extraction of critical metals from mineral oresto the extraction of critical minerals from end-of-life products, as described below. and tailings. This innovative process is particularly effective for copper extraction from hard-to-extract sulphide ores and concentrates, significantly improving metal recovery rates compared to traditional acid heap leaching techniques.

The team is collaborating with key industry partners—including BHP, IGO, Emew, and Scimita—as well as government institutions such as the Minerals Research Institute of Western Australia to scale this technology to a pilot stage. Successful commercialisation of this process will position Australia as a global leader in critical minerals production while making a substantial contribution to global efforts to achieve a low-carbon future.

Recycling

What it is, and why it's important
Recycling critical materials – especially those used in high-tech and clean energy applications – is crucial for reducing our reliance on finite resources, minimising environmental impact, and securing supply chains. Its importance spans several areas. Critical materials are limited and often come from regions with geopolitical risks. Recycling helps conserve these resources and reduces the need for new mining operations. Furthermore, recycling helps reduce the environmental consequences of exploration, extraction, and processing. These impacts include habitat destruction, water contamination, and greenhouse gas emissions. Recycling also alleviates pressure on supply chains, leading to enhanced supply chain security.

However, it is not easy. Critical materials are often found in small quantities and are dispersed in complex products such as electronics, making them difficult to recover efficiently. Furthermore, current recycling technologies may not be fully capable of efficiently extracting critical materials from complex products, making recycling less economically attractive. Finally, governments can set regulatory and policy barriers that constrain opportunities for recycling.

A study by the European Commission[26] found that raw materials such as gallium and indium cannot be recycled. In such cases, the only alternative is substitution. We will delve into this important consideration in more detail below.

What the Net Zero Institute is doing
Several Net Zero Institute researchers are investigating technologies for extracting valuable materials from waste streams. Prof Marjorie Valix and A/Prof John Kavanagh are collaborating on innovative research that integrates the use of acid-generating microorganisms and other hydrometallurgical approaches with electrodialysis to extract metals from both domestic and industrial waste streams, including mine tailings and low-grade ores. Some of the Net Zero Institute's international partners at the VTT Technical Research Centre of Finland are also exploring the issue. An example is provided in the case study below.

How this aligns with government priorities
Australia's National Science and Research Priorities include a transition to net zero by, among other initiatives, eliminating or managing the environmental impacts of emissions reduction, removal, and storage technologies and shifting towards a circular economy through advanced materials and processes.

Geoscience Australia has released an online Atlas of Mine Waste[27], highlighting the potential to extract critical minerals and other resources by reprocessing previously mined material. The atlas has identified 1,050 sites across Australia that could serve as sources of critical minerals. Australia can maximise the value of its critical minerals throughout their lifecycle by embracing the circular economy. To guide the government in this transition, a national Circular Economy

Case study: Chemicals from waste dust

by Riihimäki Teppo, VTT Technical Research Centre of Finland Ltd

At its pilot centre in Bioruukki, Finland, VTT is demonstrating novel approaches to the recycling of metals. For example, Electric Arc Furnace (EAF) dust is produced as a steelmaking side product in Europe at a rate of around 1 million tonnes annually.

VTT Bioruukki has developed a hydrometallurgical process for EAF dust, which involves the recovery of iron as ferrous sulphate, used as a water treatment chemical, and the recovery of zinc as zinc sulphide, a raw material for zinc production.

The process also utilises scrap iron for process solution neutralisation, ensuring that separate neutralisation residue or iron waste is not formed. Optionally, lead can be recovered from leach residue, and manganese and other trace metals such as nickel and cobalt can be recovered from the bleed solution, depending on the EAF dust composition.

The overall process concept involves converting waste feeds such as EAF dust and scrap into valuable chemicals with minimised waste formation, making the process both environmentally and economically viable.

This solution is beneficial as it helps minimise waste landfilling in steelmaking and reduces the demand for natural resources by producing chemicals from waste.

Advisory Group has been established to address the challenges and opportunities. The group is focused on helping Australia leverage a circular economy approach to maximise critical minerals' value and trade opportunities, including recovery, reprocessing, and recycling within the country.

The US Department of Energy's critical minerals and materials strategies include building a circular economy for critical materials. This involves remanufacturing, refurbishing, repairing, reusing, recycling, and repurposing all materials used in a modern economy to extend their lifetime and reduce the need for new material extraction. The National Renewable Energy Laboratory (NREL) is also researching the role of the circular economy in strengthening critical material value.[28] NREL's research highlights the challenges and potential solutions for recycling critical materials used in clean energy applications. NREL is developing low-emissions materials to address supply chain limitations, creating designs that increase recyclability, and designing manufacturing processes that reduce material use. It emphasises the importance of a just circular transition, exploring ways to reduce waste and foster product innovation while supporting human health, livelihood, and job creation. A just circular transition should aim to reduce inequalities and benefit all communities. The EU also stresses the importance of recycling for supply security.[29]

Examples from the literature

The literature contains an extensive library of the future recycling of critical materials and the move to a circular economy in critical materials.

Many of the studies looked at specific products or critical materials. For instance, Kumari and Sahu[30] discuss the recycling of spent neodymium iron boron (NdFeB) magnets. The NdFeB magnet is an essential component of green energy technologies and contains critical rare earth elements (neodymium, praseodymium, and dysprosium).

Some researchers have explored new methods for extracting important materials from waste streams. For example, Danouche et al.[31] studied the recycling of rare earth elements and found that recycling eliminates the need to separate low-value or coexisting radioactive elements from rare earth elements when obtained from raw ore. This will significantly reduce the environmental burden of rare earth element production.

Lastly, some researchers look at the big picture. In their research, Della Bella et al.[32] developed an integrated multi-regional waste input-output model to assess the balance between demand and supply and the potential for recycling cobalt, lithium, neodymium, and dysprosium. They focused on various energy scenarios projected up to 2050. They highlighted the need for urgent recycling efforts to complement the primary supply due to the significant increase in demand and the long lead time required for opening or expanding new mines. A similar study was reported by Rennenberg et al.[33] They looked at the potential impact of circular economy strategies on mitigating niobium's criticality within Europe.

Ramifications for the Net Zero Institute

The Net Zero Institute will do well to focus on further research into new approaches to the exploration and extraction of critical minerals. This aligns with national R&D priorities and current research activities.

Current research at the University into the circular economy should be extended to include focused research into the recovery and reuse of rare earth metals.

Several papers in the literature explained that solutions to the supply of critical minerals will not be found solely in the domains of science and engineering. Social issues cannot be ignored. This is discussed in the next section.

Build the community

In this section, we follow up and build on comments made in the earlier section about the limitations of solutions that focus on technology, without adequately considering the importance of the social sciences.

Why it is important
In the introduction to this white paper, we outlined the drivers of the focus on critical materials. They go way beyond the net zero transition and include national security and community trust in politics. National security is likely to shape our local critical minerals policy, and the extent to which communities trust and engage in the policy process is likely to shape whether communities are open or hostile to new industry policies around critical minerals.

There is a risk that the impetus to reduce emissions and strengthen critical material supply chains will swamp other concerns. Hine, Gibson, and Mayes took up this issue in their paper, which questioned extractivism, as they called it.[35] The article questions the urgency behind the push to mine critical minerals. The urgency seems to stem from the need for decarbonisation, which is crucial for fighting climate change. However, labelling it a "critical materials crisis" might support a political narrative that allows the urgency for decarbonisation to overshadow important issues like redressing regional inequality, social justice, rights, and responsibilities. Crisis narratives and fast-tracked regulations may hide significant social and environmental justice concerns while ignoring technical obstacles to resource development.

Berthet et al. quantified the social and environmental impacts of critical mineral supply chains for the energy transition in Europe.[36] They developed a new methodology based on a Multi-Regional Input-Output model, which included detailed mineral production data and socio-environmental information. Their research suggests that the EU's energy goals may lead to modern slavery risks for 15,000 to 89,000 African miners, and could result in the consumption of up to 73 million m^3 of water in water-scarce areas. Additionally, they found that current EU regulations do not effectively address supply, environmental, and social risks together.

Moreover, the place-based nature of critical minerals concerns not only the physical location of extraction but also the location of the supply chain, which is shaped by place and has the potential to help or hinder communities. The development of advanced manufacturing associated with critical minerals has the potential to support community and urban renewal. In addition, the need for a pipeline of skilled employees and the agglomeration of relevant industries will also impact the geography of community benefit. We can plan a net zero future, but we must negotiate it with affected communities to make it happen.

The question of community benefit, however, is not unilateral. While an industry perspective might assume or suggest that a community might welcome new critical minerals industries, this is not always true. Increasing opposition to offshore windfarms, transmission lines and desalination plans associated with hydrogen labs reveal that when communities are the object of transition, rather than actively involved in shaping transition, community opposition can occur.

Indeed, Australia has witnessed rising distrust in political and corporate decision makers,[37] which is also contributing to delays in the implementation of net zero policies. Not only is engaging communities in the process of transition the 'right thing to do' it is also the politically strategic thing to do if policy priorities are to be realised in new renewable industries.

The place-based process of extracting and using critical minerals and materials happens in the community. Most obviously, in Australia, extraction very often occurs on Indigenous land. Consequently, the location of any extraction and the nature of any benefits associated with extraction are, at best and often governed through, the force of Native Title and environmental protection legislation involving a negotiation with Aboriginal communities.

Innovative solutions developed at the Net Zero Institute
The Net Zero Institute is alert to the need to build a meaningful process of community benefits into its work on critical minerals. In doing so, we are not seeking to bring the community to the critical minerals conversation at the end of the research process, but to engage in community-led research and co-design processes to enable community needs and interests to be combined with, and potentially connected to, the opportunity for critical minerals and materials.

The Net Zero Institute is harnessing the work and expertise of the five-year Real Deal for Australia project led by A/Prof Amanda Tattersall and its four place-based projects that have sought to build community-led transition.[38] In those places, the Real Deal has led a process of testing and exploring how new infrastructure and industry can generate community benefits by negotiating with broad-based community coalitions to explore how new infrastructure and industry can be shaped to address community needs. The research method process used in this work is called the relational method, and its cyclical approach is shown in Figure 5.

Figure 5: The Relational Method is a community-led approach to policy development that prioritises the active participation of people affected by the issues at hand. This approach recognises that good policy is best sourced from the lived experiences and wisdom of diverse communities, rather than from top-down, expert-driven processes. (credit: A/Prof Amanda Tattersall).

Case study: Real Deal and five years of community benefits work in places around Australia

by A/Prof Amanda Tattersall

In Gladstone, the community benefits work involved a listening process of 316 people and a community consultation process that is considering the merits of a Community Benefits agreement process for a proposed desalination plant connected to the Hydrogen Lab. In the Hunter region, 40 community listening sessions were held alongside negotiations with the Minister for Climate and Energy. Geelong has seen a similar listening process with 248 participants, which has led to a focus on collaboration with the Geelong Council to address affordable housing.

In each place, climate transition has been connected to community engagement. In each place, the community benefits process has created a supportive environment for new infrastructure, rather than it being opposed or resisted. This offers a promising pathway for critical minerals and materials, as it demonstrates that by using community-led processes - communities and critical minerals infrastructure can find common ground by designing projects with community in ways that connect them to local interests and needs.

A/Prof Shumi Akhtar, a Net Zero Institute colleague in the University of Sydney's Business School, along with partners at Macquarie University, is evaluating the impact of Australian companies in the critical minerals and materials sector on environmental, social, and governance factors, as well as on the nation's economic growth. Understanding these impacts is essential for achieving net zero targets and aligning with the United Nations Sustainable Development Goals.

The University of Sydney established the Sydney Policy Lab in 2018 to analyse real and potential policies in a non-partisan way. People from different backgrounds come together to create public policies that positively impact people's lives. The lab is guided by the community and draws on the wide-ranging knowledge of the University and its partners. It takes an experimental approach to complex challenges and aims to achieve real, positive changes in people's lives. Dr Gareth Bryant from the Faculty of Arts and Social Sciences and the Sydney Policy Lab has analysed the "Future Made in Australia" (FMiA) policy looking at the interaction between the FMiA policy and critical minerals.

We can plan a net zero future, but we must negotiate it with affected communities to make it happen.

Case study: Critical minerals and the ESG landscape of Australian companies

by A/Prof Shumi Akhtar and Dr Farida Akhtar

The extraction and processing of critical minerals poses significant environmental challenges, including land degradation, high water consumption, and greenhouse gas emissions. To tackle these issues, companies need to embrace sustainable practices, employ advanced waste management strategies, and comply with strict regulatory frameworks to minimize their ecological impact. Socially, mining operations can have a profound impact on local and Indigenous communities, potentially disrupting traditional lands and cultural heritage.

It is crucial for companies to engage with these communities respectfully, ensuring that their activities demonstrate a commitment to environmental and social improvement. This balanced approach has the potential to support community well-being and enhance the companies' social licence to operate.

Research by the University of Sydney's Business School, in collaboration with Macquarie University, is exploring effective governance, which is crucial to manage the complexities of the critical minerals supply chain. Transparent policymaking and collaboration between government, industry, and stakeholders is essential to safeguard national interests, especially given the sector's significant role in driving Australian economic growth. Attracting foreign investment, managing market volatility, and aligning operations with long-term sustainability goals, including climate risk management, are key to ensuring the sector's success. Sustainable growth in Australia's critical minerals sector ultimately depends on integrating economic objectives with responsible environmental management, social inclusivity, and strong governance practices.

Case study:

Future Made in Australia and Critical Minerals

by Dr Gareth Bryant

The Australian government introduced the Future Made in Australia (FMiA) agenda in early 2024 to support industries contributing to climate and security goals. FMiA aims to guide private sector investment by providing tax credits, loans, and price floors for critical industries. It focuses on "net zero" and "economic resilience and security" and includes "community benefits principles."

Building 'sovereign capability' in critical minerals processing has been a key focus of initial FMiA announcements. One of the key initial pieces of industry support in FMiA is the Critical Minerals Production Tax Incentive (CMPTI). As currently outlined in a government consultation paper, the CMPTI will allow critical minerals companies to claim 10 per cent of processing and refining expenditure for 31 critical minerals as a refundable tax offset between 2027/8-2039/40 (investment decisions need to be made by 1 July 2030).

While the value of this policy has been estimated at $7 billion over 10 years, it is uncapped and therefore, the total support provided could be far greater, depending on production levels. The policy is partially modelled on the Advanced Manufacturing Production Credit (AMPC) in the US Inflation Reduction Act, and there is a similar Hydrogen Production Tax Incentive (HPTI) proposed in FMiA. FMiA will also provide direct financial support through loans, guarantees and equity to certain critical minerals projects through the Critical Minerals Facility and the Northern Australia Infrastructure Facility.

The government aims to engage with researchers, industry, and community to improve policy design and outcomes. This includes addressing issues related to First Nations participation, benefits for regional communities, and environmental protection. Consideration is also needed on securing an adequate share of any returns for the Australian public.

Lithium mine processing plant, Western Australia.

Break down the silos

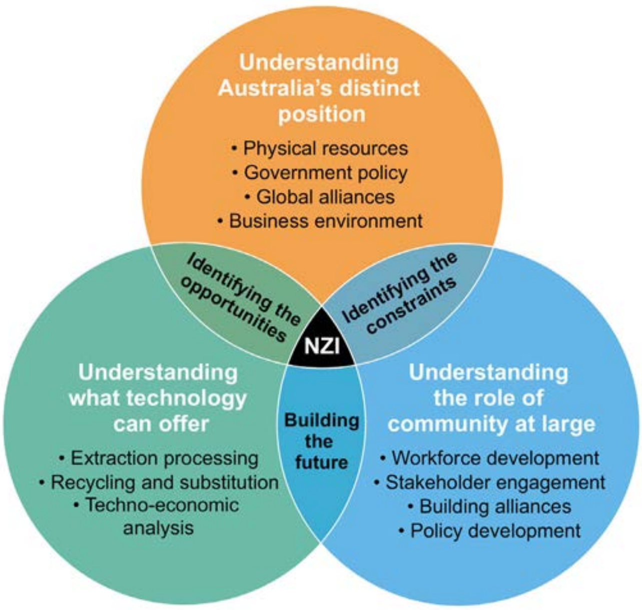
In this section, we follow up and build on comments made in the earlier section about the limitations of solutions that focus on technology, without adequately considering the importance of the social sciences.

Our discussion of existing research to improve the value chain focused on hard science and technology. However, the need to build the community highlighted the importance of the social sciences in realising a more effective value chain. In his book *Convergence: The Idea at the Heart of Science*, author Peter Watson argues that scientific disciplines have converged over the last 150 years despite their differing origins. He suggests that significant advances in knowledge have occurred when ideas from different disciplines are combined.

We can apply this lesson to the Net Zero Institute: solutions will be developed at the boundaries of disciplines. Figure 6 outlines how the Net Zero Institute's multi-disciplinary approach can lead to research outcomes that support the sustainable supply of materials from Australia for the clean energy transition.

Geology and geophysics provide insights into physical resources, specifically critical mineral ore bodies. The Net Zero Institute's activities to enhance understanding of these vital mineral resources have been previously discussed. Colleagues in the Faculty of Arts and Social Sciences are involved in exploring government policy through the Policy Lab and global alliances through the US Studies Centre. Additionally, the University of Sydney's Business School researches the business environment in Australia.

Figure 6: The multidisciplinary approach offered by the Net Zero Institute



Combining these insights with the STEM-based work of colleagues in the faculties of Engineering and Science will yield a robust appraisal of the possibilities available to Australia to supply more of the world's critical materials, and to do so sustainably. STEM-based research will tell us what is technically possible.

However, as we highlighted earlier, solving the technical side is insufficient; we need to understand the social, legal and economic aspects. Were time on our side, these latter challenges could be addressed after the technical solution is proposed. However, time is not on the world's side if net emissions are to be reduced in time to stop dangerous human-induced climate change. The social, legal and financial solutions must be developed concurrently with the technical solutions. Collaboration between researchers across multiple disciplines is essential if feasible opportunities are to be identified (and realised) in the necessary timeframe. The Net Zero Institute provides a platform for this essential collaboration.

Dr Danielle Kent's work at the University of Sydney's Business School exemplifies what is possible. Her research focuses on behavioural insights. Australia has the potential to become a global leader in supplying critical minerals and materials essential for renewable energy technologies. However, seizing this opportunity requires more than just resource availability. It requires strategic cooperation and a forward-looking mindset. Behavioural insights, especially the principle of reciprocity, can play a crucial role in promoting collaboration among international stakeholders, driving innovation, and enhancing Australia's ability to meet global demand. The case study shows more.

The social, legal and financial solutions must be developed concurrently with the technical solutions.

Case study: How behavioural insights can boost Australia's critical minerals and materials leadership

by Dr Danielle Kent, A/Prof Shumi Akhtar and A/Prof Joakim Westerholm

All-electric cars in Norway.

Cooperation is fundamental to our survival. Insights from behavioural finance and economics show us that they key to achieving cooperation is reciprocity. Reciprocity involves the exchange of benefits for benefits, and sanctions for non-cooperation. By engaging in reciprocal agreements, Australia can encourage sustained collaboration, ensuring that all parties benefit from the shared investment in critical minerals. For instance, partnerships with countries like China, the world's largest consumer of critical minerals, can be structured to offer Australia stable export markets in exchange for technological or financial investments in downstream production capacity.

This mutual exchange can align incentives, create long-term partnerships, and reduce the risks associated with volatile market conditions. Reciprocity also extends to domestic collaborations, where mining companies, governments, and local communities can work together to ensure that the benefits of mineral production are equitably shared.

A forward-looking mindset is important in the context of critical minerals and materials because of the very long-time horizons between investment and production. By anticipating future trends and focusing on long-term value creation rather than short-term gains, Australia can build its capacity for higher value downstream manufacturing of critical minerals and materials. This involves incentivising investing in long-term sustainable mining practices, innovative processing technologies, and robust supply chains that can meet future demands for critical minerals. A forward-looking approach also includes preparing for the next phases of the green economy, such as the recycling of critical materials and the development of secondary markets. By planning for these future needs, Australia can ensure that its leadership in critical minerals is not only maintained but expanded over time.

An example of how reciprocity and a forward-looking mindset have successfully created new markets and expanded production capacity is Norway's partnership with global automotive manufacturers in the electric vehicle market, which helped Norway become a global leader in EV adoption and established a robust market for clean energy technologies. Another example is the way that Chile secured foreign investments in its lithium extraction technology and infrastructure by providing stable and reliable access to its lithium reserves.

By applying similar strategies, Australia can harness behavioural insights to enhance cooperation, drive innovation, and secure its place as a critical player in the global transition to net-zero emissions.

Through reciprocity and a forward-looking mindset, Australia can build the partnerships and infrastructure necessary to lead in the production of critical minerals and materials.

Australia's unique position is defined by its critical mineral resources as well as its economic and political environment. To fully benefit from these resources, it is crucial to identify the barriers to development. These barriers include shortages of skilled workers, obtaining social licence and genuine engagement with First Nations communities, and conflicting environmental goals. Recognising these constraints requires collaboration between experts who understand the economic and political environment and those who can devise strategies to develop the workforce and involve stakeholders, including governments.

New technologies are being developed to make the value chain more effective, and new approaches are being applied to building communities. Both of these developments are necessary to achieve net zero targets. It is essential that STEM researchers – who focus on creating new zero-emissions technologies – collaborate with social scientists who are developing new approaches to community engagement. Together, they must identify potential roadblocks so that a net zero future can be built in time to avoid dangerous climate change.

We see roadblocks as well as opportunities in the legal space, and Net Zero Institute researchers at the Sydney Law School can explore these issues. For example, work is being done by A/Prof Jeanne Huang and Prof Luke Nottage from the Sydney Law School, along with Prof Hans Hendrischke from the University of Sydney's Business School. They are examining the role of Digital Product Passports for the cross-border supply chain of critical raw materials from a legal and industry perspective.

New technologies are being developed to make the value chain more effective, and new approaches are being applied to building communities.

We see that transitioning to a net zero world by 2050 demands close collaboration between STEM researchers and social scientists across finance, policy, law and community engagement. The Net Zero Institute has assembled just such a team of collaborators and is well-positioned to develop the new systems to deliver a sustainable supply of materials for the clean energy transition.

Case study: Addressing conflicts of laws and facilitating Digital Product Passports in cross-border supply chains

by A/Prof Jeanne Huang, Prof Luke Nottage, and Prof Hans Hendrischke

The Digital Product Passport (DPP) is a structured digital repository of product-specific information, designed to provide crucial information about a product and its production, consumption, and circularity. The objectives of the DPP include promoting sustainable production practices, aiding authorities in verifying regulatory compliance, assisting consumers and investors in making informed and sustainable choices, and facilitating the transition to a circular economy.

The DPP has become a crucial traceability reporting tool in the critical raw materials industry to document provenance and demonstrate ESG compliance. However, the implementation of DPPs needs to address serious conflict-of-law issues in different countries involved in the critical raw materials supply chains.

Our project intends to present the status quo of conflict of laws in existing national and international laws and propose solutions for legal coordination in trade facilitation and e-commerce. This includes addressing diverse national requirements for cross-border data transfer, mutual recognition of ESG certificates, interoperability between different DPPs, and incorporating industry standards/good practices into international and national trade laws for the adoption of DPPs.

The case study aims to support the UN focus on extractive industries and deliver digital standards for sustainable supply chains. It will provide pathways to scale from critical raw materials to other products and enhance the adaptation of DPPs across different industries in both developed and developing countries.

The Núi Pháo tungsten mine in Thái Nguyên Province, northern Vietnam (credit: N. A. Tuan and N. T. A. Tuyet).

Case study: Applying new, green technology and focusing on science and technology development in Vietnam's mining industry

by Nguyen Thi Anh Tuyet, Hanoi University of Science and Technology

Vietnam currently ranks 15th in the world in terms of mineral area, 65th in terms of geological age, and has reserves of 60 of the world's 200 most common minerals. Vietnam is also the third largest mineral producer in ASEAN region, with significant reserves of coal, bauxite, titanium, iron ore and rare earth metals. The mining industry is the third largest contributor to Vietnam's GDP. However, this contribution is mainly from 200 coal mines with a total reserve of about eight billion tonnes.

In addition, the exploitation of mineral resources still has many shortcomings, including the loss and waste of resources. In addition, the processing of minerals in Vietnam mostly stops at the level of refined ore products, the value and efficiency of use is low, and is not commensurate with the value of its mineral resources.

Up to now, deep processing to the final product (metals) is only done for minerals such as zinc, copper, iron, and antimony. There are still high-level losses of resources during the exploitation process, especially in underground mines and locally managed mines. Due to the low level of mechanisation, most small mines today only take the richest reserves, discarding all the poor ores and accompanying minerals, leading to a waste of resources and causing environmental pollution, at the same time. This reality affects the health of surrounding people and causes difficulties in land reclamation.

Vietnam needs to acknowledge the shortcomings in mining activities to find solutions together, propose policy mechanisms in governance, and combine scientific research results to contribute to the sustainable development of the country's mining industry in the context of Industry 4.0.

Strengthen global partnerships

Human-induced climate change is a global problem caused by the actions of all nations and must be solved by nations working together. The value chains for critical materials span nations and making the value chains more effective is a multi-national challenge.

A research team led by Prof Susan Park in the Faculty of Arts and Social Sciences is investigating governance institutions and initiatives at a transnational level to address the socio-ecological impacts of mining critical minerals for the energy transition. Although renewable energy plays a crucial role in achieving net zero emissions, there is insufficient regulation and understanding of the socio-ecological effects of solar photovoltaics panels and lithium batteries on human health. These impacts occur across the entire life cycle of the technologies.

States are expected to regulate the extraction and refining of minerals and metals, as well as the industrial activity involved in producing technology – determining its placement and use, and managing its disposal. However, many states cannot effectively regulate multinational corporate activity. With the urgent global shift to renewable energy due to the climate crisis and the fact that solar panels and lithium-ion batteries are produced in global supply chains, it's important to examine the international and transnational governance in place to minimise their socio-ecological impacts. Researchers from Australia, Canada, Chile, and the UK are all involved in this research.

The work of A/Prof Jeanne Huang and Prof Luke Nottage from the Sydney Law School, and Prof Hans Hendrischke from the University of Sydney's Business School looking at the role of Digital Product Passports for cross-border supply chain of critical raw materials from a legal and industry perspective is another example of cross-jurisdictional study.

The Net Zero Institute has developed strong links with several regional universities, which allow it to examine these questions. Two case studies are outlined below.

Case study: Exploring Policy Strategies for Development of Critical Materials in Indonesia

by Widodo Wahyu Purwanto and Nadhilah Reyseliani, Universitas Indonesia

Indonesia faces a significant increase in demand for key minerals, particularly nickel, to support cleaner energy technologies and electric vehicle (EV) production. While the country has abundant nickel reserves, class 1 nickel production necessary for battery manufacturing remains a challenge. The government has introduced incentives since 2013 to foster an EV ecosystem, aiming for a comprehensive supply chain by 2030.

However, challenges include the need for sustainable mining practices, advanced refining technologies, and strategic partnerships with other countries. Addressing these issues is essential for Indonesia to enhance its economic growth and secure its position in the global EV market.

To address these issues, the Sustainable Energy Systems and Policy (SESP) and Advanced Material Research Centres (AMRC) within the Net Zero Initiative at Universitas Indonesia, in partnership with the Indonesian Ministry of Energy and Mineral Resources and Ministry of Industry, are examining key challenges and policy gaps in critical materials development for the EV market.

The project aims to develop a policy strategy that balances the objectives of value adding to critical materials, with the need to accelerate the clean energy transition. Central to the work is ensuring a just energy transition for local communities and local governments. The project is also examining strategic alliances with exporting countries such as Australia and Philippines that are vital to create strong regional supply chains for the EV ecosystem.

Making critical materials *less critical*

In 2017, Mining Technology, an industry news site, published an interesting interview with Dr Lawrence Meinert, the deputy associate director for energy and minerals at the US Geological Survey.[40] Dr Meinert explained how the USGS had estimated global zinc reserves at 77 million tonnes in 1950. Yet in 2000, the US Government announced reserves of up to 209 million tonnes: the value chain of zinc was strengthened from 1950 to 2017.

In the same interview, Dr Meinert discussed cryolite, a mineral used in the production of aluminium. The sole source of cryolite had been a mine in the remote mining town of Ivigtut on the west coast of Greenland. In 1987, the mine ran out of minable ore. However, aluminium production continued, as cryolite's use as a flux in the production of the metal had been replaced by synthetic sodium aluminium fluoride produced from the common mineral fluorite. Hence, material substitution had solved the problem of the loss of cryolite. We discuss material substitution in a later section.

The Energy Transitions Commission (ETC) is a global coalition of energy industry leaders dedicated to achieving net-zero emissions by mid-century. The ETC recently reviewed the material and resource requirements for the energy transition and arrived at some interesting conclusions.[41] They found that there are enough raw materials, land area, and water resources to support the energy transition in the long term. In cases where current assessed 'reserves' fall short of potential cumulative demand, such as copper and nickel, reserve expansion is possible. However, it's critical for mining expansion to be sustainable and responsible. The ETC report includes supply-demand forecasts for critical minerals up to 2030 and 2050.

We use lithium to highlight certain features. These features are also seen in the other critical minerals assessed by the ETC. The ETC forecasts a shortfall in the demand for lithium in 2030, and the magnitude of the shortfall depends on the development of better EV batteries (Figure 7). Figure 8 shows the case to 2050. The importance of recycling, efficiency improvements and material substitution (such as sodium-ion batteries) in reducing primary demand is clear.

Without these enhancements, the cumulative demand to 2050 of 21 million tonnes approaches the available reserves of 26 million tonnes. Lithium resources are 80 million tonnes and can meet the demand for several decades after 2050. But there are two issues. Firstly, mineral resources – as opposed to mineral reserves – are more complex and more costly to extract[42]. Secondly, the true net zero goal isn't just to reach net zero by 2050 but to also maintain it every year after that. Products such as EVs, wind turbines, and solar panels have a limited life, and in the absence of recycling, the primary demand will continue to grow, eventually exhausting the resources.

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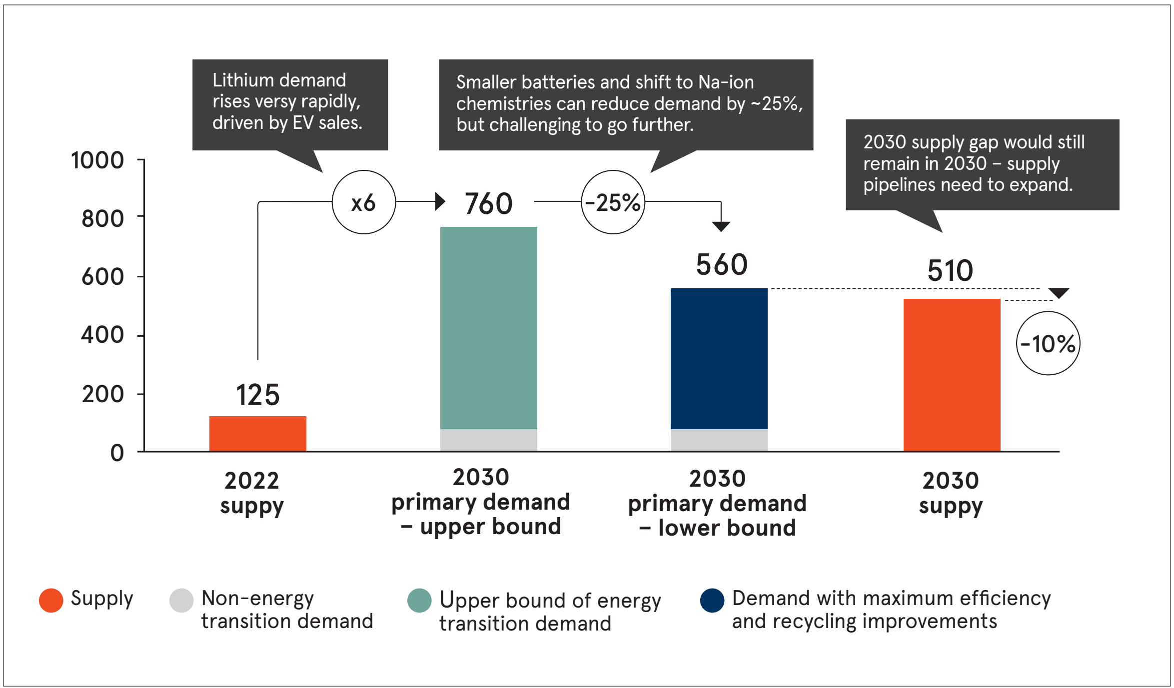


Figure 7: Demand and primary supply of lithium in 2030 (thousand metric tonnes) Source: ETC40.

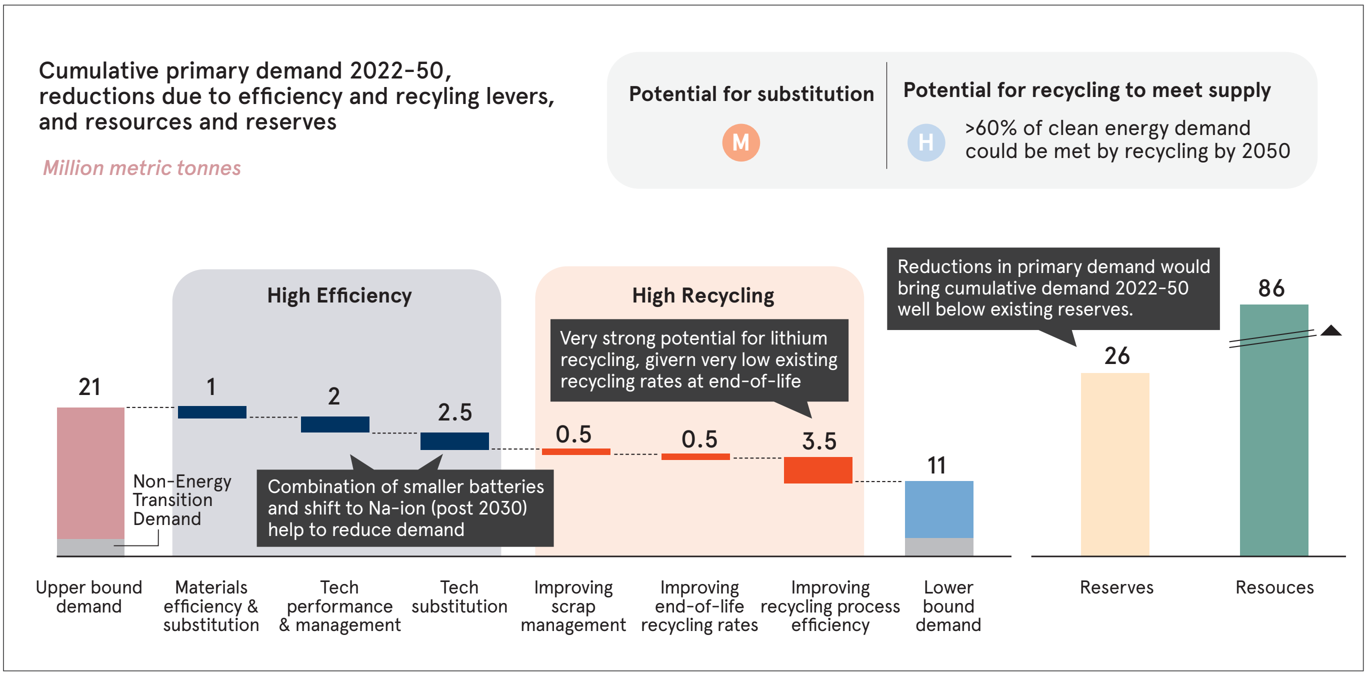


Figure 8: Cumulative primary demand and supply of lithium from 2022 to 2050 Source: ETC38.

The IEA reached similar conclusions.[44] It forecasts that in 2035, there will be a big difference between the amount of copper and lithium needed and the amount available. Nickel and cobalt supplies could be tight, but new extraction projects might help. While there might not be a problem with the amount of graphite and rare earth elements available, there's a concern about too much reliance on China.

The work described above reinforces earlier observations. First, recycling critical materials is essential if the current generation's consumption of critical materials is to meet the definition of sustainability.[45] The projections of critical mineral resource consumption show how the cumulative consumption of some materials will exceed available reserves by 2050. Adequate critical mineral resources are available, but the challenges of accessing these resources are not known. Second, the ETC's forecasts included performance improvements and substitution in the suite of opportunities to reduce the primary demand for critical materials.

Recycling to reduce the demand for resources

Opportunities to increase the recycling of critical materials fall into two broad categories. *Advanced recycling technologies* are new methods for efficiently separating and recovering critical materials. Innovations like waterless extraction, bioleaching, and electrochemical processes show promise. *Design for recycling*, which requires product manufacturers to design products with recycling in mind, can help make the recovery of critical materials more straightforward and cost-effective. Examples of each follow.

The difficulties in recycling products containing critical materials can be seen in the treatment of end-of-life lithium-ion batteries. These batteries are an excellent example to consider because the future dominant source of end-of-life lithium-ion batteries will be EVs, and the high recycling rates of lead-acid car batteries suggest that most end-of-life lithium-ion batteries will be collected for recycling.

The challenges come when considering the processes required to recycle the critical material in lithium-ion batteries. Milian et al.[46] explored this. They highlighted two issues. First, the current approaches to recycling lithium-ion batteries have problems: cost, complexity, emissions, and low efficiency. Second, the need to disassemble the batteries in order to recycle critical materials effectively increases the cost and complexity of recycling. This latter observation points to the need to better design products for recycling.

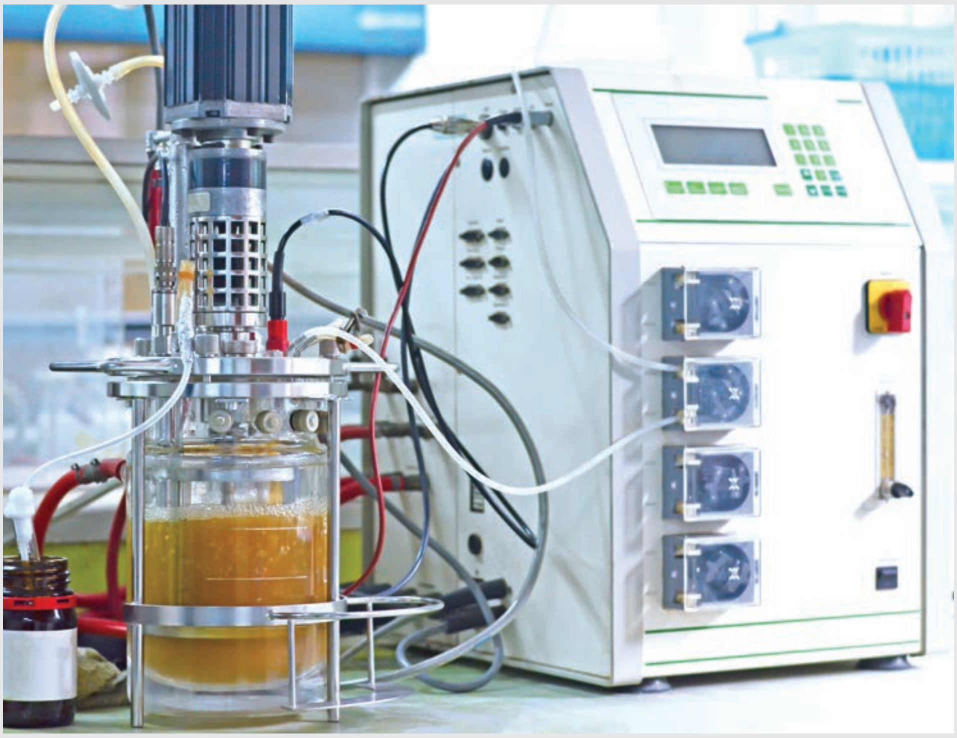
The lithium-ion example highlights the need for new approaches to the recovery of critical materials from the disassembled end-of-life product. Approaches being examined for lithium-ion batteries include new approaches to leaching (eg. salt leaching or microwave or ultrasound assisted leaching), as well as improved direct recycling by upgrading the degraded components such as the cathodes.

Biological recycling is also under consideration. Auerbach et al.[47] described the bioleaching of rare earth metals from end-of-life magnets using various bacteria. Extraction rates of the rare earth metals up to 100% with a purity of 98% were achieved.

Prof Marjorie Valix, a Net Zero Institute researcher, also explores bioleaching to extract critical materials. The case study describes one aspect of this work, along with tackling the significant issue of waste from critical mineral mining. The ongoing buildup of mine tailings presents significant safety, environmental and safety risks, which are likely to intensity with the growing demand for critical minerals during the energy transition, posing further environmental, social, and governance challenges for the mining industry. Although significant efforts have been exerted to mitigate harm through better storage management practices, adopting circular approaches that eliminate the need for tailings storage offers a pathway for achieving a longer-term solution.

Case study: Recycling e-waste and generating secondary materials for construction based on ecologically sound methods

by Prof Marjorie Valix



Bioacid production in laboratory fermentor.

The transition to low carbon energy and reduction of carbon emissions in construction are keys to curving CO_2 accumulation to mitigate climate change. This project aims to support addressing these two key challenges by developing low-carbon cement and metallic products by recycling e-waste components using eco-friendly methods. This study is exploring an integrated material recovery system aimed at achieving zero waste through comprehensive recovery of all wastes components. To this end, this project focuses on three key aspects:

- Utilisation of bioleaching and electrodialysis to recover critical metals from waste streams essential for producing low-carbon energy technologies, such as batteries
- Repurposing waste glass and plastics as binders and aggregates in a broader initiative to reduce and replace concrete components with materials derived from waste streams
- Explore through case studies the implementation of low-carbon cement combined with repurposed wastes in construction of assets, including pipes, roads and mine backfill.

This initiative is uniting mining, recycling, concrete, pipe manufacturing, water, and roads & transportation sectors to advocate and support for circular solutions. By fostering partnerships and knowledge sharing we are tacking the pressing issues of waste, such as e-waste and mine tailings, accumulation through a holistic circular business model. This approach not only promises significant economic benefits but also strengthens mineral security vital for the energy transition.

Shredded e-waste.

We noted above how difficulties in disassembling end-of-life products complicate the recycling of critical materials found in the products. This point was taken up by Babbitt et al. They looked at the role of design in circular economy solutions for critical materials.[48] They explained how products containing critical materials are rarely designed to be upgraded, reused, or disassembled at the end of life to access the valuable materials.

A good example is in Figure 9, which shows where certain critical materials are used in a smartphone and how the design of the phone makes it difficult to access and recycle the critical materials.

To establish a circular economy for critical materials, we need innovation at every stage of a product's lifecycle, from the molecular level to the construction of the built environment. This involves disassembly and reuse at a molecular level, early-stage technology design, and loop-closing chemical recycling. Reuse and remanufacturing can occur at a product or component level, and all phases of a product's life cycle require interaction with urban and industrial infrastructure and communities. Achieving a circular economy requires the integration of different fields of study and knowledge and the ability to quickly implement solutions that promote circularity in both materials and societies. The Net Zero Institute is positioned to facilitate the necessary integration of disciplines and knowledge.

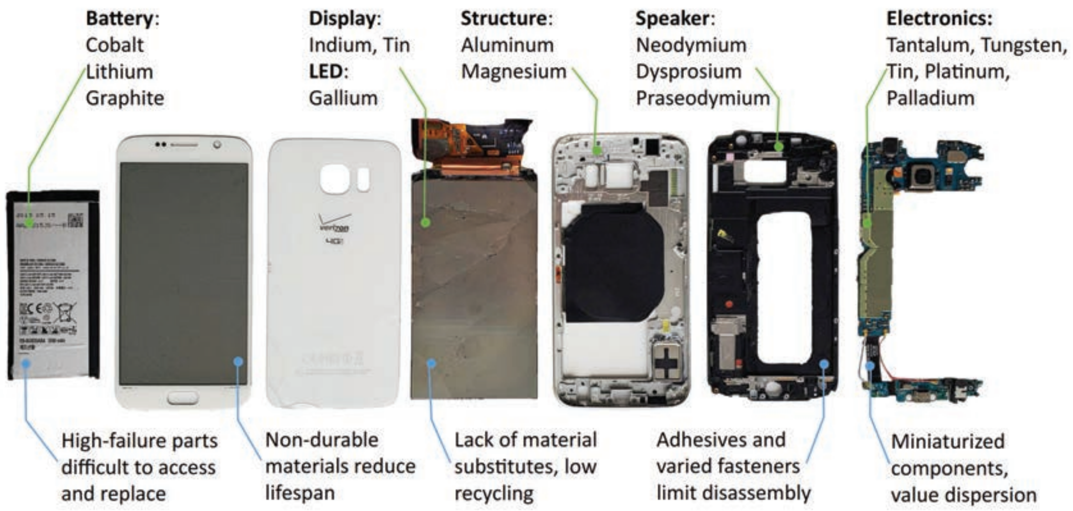


Figure 9: Critical material used in a smartphone and the design challenges that limit circular economy strategies. Source Babbitt et al.[42]

Material substitution to reduce the demand for resources

"The Stone Age didn't end because we ran out of stones, and the age of oil won't end because we run out of oil."

The quotation is attributed to Saudi Arabia's former Minister of Petroleum and Mineral Resources – and it could equally apply to the age of critical materials, if material substitution reduces the demand for critical materials.

An interesting case study is the emergence of sodium-ion batteries as a substitute for lithium-ion batteries. CATL, the largest battery manufacturer in the world, has recently begun commercial production of sodium-ion batteries. Sodium-ion batteries fall short of lithium-ion batteries in energy density, a critical requirement for EVs. However, sodium-ion batteries have many significant advantages over lithium-ion. They are safer, use fewer critical materials (lithium and copper), have longer lifespans, can be charged more rapidly and have much better low-temperature performance. While lithium-ion batteries may remain preferred for high-end EVs and portable electronic applications, sodium-ion batteries may replace lithium-ion batteries in many other applications where energy density is not a critical requirement.

Other examples of material substitution are the development of perovskite solar cells and strong magnets that either don't use rare earth metals or require lower concentrations.

The Solar Research Group at the University of Sydney, led by Prof Anita Ho-Baillie, is exploring new types of solar cells that offer higher performance and lower use of critical materials. They are working to incorporate metal halide perovskites into multi-junction solar cells and resolve the key instability problem with perovskite cells by preventing them from degrading during field operation. The objective is to develop durable, commercially viable perovskite cells. Net Zero Institute researchers are also exploring how additive manufacturing can produce strong, permanent magnets that require lower concentrations of rare earth metals.

Case study: An additive manufacturing solution for rare earth permanent magnets

by Prof Simon Ringer and Dr Hansheng Chen

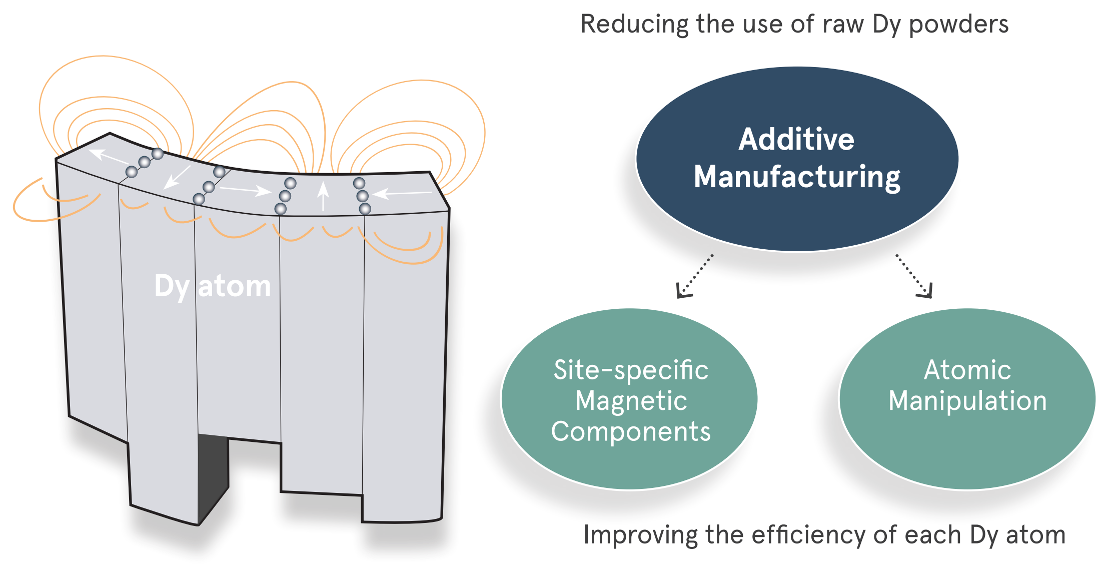
Metal additive manufacturing offers a significant opportunity to create high-performance Nd-Dy-Fe-B (neodymium, dysprosium, iron and boron) permanent magnets. The project aims to reduce the amount of dysprosium in Nd-Dy-Fe-B magnets using additive manufacturing, while maintaining magnetic performance. This method also enables the production of complex shapes while preserving essential magnetic properties.

Nd-Dy-Fe-B permanent magnets are essential for the global transition to renewable energy and zero carbon emissions, particularly in applications like hybrid electric vehicles and wind turbines. In 2023, the market for these magnets is valued at approximately A$3 billion, with a compound annual growth rate of 7.9%.

These permanent magnets heavily rely on expensive heavy rare earth elements such as dysprosium, which is identified by the United Nations as one of the most critical and endangered elements, with an anticipated shortage of 1,500 tonnes by 2025 – a situation that is rapidly worsening. The development of additively manufactured Nd-Dy-Fe-B magnets, which allows for more versatile shape design, addresses a crucial market demand for high-power-density and cost-effective hybrid electric traction motors.

Nd-Dy-Fe-B (neodymium, dysprosium, iron, boron) permanent magnets are essential for the global transition to net zero ... particularly in applications like hybrid electric vehicles and wind turbines.

Figure 10: A Materials Science Solution



The response of *the Net Zero Institute*

The transition to a zero net emissions future is reliant on technologies that require significantly more mineral resources than previously used. Ensuring a reliable supply of critical materials is therefore essential for achieving the transition to a more sustainable future, safeguarding energy security and addressing national security concerns, as well as the needs of future generations.

In addition to focusing on the supply chain and technological advancements, our collective research in Critical Minerals and Materials across the University of Sydney recognises that simply increasing production is insufficient. Instead, a holistic view of sustainability must consider the potential exhaustion of non-renewable resources.

Across the University of Sydney, and as part of the Net Zero Institute, our researchers are exploring not only the extraction and processing of these minerals, but also innovative recycling technologies and material substitutions that can mitigate our reliance on primary mineral resources.

This comprehensive and holistic approach addresses the technological, environmental, and social challenges associated with critical minerals. The Net Zero Institute provides a platform for the essential collaborative efforts across disciplines to drive innovation and create resilient systems that support long-term environmental, economic and social goals.

The Net Zero Institute's work is highly relevant in the context of Australia's commitments to achieving net zero emissions by 2050, as outlined in the Climate Change Authority's Sector Pathways Review released in early September 2024,[49] and Australia's National Science and Research Priorities issued in August 2024.[50]

Just as crucial as multidisciplinary collaborations, are the partnerships with existing centres at the University, including the Sydney Policy Lab and Sydney Environment Institute, with which we are actively engaged in discussions on protecting and restoring Australia's environment (Priority area 4 in the National Science and Research Priorities) in concert with transitioning to a net zero future (Priority area 1). We are also working to incorporate the perspectives of Aboriginal and Torres Strait Islander peoples, acknowledging their profound connections to land and sea. By integrating

First Nations voices throughout the project lifecycle, we can respect cultural significance and community impacts, leading to equitable outcomes and enhanced collaboration.

Finally, we recognise the crucial importance of international partnerships in critical minerals to diversify supply chains and ensure energy and national security. In recent years, Australia has entered into various agreements with countries such as the United States, Japan, and South Korea, focusing on technology sharing, research collaboration, and investment in critical mineral projects. These partnerships not only facilitate the exchange of knowledge and technology, but also help mitigate risks associated with supply chain disruptions.

The Net Zero Institute, through its international industry and scientific advisory boards – who have both generously contributed to this paper – aims to deepen its partnerships through programs that support researcher exchanges, knowledge sharing and capability building.

All these initiatives will enable the Net Zero Institute to fulfil its mission to accelerate the transition to net zero emissions responsibly.

Figure 11: Closing the loop on the critical minerals value chain

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