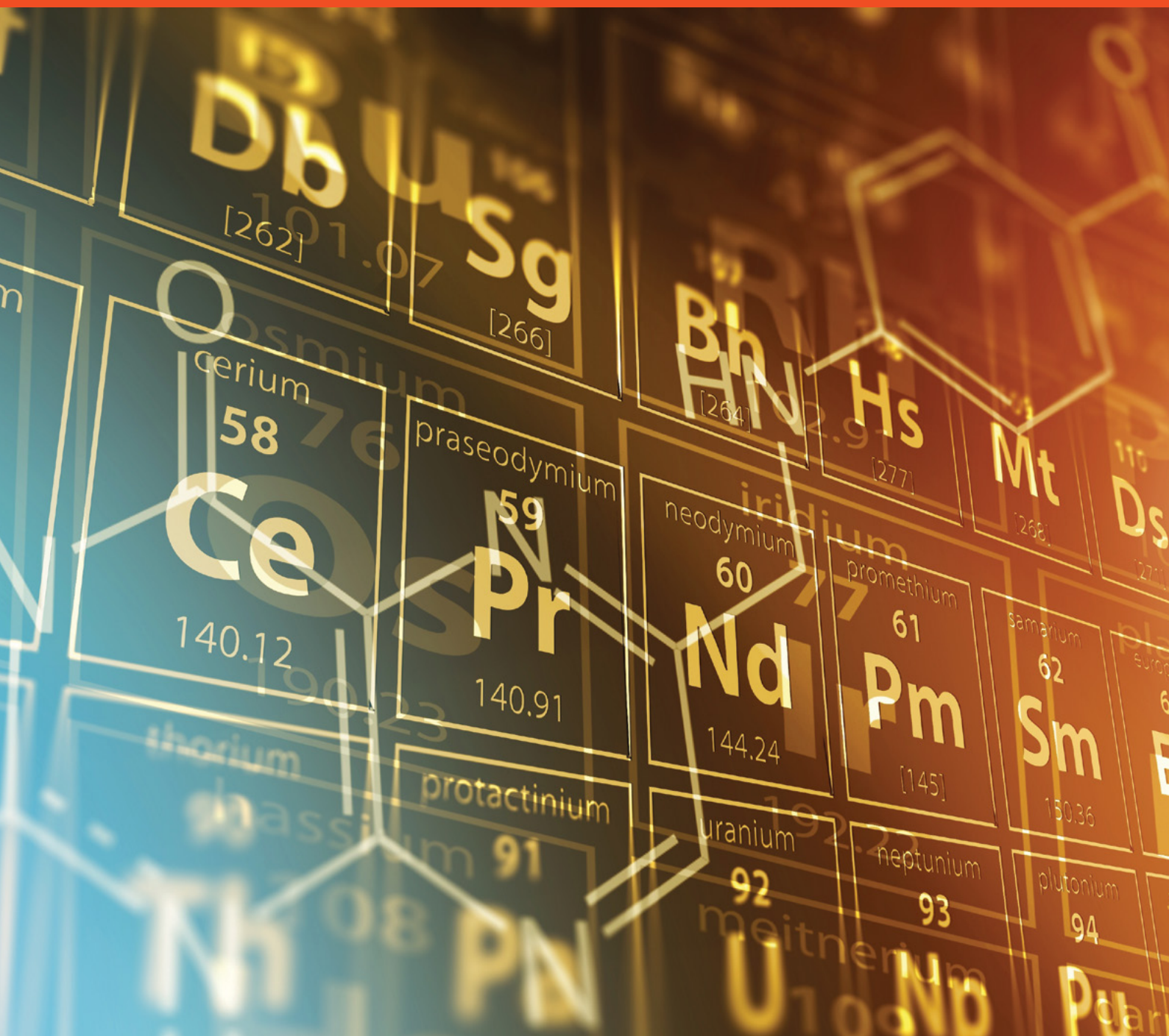


Critical Minerals and Materials



*The sustainable supply of materials
for the clean energy transition.*



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

The Net Zero Institute (NZI) was launched at the University of Sydney in mid-2024, and this publication focuses on one of its key pillars: Critical Minerals and Materials. In 2024, the NZI published its first white paper on critical minerals and materials. That paper drew on contributions and case studies from more than 40 researchers across the University and from the Net Zero Institute's Industry and Scientific Advisory Boards, who collectively shared their expertise through workshops and associated working groups.

This document provides a capability update to the 2024 white paper, with contributions from a cross-campus network of researchers, including members of the Sydney Environment Institute (SEI) and the Faculty of Arts and Social Sciences. It reports on recent work by these researchers across the University of Sydney aimed at better understanding the supply of critical minerals, reducing the adverse impacts of extracting critical materials, making supply chains more sustainable and finding substitutes for critical materials.

The transition to a net zero future depends on technologies that require significantly more mineral resources than those traditionally used. Ensuring a reliable supply of critical materials is essential to the transition, to energy security and to national security. It is also essential to meeting the needs of a growing human population while maintaining the resilience of planetary ecosystems for future generations.

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

About the Net Zero Institute

The University of Sydney launched the Net Zero Institute, previously the Net Zero Initiative, in mid-2024. The Institute brings together more than 180 researchers from across the University of Sydney, working with industry, government and community partners to co-design solutions across disciplines. The Institute aims to accelerate practical decarbonisation solutions to help the world meet its goal of net zero emissions by 2050.



Contributors

The Net Zero Institute team gratefully acknowledges the following contributors to the critical minerals pillar roadmapping process and to this capability update. We also thank generous collaborators from the Sydney Environment Institute and the Faculty of Arts and Social Sciences who have shared insights and expertise as part of a cross-campus critical minerals network.

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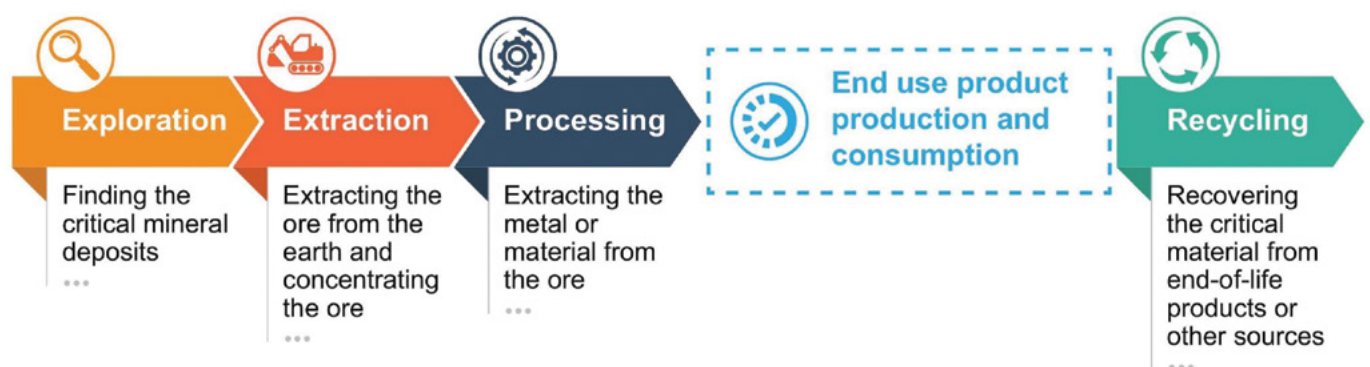
A Systems View: From Critical Minerals to Circular Materials

The critical materials story is no longer only about what can be mined, but about how material systems are built, connected and reshaped for a net zero economy.

This publication examines critical minerals and materials through a systems lens. It brings together research that spans geology, engineering, chemistry, sustainability, business, law and policy.

For Australia, the opportunity is not simply to supply more raw materials. It is to build capability across the system – from exploration and processing to circularity, traceability, substitution and more resilient supply chains. That broader framing underpins the case studies and insights that follow.

Critical minerals: *linear value chain*



Critical materials move through a chain of decisions that shape where value, risk and capability sit.

Closing the loop: *The critical minerals circular value chain*

The figure below, developed for the Net Zero Institute’s 2024 white paper on Critical Minerals and Materials, shows that closing the loop on the critical minerals value chain requires more than technical solutions. Alongside recycling and material recovery across exploration, extraction and processing, it highlights the essential

roles of policy, governance, community engagement, international partnerships, and financial and legal frameworks. Together, these multidisciplinary elements support a more circular and resilient system that retains value, manages social and environmental risks, and strengthens long-term critical material security.



A circular framing highlights why recovery, reuse and system design matter alongside supply.

Introduction

Critical materials have become a defining issue for energy security, national security and industrial strategy as well as for the net zero transition.

Since the publication of the Net Zero Institute's 2024 white paper on critical minerals and materials,¹ the challenges surrounding critical mineral supply chains have intensified.

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".² Other national governments adopt similar definitions. The list of critical minerals is long. In 2022, the U.S. Geological Survey³ identified more than 50 elements as critical minerals – more than half of these being naturally occurring elements. Australia lists 32 critical minerals, although it groups the 17 rare earth elements and the six platinum-group elements into single categories.

Critical materials matter for several overlapping reasons:

- national security – critical minerals are used in advanced defence systems
- living standards – the technologies that underpin modern life rely on critical minerals
- energy supply – the clean energy transition will require these materials at scale

Five years ago, attention centred mainly on the role of critical minerals in the clean energy transition. The International Energy Agency noted that an electric vehicle requires six times as much mineral input as a conventional car, and an onshore wind farm requires nine times as much mineral input as a gas-fired power station. The shift to renewable generation has increased the average amount of minerals required for each new unit of power generation capacity by 50 per cent since 2010.⁴

The major wars in Ukraine and the Middle East have since sharpened the focus on national security as well as energy security. A February 2026 resources outlook argues that geopolitical conflict is increasing demand for military metals such as tungsten, tin and antimony, rather than only transition minerals. It also warns that parts of the rare earth sector may be entering a phase of speculative overinvestment, underscoring the need for closer analysis of real supply bottlenecks – especially in midstream processing.⁵

Over 2025–2026, the critical minerals sector evolved from what was largely an industrial supply-chain issue into a cornerstone of national security, foreign policy and global economic strategy. Australia is positioning itself as a trusted, democratic and lower-risk supplier in a world where critical minerals are becoming a geopolitical battleground. The National Critical Minerals Strategy⁶ focuses on expanding mining and exploration, building domestic refining and processing capability, supporting downstream industries such as batteries and magnets, and partnering with allies to create more secure supply chains.

China remains the world's leading processor of rare earths, holding 60 per cent of global production and 90 per cent of refining capacity. Countries are increasingly concerned that Beijing is using that dominance for political and economic influence, especially ahead of key trade negotiations in late 2026.⁷

That concentration has prompted responses from other nations. At the February 2026 Critical Minerals Ministerial, the United States convened representatives from 54 countries and the European Commission to coordinate



efforts to diversify and secure supply chains for critical minerals and rare earths. Analysts have described this as part of a broader scramble to secure essential minerals in a more fractured global economy.⁸

The Ministerial produced new bilateral frameworks and memoranda of understanding with 11 countries, alongside U.S. financing announcements for strategic mining projects and the launch of FORGE – the Forum on Resource Geostrategic Engagement.⁹ In parallel, the United States, European Union and Japan moved to promote joint investment in mining, refining, processing and recycling, as well as coordinated market interventions such as price floors, standards-based markets and offtake agreements.¹⁰

The Quad Critical Minerals Initiative¹¹ addresses several of the same issues. It is focused on reducing reliance on China's dominance in critical minerals through programs that improve e-waste recovery and reprocessing, build regional refining and processing capacity, and support coordinated research, technology sharing and skills development.

The actions now being pursued to strengthen critical material supply fall into four broad categories:

- finding more critical mineral resources
- developing better ways to extract critical materials from ore and waste streams
- reducing demand by increasing recycling or finding substitutes
- ensuring that critical material supply chains are sustainable

The purpose of this document is to update the picture of capability within the University of Sydney since the first publication in 2024, and to show how research and focus have responded to current climate, geopolitical and supply-chain pressures.

An Update on our Research

Understanding critical material resources

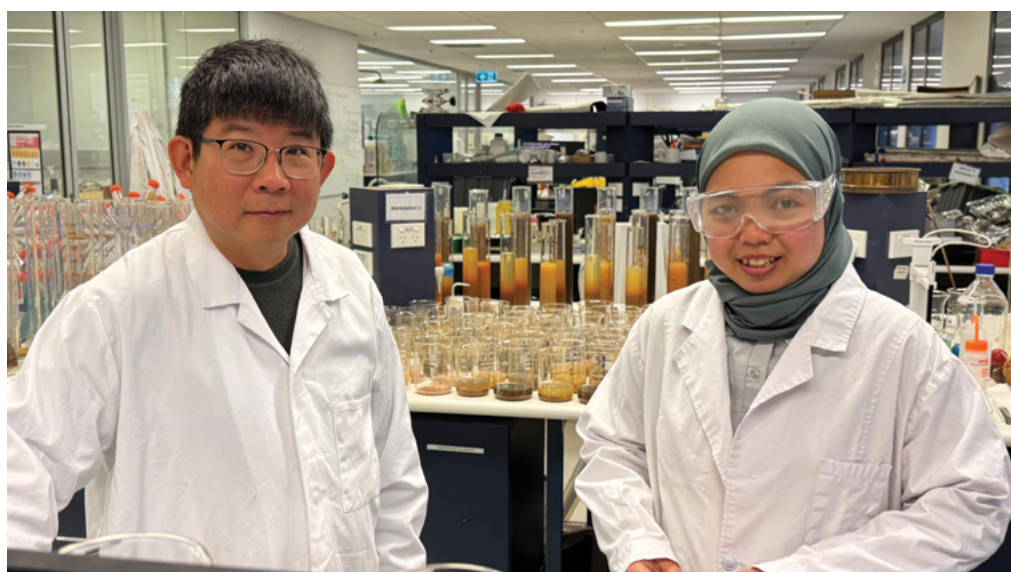
Research in this area spans AI-enabled exploration, digital soil mapping and critical scrutiny of where and how new mineral resources should be pursued.

Since the publication of the 2024 white paper on critical minerals and materials, the world has seen a dramatic increase in the capability and application of AI systems. Researchers in the University of Sydney's EarthByte Research Group are applying AI tools to better understand the evolution of geological structures that may contain mineral and petroleum resources. A good example is Project STELLAR (Spatio Temporal exPLoRAtion for Resources), a collaboration between BHP and the EarthByte Group that is implementing large-scale spatio-temporal data analysis and modelling to support BHP's global exploration needs.

As shown in the case studies below, the EarthByte Research Group is applying AI to diverse geological datasets to identify regions where critical mineral reserves are likely to be found. Through a deep understanding of Earth's geological and climatic history, researchers can effectively see beneath the surface crust to highlight regions where geological history points to the formation of critical mineral resources.

While the EarthByte Group uses advanced data science to look across time and space, the team led by Professor Alex McBratney and Professor Budiman Minasny is searching for critical minerals closer to the surface. Their digital soil-mapping work has strengthened Australia's understanding of vanadium resources and shows how new pre-competitive soil data can identify areas where undiscovered ore bodies may exist.

Not all research in this area is about finding more resources. Some researchers are asking whether resources should be exploited at all. Professor Susan Park from the School of Social and Political Sciences and her co-workers examined the case for deep-sea mining and found that the minerals targeted by prospective deep-sea miners are not especially scarce. Scarcity, they argue, is therefore not a sufficient justification for opening up the deep ocean to mining.



Professor Budiman Minasny (left) worked on the project with Marliana Widyastuti. Image: Stefanie Zingsheim / University of Sydney.

Case Study

AI-driven discovery of rare earth element systems in the Flinders Ranges

Professor Dietmar Müller and Dr Ehsan Farahbakhsh, EarthByte Research Group

Discovering new deposits of critical minerals is becoming increasingly difficult, as many of the most accessible resources have already been identified. In regions where mineralisation is concealed beneath weathered cover or structurally complex terranes, conventional exploration methods alone are often insufficient. This challenge is particularly relevant for rare earth elements, which are essential for technologies including electric vehicles, renewable energy systems and advanced electronics.

Researchers from the EarthByte Group at the University of Sydney, working with the Geological Survey of South Australia, are developing new artificial-intelligence approaches to mineral exploration. Their work integrates diverse geological datasets with advanced machine learning to identify regions with high mineral prospectivity.

One example is the DEEP-SEAM framework, an explainable semi-supervised deep-learning system designed to predict rare earth element prospectivity using integrated geological, geophysical, geochemical and remote-sensing datasets. The method addresses a common challenge in mineral exploration: there are often too few known deposits to train predictive models in conventional ways. Rather than relying on large labelled datasets, DEEP-SEAM learns from a small number of known mineral occurrences together with extensive unlabelled geoscientific data.

The approach has been applied to the Mount Painter and Mount Babbage inliers in the north-eastern Flinders Ranges of South Australia, an area known for complex mineral systems containing uranium, copper and rare earth elements. These Mesoproterozoic inliers host rare earth element-bearing mineralisation associated with felsic intrusions, hydrothermal alteration and structurally controlled breccia systems.

The machine-learning models integrate multiple geoscientific datasets, including geological mapping and stratigraphy, aeromagnetic and gravity anomalies, radiometric signatures related to uranium-thorium enrichment, geochemical datasets, and satellite-derived alteration indicators. By analysing patterns across these datasets simultaneously, the model can identify

geological environments that resemble known rare earth element mineral systems. The resulting prospectivity maps highlight areas where exploration efforts are most likely to succeed.

Importantly, the framework also incorporates explainable AI methods, allowing researchers to identify which geological features contribute most strongly to predicted mineralisation zones. This transparency helps geologists validate model predictions and integrate them with existing mineral-system knowledge.

Field observations from the Mount Painter region illustrate the geological complexity of these systems. Rare earth element mineralisation commonly occurs in hydrothermal breccias, metasomatised granites and monazite-rich metamorphic rocks associated with major structural zones.

Luo, Z., Farahbakhsh, E., Hore, S., and Müller, R. D.: DEEP-SEAM: an explainable semi-supervised deep learning framework for mineral prospectivity mapping, Geosci. Model Dev., 19, 2593–2625, <https://doi.org/10.5194/gmd-19-2593-2026>, 2026.



Monazite-bearing schist exposure southwest of the Paralana Plateau in the Mount Painter Inlier, north-eastern Flinders Ranges. These metamorphic rocks host rare earth element mineralisation associated with hydrothermal alteration and structural pathways.

Case Study

The false promise of deep-sea mining

Professor Susan Park

In “The false promise of deep-sea mining”,¹² Susan Park and her co-authors argue that commercial mining of the international seabed is an unnecessary and risky venture built on false assumptions about mineral scarcity, social benefit and economic opportunity.

The paper first examines the mineral-scarcity argument often used to justify deep-sea mining. Proponents claim that critical minerals needed for renewable energy technologies, including solar panels and electric vehicles, are in short supply. The authors show that terrestrial reserves of key minerals are already abundant and widely distributed, and that technological shifts, new battery chemistries, recycling and more efficient material use may further reduce long-term demand pressures.

The article then addresses the claim that deep-sea mining will produce social benefits by avoiding the harmful social and human rights impacts associated with terrestrial mining. Proponents argue that seafloor mining prevents issues such as displacement, conflict and unsafe labour conditions, but this claim only holds if deep-sea mining replaces land-based mining – which it is unlikely to do.

The third major claim is that deep-sea mining will generate substantial economic benefits, particularly for developing countries. The authors point out that the industry has so far been characterised by speculative investment, opaque ownership structures and repeated failures. The paper concludes that deep-sea mining is a costly distraction from more effective strategies for climate mitigation, mineral recycling and circular economy development.

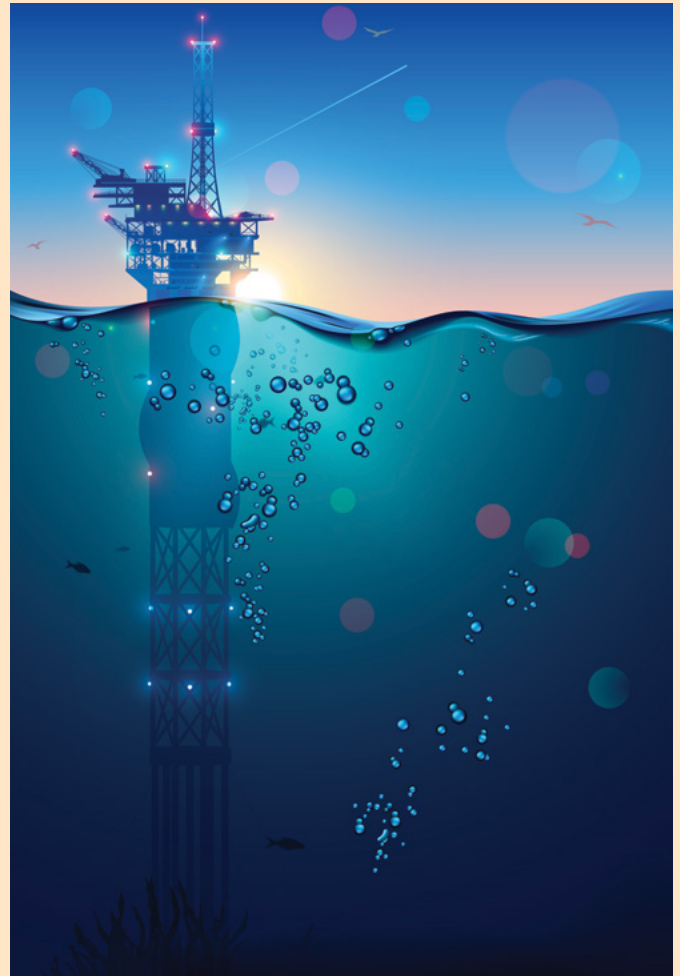


Table 1: Total World Production and Known Terrestrial Reserves of Critical Minerals

	Mine production 2024 (metric tons)	Known Terrestrial Reserves (metric tons)
Cobalt	290,000	11,000,000
Copper	23,000 (27,000)*	980,000
Manganese	20,000	1,700,000
Molybdenum	260,000	15,000,000
Nickel	3,700,000	>130,000,000

*This is refined copper production

Extracting and recycling critical materials

Exploring more sustainable ways to extract, recover and reuse critical materials – and the business, policy and circular systems needed to move them beyond pilot scale.

In many cases, the challenge with critical minerals is not the existence of the resource itself. The real difficulty lies in extracting the desired material or metal from the ore. Meeting growing demand therefore requires not only more extraction, but better extraction – with lower environmental costs. Conventional extraction is associated with habitat destruction, water pollution, soil degradation, greenhouse gas emissions and significant waste generation.

Many of these adverse effects can be reduced when critical materials are recovered from waste rather than newly mined ore. Recovery from waste streams is the focus of several University of Sydney researchers.

Professor Marjorie Valix from the School of Chemical and Biomolecular Engineering is researching ways to improve the effectiveness of bioleaching, in which microorganisms convert solid metals into soluble, extractable forms with comparatively low environmental impact. She is also investigating better ways to recycle copper. One recent study proposed an environmentally friendly approach that uses a deep eutectic solvent – choline chloride–ethylene glycol – as a green solvent for the selective extraction of copper from scrap printed circuit boards. With hydrogen peroxide as an oxidising agent, copper species were efficiently leached through oxidation-complexation reactions. A life cycle assessment found that this solvometallurgical recycling pathway could significantly reduce carbon dioxide emissions and lower the carbon footprint of global copper use.

Reducing the environmental impact of metal extraction is also central to research by Associate Professor Alejandro Montoya. His work aims to deliver an optimised prototype electrolysis platform for more efficient production of copper, nickel and zinc from e-waste feedstocks. The technology fully regenerates all chemicals, operates under atmospheric and mild chemical conditions, minimises

chemical consumption and avoids aggressive reagents. It offers a high-purity separation pathway in which base metals are recovered in solution for downstream refining and noble metals are physically concentrated for collection. The platform is supported by pilot-scale capabilities at the University of Sydney, allowing researchers to process a range of e-waste feedstocks, optimise operating conditions and validate product quality as scale-up progresses.

Rare earth elements present a particular challenge. Despite their name, they are not especially rare in the Earth's crust. The difficulty is separating individual metals from one another, because they share closely related chemical properties. Existing approaches to rare earth processing are highly energy intensive and have major environmental impacts. Researchers led by Dr Haihui Joy Jiang are developing a fundamentally new approach in which an electrified, low-carbon refinery platform with dynamically tuned, electrically controlled extraction replaces the static, harsh-chemistry methods used today.

Understanding impacts is just as important as improving process chemistry. Professor Arunima Malik and Professor Manfred Lenzen from the Integrated Sustainability Analysis team use multi-region input-output analysis and life cycle assessment to quantify the environmental and social consequences of extraction, production, waste and recycling. This work helps identify where burdens are concentrated across supply chains and where reforms are most needed.

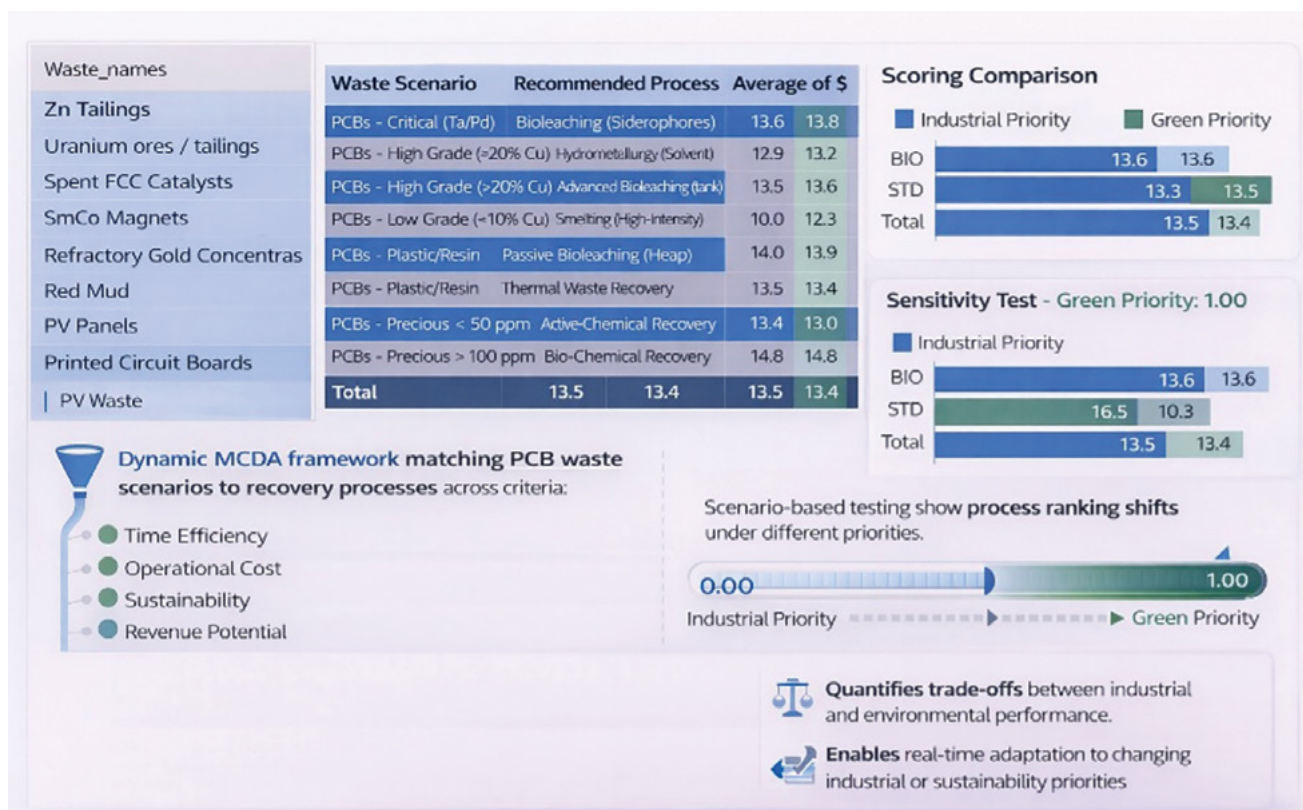
A more holistic view of recycling is being developed by Professor Gwénaëlle Proust from the School of Civil Engineering. Her work applies materials engineering to the circular economy for metals by transforming heterogeneous scrap streams from sectors such as civil infrastructure and transport into high-quality feedstock for advanced manufacturing, including additive

manufacturing. Rather than recycling only for bulk material recovery – which can degrade composition and performance – this approach combines advanced sorting, refining and alloy redesign to meet the compositional and microstructural requirements of high-performance components.

Business models and policy settings also matter. Associate Professor Krithika Randhawa from the University of Sydney Business School is developing business models to support circular value chains for critical materials. At the same time, work led by Nika Asasi and Professor Marjorie Valix examines the policy drivers needed to advance critical minerals recycling in Australia and the strategic implications of treating recycling as part of national supply security. A related project has developed a dynamic multi-criteria decision analysis framework to classify and prioritise waste streams for rare earth recovery across more than 40 recovery scenarios. Its findings show that the best pathway depends on feedstock quality, process conditions and stakeholder priorities, underscoring the need for flexible policy and investment settings (Figure 1).



Figure 1: Process Assessment and Sensitivity Analysis: Matching printed circuit board (PCB) Waste to Optimal Recovery Pathways



Case Study

A Circular, Low-Carbon Platform for Rare Earth Extraction

Dr Haihui Joy Jiang, Prof. Deanna D'Alessandro, Prof. Gregory G. Warr and Prof. Markus Müllner

Rare earth elements (REEs) are central to the modern energy transition, particularly in the permanent magnets used in electric vehicles and wind turbines. While Australia holds some of the world's richest REE deposits, downstream processing still relies heavily on legacy technologies that are energy intensive, chemically severe and environmentally challenging.

Current refining pathways face three major bottlenecks. The first is high-emissions cracking, where complex mineral ores are broken down using extreme thermal heat and large volumes of concentrated acids. The second is hazardous purification, where target elements are isolated and trace radioactive impurities removed using large volumes of flammable and hazardous organic solvents. The third is legacy waste, with purification generating substantial phosphate residues that are typically treated as a liability rather than a resource.

To address these challenges, researchers led by Dr Haihui Joy Jiang from the School of Chemistry, in collaboration with the Australian rare earth industry, are developing an electrified, low-carbon refinery platform for REE processing. The approach replaces static, harsh chemistry with dynamically tuned, electrically controlled extraction, opening a pathway to more sustainable rare earth refining.

The platform brings together three modular components. The first is electrified plasma leaching, which replaces energy-intensive thermal acid baking with a non-thermal plasma process that drives reactions at the air-water interface. By generating highly reactive transient radicals, the system disrupts mineral lattices at ambient temperatures and reduces the energy and acid intensity needed to release REEs. The second is precision green separation, which avoids reliance on flammable organic extractants by using electro-switchable green chelators, including water-based polymers and advanced solid-state materials. Applied voltage acts as a selectivity switch, enabling safer and more precise removal of trace



Conceptual schematic of a low-carbon platform for rare earth element extraction, combining electrified leaching, selective extraction using green chelators and electricity, and waste upcycling into higher-value by-products or extractant precursors.

radioactive impurities to strict regulatory thresholds. The third is circular waste upcycling. Rather than disposing of phosphate residues, the process transforms them into higher-value products such as slow-release fertilisers and fire-resistant, zero-carbon construction materials. Recovered phosphate can also be looped back into the manufacture of the green extraction reagents used in the separation stage, creating a more genuinely closed-loop system.

By shifting from hazardous legacy methods to an electrified, water-based platform, this work has the potential to significantly lower the carbon footprint of critical mineral processing. It also offers the kind of lower-impact, high-value processing pathway increasingly demanded by global ESG standards, while improving worker safety and reducing ecological contamination risks. By linking green chemistry with industrial process engineering, the platform directly supports the Future Made in Australia agenda and strengthens the case for an Australian critical minerals sector that is both globally competitive and environmentally responsible.

Case Study

Recovering critical metals through solar-thermal liquid metal processing

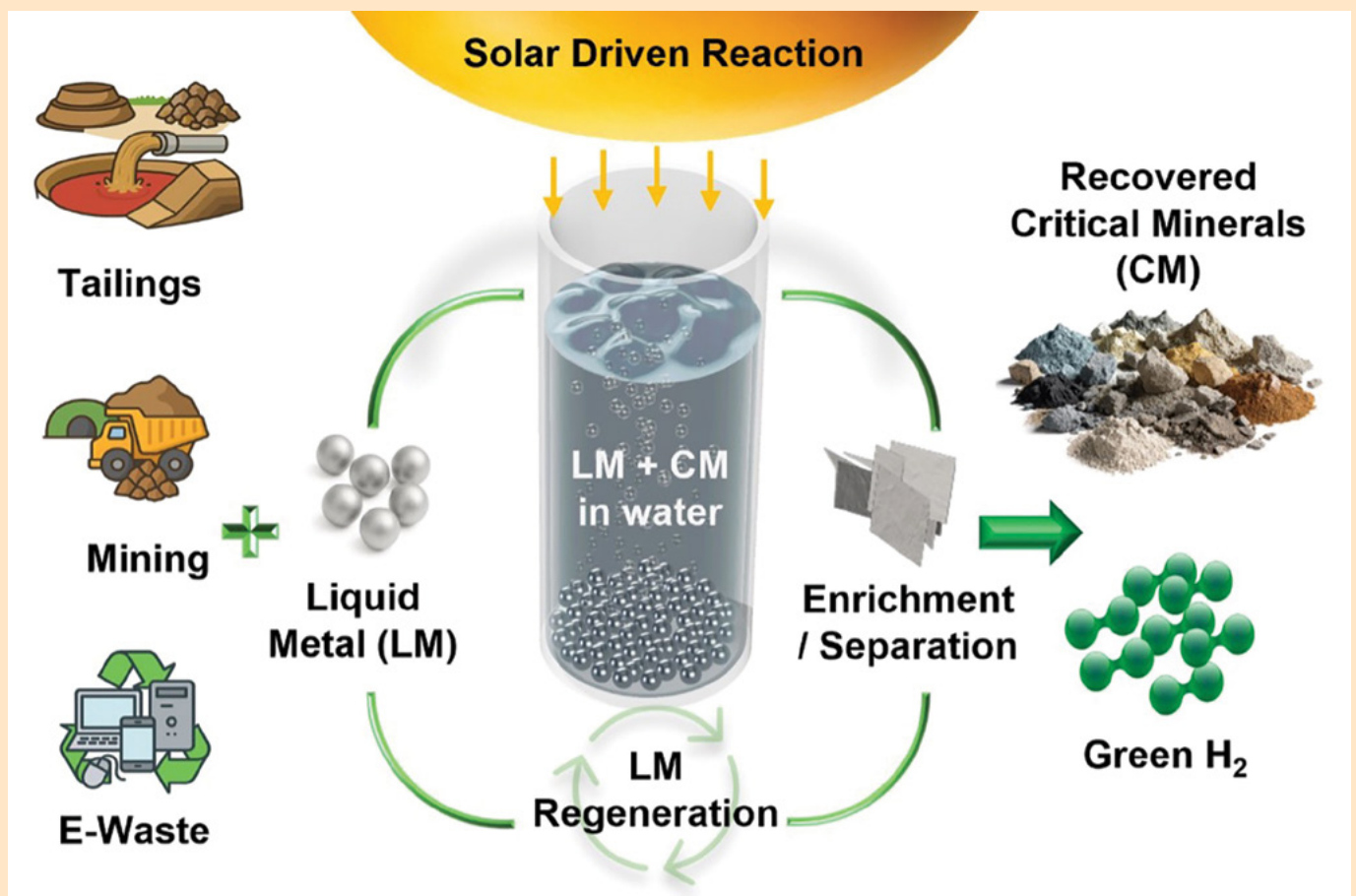
Dr Francois-Marie Allieux, Luis G. B. Campos, Professor Kourosh Kalantar-Zadeh

Recovering critical metals from low-grade and complex feedstocks is an increasing challenge for the net zero transition. Conventional processing routes are often energy intensive and poorly suited to secondary sources such as e-waste, industrial residues and tailings.

Dr Francois-Marie Allieux and his co-workers are developing a solar-thermal liquid metal platform for

recovering critical metals from tailings and e-waste, with germanium as the first commercial target. Germanium is essential to fibre optics, infrared systems and advanced semiconductors, and its supply is highly geographically concentrated.

The process uses a liquid metal-based approach and solar-thermal input to support critical metal recovery under comparatively mild conditions, avoiding aggressive chemical leaching and high-temperature furnaces. The liquid metal is regenerated and reused in a circular configuration, and hydrogen is produced as an additional value stream. The platform can also operate with brackish water, seawater and aqueous mine tailings, improving its relevance in remote and off-grid settings.



Conceptual schematic of a solar-driven liquid metal platform for recovering critical minerals from tailings, mining streams and e-waste, while regenerating the liquid metal and producing green hydrogen. Image by: Francois-Marie Allieux, Kourosh Kalantar-Zadeh and Luis Gustavo Bezerra de Campos.

Case Study

Carbon and social impacts in the EU's consumption of fossil and mineral raw materials

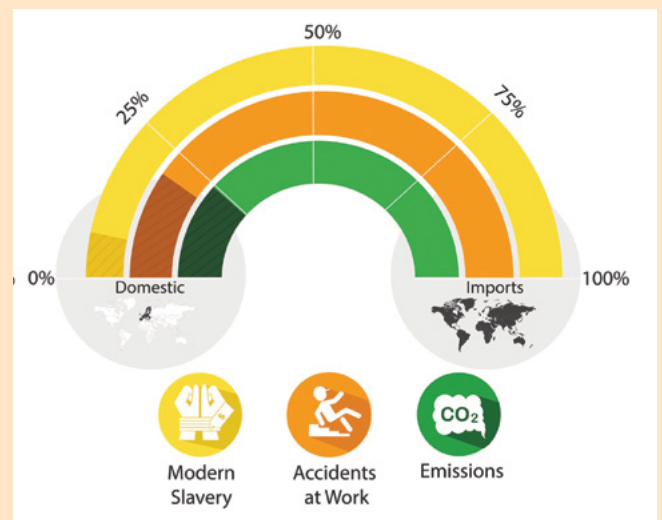
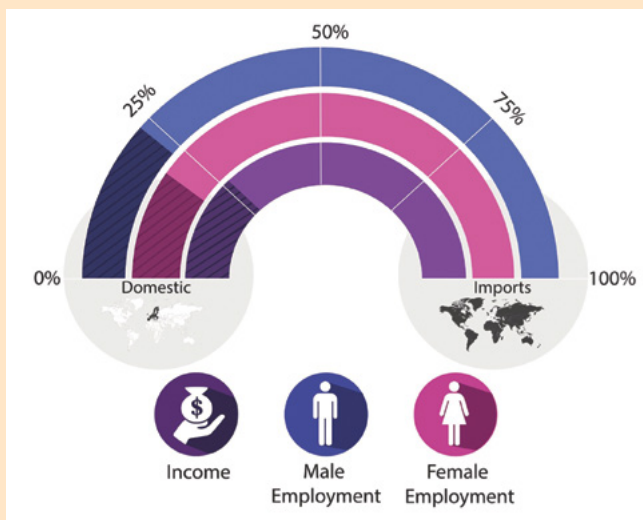
Professor Arunima Malik and Professor Manfred Lenzen

Arunima Malik, Manfred Lenzen and their co-workers have analysed how consumer demand in the European Union drives environmental and social impacts across the global mining sector.

Using multi-region input-output analysis, the team quantified both positive effects, such as income and

employment, and negative effects, including greenhouse gas emissions, accidents at work and modern slavery. They found that the EU's consumption is associated with substantial spillover impacts, particularly in Central Asia, the Asia Pacific and Africa.

The researchers mapped these results within a three-pillar framework and proposed policy responses that combine domestic regulation, international diplomacy and finance, and more responsible consumption, recycling and innovation. The work highlights the need for stronger reforms in mining industries and trade policy if adverse social and environmental impacts are to be reduced.



Domestic and import-related social and environmental impacts associated with critical material supply, including income, employment, modern slavery, workplace accidents and emissions.



Case Study

Designing circular business models for critical minerals value chains

Associate Professor Krithika Randhawa

Critical minerals sit at the heart of the net zero transition, with demand for lithium, nickel, cobalt and rare earth elements rising rapidly. While expanding mining and processing capacity remains essential, long-term resilience will also depend on circular approaches that recover, reuse and recycle materials. Despite progress in recycling and material substitution, far less attention has been paid to the business models needed to make circular systems work at scale. Yet achieving circularity is not only a technological challenge – it is also a business model challenge.

Recent research by Associate Professor Krithika Randhawa and colleagues examines how managers make decisions at the intersection of climate goals and financial performance. This experimental study with senior managers shows that business model design involves complex trade-offs between climate value creation – such as emissions reduction or resource efficiency – and value capture mechanisms such as pricing, market share and return horizons. The findings reveal that managers often favour models that deliver clearer or faster financial returns, even when alternatives generate greater environmental benefits.

These trade-offs become even more pronounced in circular economy strategies. Closing material loops requires coordination among miners, manufacturers,

recyclers, technology providers and regulators, often across jurisdictions. While investments in recycling infrastructure, material recovery and product redesign can deliver system-level benefits, the economic value is often distributed across the value chain rather than captured by a single firm.

For critical minerals industries, this means circularity depends on new forms of ecosystem coordination and value creation. Actors need to align incentives across the full lifecycle of materials – from extraction and processing through manufacturing, product use and end-of-life recovery. This shifts the model from one-off transactions to capturing value across multiple lifecycle loops.

Emerging innovations illustrate this shift. Digital product passports and traceability systems are enabling the tracking, recovery and reuse of materials used in batteries and electronics. These tools can unlock new services such as lifecycle monitoring, recovery and reuse. Recycling hubs and industrial symbiosis initiatives are also helping turn waste streams and mine tailings into inputs for new production.

For countries such as Australia – home to significant reserves of many critical minerals – this presents a strategic opportunity. By supporting circular business model innovation alongside resource development, Australia can strengthen supply security, capture greater downstream value and help lead the development of more sustainable critical minerals value chains for the global net zero transition.



Case Study

Advancing the recycling of critical minerals in Australia: policy drivers and strategic implications

Nika Asasi and Professor Marjorie Valix

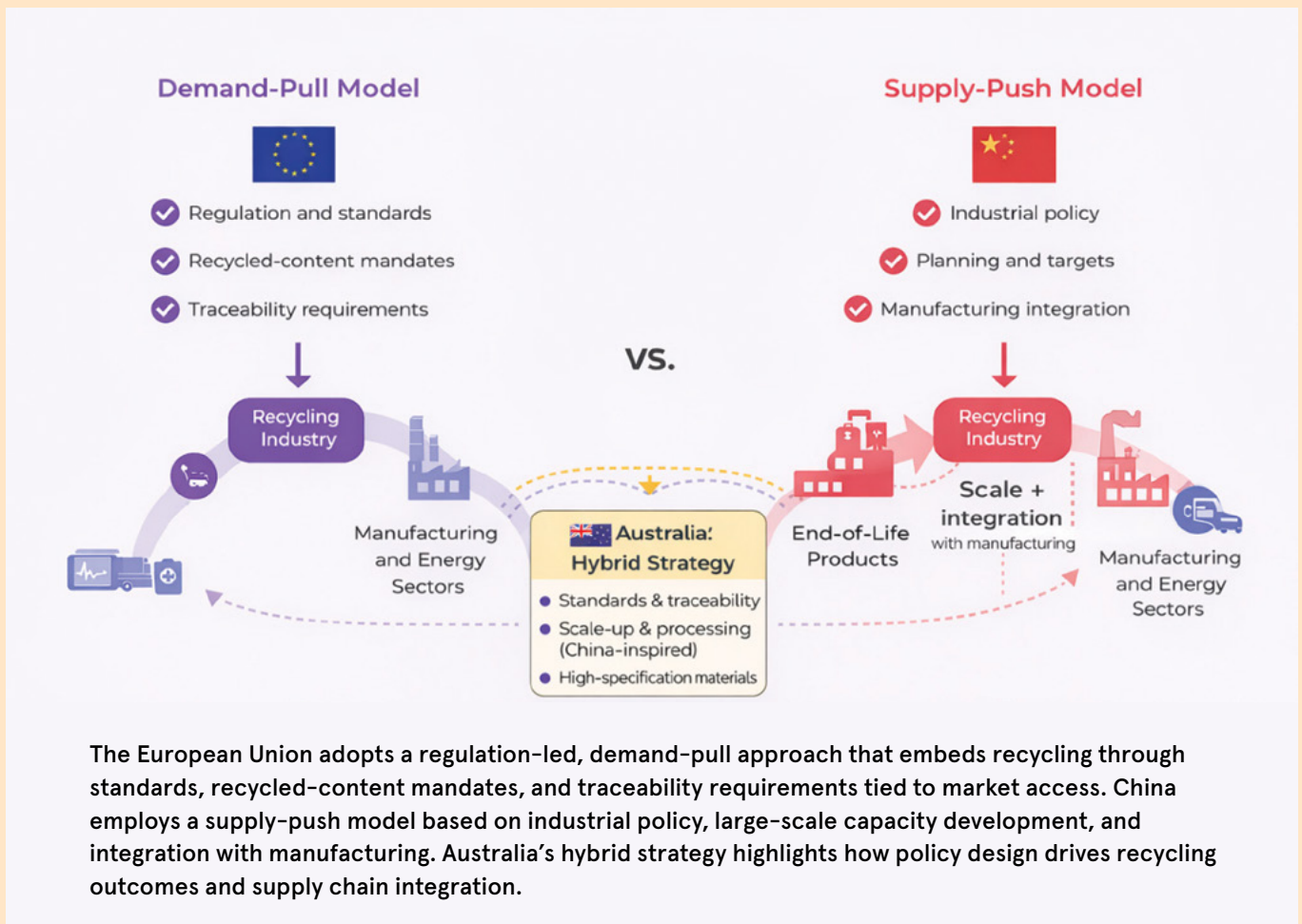
Critical minerals underpin batteries, renewable energy systems and advanced manufacturing, yet supply chains remain highly concentrated at the refining stage, exposing countries to geopolitical risk and supply disruption. Recycling is increasingly recognised not as a waste management activity alone, but as a strategic supply solution.

Research led by Nika Asasi and Professor Marjorie Valix argues that recycling systems are constrained less by technology than by structural market failures

– including unpriced environmental externalities, coordination challenges and demand uncertainty. The work compares two dominant international policy models: the European Union’s demand-pull approach, built around regulation, recycled-content mandates and traceability requirements, and China’s supply-push model, built around industrial policy and integration with manufacturing.

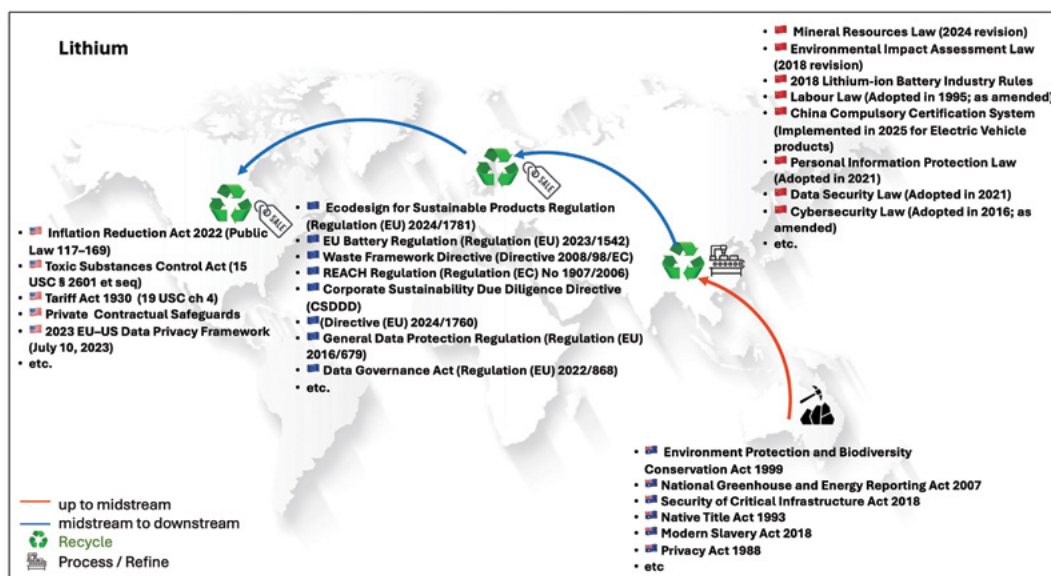
For Australia, the argument is for a hybrid strategy. The research suggests that recycling should be treated as strategic infrastructure and supported by mandatory stewardship, national traceability systems, targeted scale-up funding, demand-pull mechanisms and stronger integration with critical minerals and manufacturing policy.

Figure 2: Comparative policy models for critical mineral recycling: demand-pull (EU), supply-push (China), and implications for Australia’s strategic positioning.



Developing sustainable supply chains

Sustainable supply chains depend on traceability, legal interoperability, geopolitical strategy and policy settings that can support more secure and responsible production.



Example of the physical and regulatory complexity of critical material supply chains.

Increasing the recycling of critical materials is one aspect of a sustainable supply chain for critical minerals and materials, and it may also support domestic production. But sustainability extends well beyond recycling. Researchers at the University of Sydney are investigating questions of traceability, regulation, geopolitics and industrial policy across critical material value chains.

One core feature of a sustainable supply chain is traceability – knowing that what you received is what you intended to source. This matters especially when the goal is to reduce environmental and social impacts by sourcing materials from producers with stronger performance, including Australian suppliers. Work by Professor Arunima Malik and Professor Manfred Lenzen has already highlighted the adverse impacts embodied in material consumption derived from mining.

Dr Mengyu Li’s research gives institutions new ways to trace material flows across global supply chains – a capability that is increasingly important in an era of accelerating demand for critical minerals. As a Horizon Fellow at the University of Sydney, she has developed high-resolution multi-region input-output models that

track material flows from extraction to final consumption and has contributed to the United Nations Environment Programme’s Global Footprint Tool.

Professor Lenzen’s work on traceability also highlights the global supply chains for coltan, a source of niobium and tantalum. Professor Hans Hendrichske from the University of Sydney Business School focuses on improving traceability through physical and regulatory mapping. His work shows how states classify critical minerals differently and impose varying compliance requirements, increasing cost and complexity for business. It argues for parallel tracking of physical and regulatory measures across the value chain and for cooperative frameworks that build predictability and mutual recognition.

One response to these challenges is the Digital Product Passport. Professor Jie (Jeanne) Huang from Sydney Law School is actively researching digital passports and related legal questions, as outlined in the case study below. Several University researchers are also examining the geopolitical dimensions of sustainable critical material supply chains. The United States Studies Centre has played a leading role here, convening dialogues on

critical minerals in December 2025 and February 2026 and bringing together government, industry and academic participants from Australia, the United States, Japan and India. These dialogues have explored supply diversification, public-private collaboration and practical ways to support alternative supply chains that are less exposed to China and less damaging to suppliers.

Onshoring critical mineral production to Australia is one way to address geopolitical, environmental and social

concerns. Professor Niel Coe and Dr Lian Sinclair from the School of Geosciences are researching the policies needed to facilitate the production and processing of energy transition materials in Australia and the role of state actors in responding to the current geopolitical, energy and environmental polycrisis. Their work identifies six forms of risk – technical, investment, market, environmental and social, workforce and regulatory – and three interconnected state strategies for derisking projects: subsidising, streamlining and brokering.

Case Study

Global supply chains of coltan

Professor Manfred Lenzen

Research led by Professor Manfred Lenzen demonstrates how critical minerals such as tantalum, sourced from columbite-tantalite or coltan, can be traced through global supply chains using hybrid life cycle assessment and multi-region input-output analysis.

The team's work maps how coltan mined in the Democratic Republic of the Congo flows through processing hubs in Germany, the United States, Kazakhstan and China before being embodied in electronics, aerospace components, medical devices and transport equipment. It shows how downstream consumers in higher-income economies ultimately consume conflict-linked minerals even when they have no direct trade relationship with the producing country.

The research is especially salient given continuing safety and governance failures in artisanal mining regions. In February 2025, more than 50 miners were killed when a coltan mine collapsed in Rubaya, North Kivu, in the eastern Democratic Republic of the Congo. Such events underscore the human consequences of weak governance, unsafe conditions and opaque trading networks.

For Australia and its regional partners, this work offers a forward-looking framework. Embedding MRIO-based risk screening within critical minerals strategy allows policymakers, development banks and investors to identify high-risk trade pathways before crises deepen and to align critical materials programs with responsible sourcing and supply-chain resilience.

Moran, D., D. McBain, K. Kanemoto, M. Lenzen and A. Geschke (2015). Global Supply Chains of Coltan. Journal of Industrial Ecology 19, 357–365.



Artisanal mining sites are a key part of global coltan supply chains, highlighting the complex social, environmental and governance challenges embedded in critical mineral sourcing.

Case Study

Digital product passports and critical raw materials for batteries

Professor Jeanne Huang

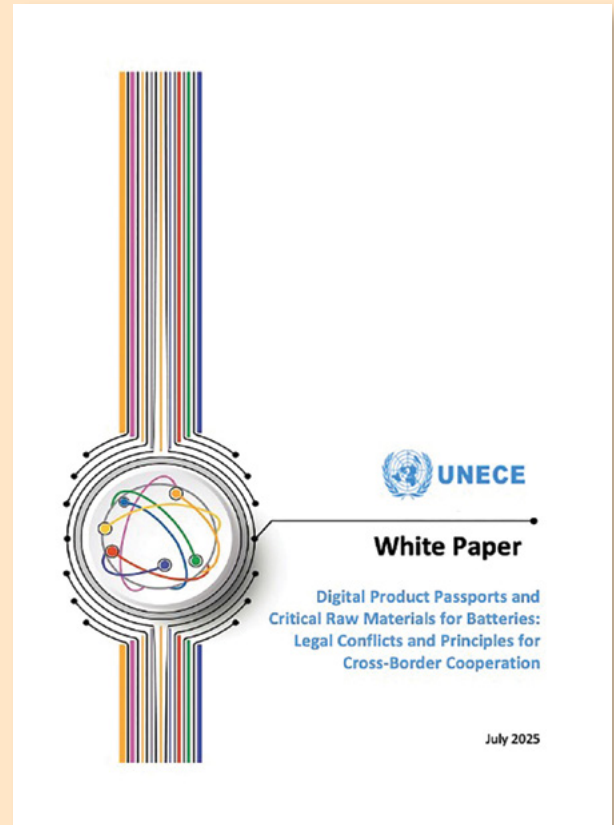
As the world moves towards cleaner technologies, demand for critical raw materials such as lithium, cobalt, nickel and copper is rising rapidly. These minerals are essential for batteries used in electric vehicles and renewable energy systems, yet their supply chains are long, fragmented and regulated across multiple jurisdictions.

Transparency across these value chains has therefore become a major challenge. One emerging response is the Digital Product Passport – a tool designed to store and share information about the origin, production and lifecycle of products across supply chains.

The white paper *Digital Product Passports and Critical Raw Materials for Batteries: Legal Conflicts and Principles for Cross-Border Cooperation*, co-authored by Professor Jeanne Huang, examines the legal challenges involved in implementing such systems in global battery value chains. It focuses on how different regulatory frameworks interact when traceability requirements extend across borders.

The research shows that critical minerals are defined and regulated differently across jurisdictions, and that traceability systems developed in markets such as the

European Union, China and the United States are not always interoperable. Transparency requirements may also conflict with domestic rules on data security, privacy and business confidentiality. Understanding these legal tensions is essential if digital traceability systems are to work across real supply chains.



Reduce the demand for critical materials by finding substitutes

Substitution, redesign and better materials performance can reduce dependence on the critical materials that are hardest to source responsibly and sustainably.



One way to make critical material supply chains more sustainable is to reduce the amount of critical material they require. Demand for products that rely on critical materials is expected to surge, especially as electric vehicles and clean-energy technologies expand, so reducing or eliminating the need for particular materials can help moderate future pressure on supply.

A good example is the work of Dr Wesley Dose from the School of Chemistry. Increasing nickel content and decreasing cobalt in battery electrodes can increase stored energy, but it can also accelerate degradation and reduce battery life. Understanding these degradation mechanisms and finding ways to stabilise these materials is therefore a major challenge. His team is also working on manganese-rich electrode materials because nickel is itself a critical material, while cobalt is a target for reduction because of its heavy social and environmental burden.

While this work focuses on battery cathodes, Professor Yuan Chen from the School of Chemical and Biomolecular Engineering is investigating ways to reduce demand for naturally occurring graphite – the main component of battery anodes and another critical material.

Professor Simon Ringer studies atomic-scale materials design. Using a materials science and engineering approach, he examines how small groups of atoms arranged in particular architectures can create materials with remarkable electronic, magnetic, chemical and mechanical properties. These insights have applications in semiconductors, catalysis and new lightweight alloys.

Professor Ringer is also working with Dr Hansheng Chen to reduce the quantities of certain rare earth elements – especially neodymium and dysprosium – needed to make the strong permanent magnets used in electric vehicle motors and wind turbine generators.

Case Study

Sustainable synthetic graphite from methane pyrolysis for battery applications

Professor Yuan Chen

The rapid growth of electric vehicles and renewable energy systems is driving unprecedented demand for lithium-ion batteries and increasing pressure on the supply of critical minerals and battery materials. Graphite is the dominant anode material in lithium-ion batteries, but conventional graphite production presents major sustainability challenges. Natural graphite extraction and purification are energy intensive and environmentally disruptive, while synthetic graphite production can carry a very high carbon footprint.

One promising pathway is methane pyrolysis, a process that decomposes methane into hydrogen and solid carbon with no direct carbon dioxide emissions. Because substantial quantities of carbon are produced alongside hydrogen, identifying high-value uses for that carbon is essential to improving the economics and sustainability of the process.

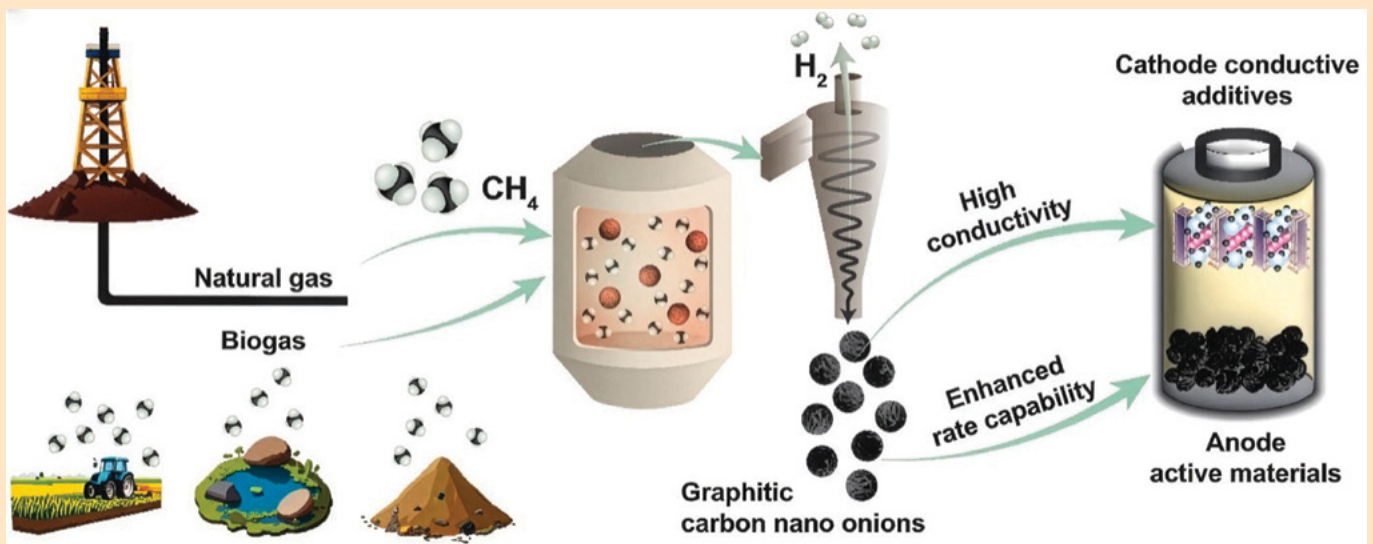
Researchers in the University of Sydney's School of Chemical and Biomolecular Engineering have explored the

potential to convert these carbon by-products into high-performance graphite materials for lithium-ion batteries. The work focuses on catalytic methane pyrolysis using low-cost iron ore catalysts in a fluidised-bed reactor to produce graphitic carbon structures.

After purification, the resulting materials show properties that improve electrical conductivity and facilitate lithium-ion transport. Electrochemical testing has shown that methane-derived graphitic carbon can perform as both an active anode material and a conductive additive in battery cathodes, with significantly improved fast-charging performance compared with commercial natural graphite.

For Australia, the technology presents a strategic opportunity to connect clean hydrogen production with critical material value chains, support more sustainable battery materials and strengthen domestic capability in next-generation energy technologies.

Prabowo, J.; Pan, Y.; Zheng, Z.; Lai, L.; Yang, X.; She, F.; Chen, J.; Liu, F.; Chivers, B.; Wei, L.; Chen, Y. Dual-functional graphitic carbon materials from methane pyrolysis for lithium-ion batteries. Carbon, 2025, 234, 120038.



Turning methane into value - a process for producing hydrogen and graphitic carbon nano-onions for next-generation battery materials.

Reflection

The University's critical materials work shows that sustainable supply depends on coordinated innovation across science, engineering, policy, governance and business.

This capability update to the 2024 Critical Minerals and Materials white paper presents a multidimensional view of the challenges surrounding critical minerals and how the University of Sydney's Net Zero Institute is responding through research, collaboration and innovation. Between 2024 and 2026, the conversation around critical minerals shifted from one focused mainly on the clean energy transition to one deeply entangled with geopolitics, national security and global economic restructuring.

The update also demonstrates the breadth of research across the University of Sydney – from deep geoscience and AI-driven discovery to business model innovation, international law, social science and global governance. It reinforces the point that critical minerals challenges are not solved simply by finding more resources. They require coordinated innovation across discovery, extraction, recycling, substitution and governance.

The EarthByte Group's work shows how data-intensive and AI-enabled approaches can transform mineral exploration. Digital soil mapping for vanadium likewise

shows how better pre-competitive geoscience can reduce risk, cost and environmental impact. The work on circular business models and materials flows is equally important because it recognises that circularity is not only an engineering challenge, but also a governance, economic and social one.

The researchers featured in this paper do not view critical minerals through a purely technical or economic lens. The case studies on deep-sea mining and global coltan supply chains highlight the dangers of allowing scarcity narratives or techno-optimism to override ethical and environmental scrutiny. The University of Sydney's work on critical minerals and materials demonstrates that multidisciplinary cooperation is not just valuable. It is essential. The problems we face – from climate change to geopolitical instability – are interconnected, and so must be the solutions.

Endnotes

1. Net Zero Institute. Critical Minerals and Materials: The sustainable supply of materials for the clean energy transition. University of Sydney, 2024.
2. Critical minerals at Geoscience Australia | Geoscience Australia (ga.gov.au) – <https://www.ga.gov.au/scientific-topics/minerals/critical-minerals>
3. U.S. Geological Survey Releases 2025 List of Critical Minerals | U.S. Geological Survey (usgs.gov).
4. The Role of Critical Minerals in Clean Energy Transitions. International Energy Agency, Paris. <https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions>, Licence: CC BY 4.0
5. War, Metals, and Market Reality: Hallgarten’s February 2026 Resources Outlook. https://hallgartenco.com/wp-content/uploads/2026/03/Portfolio_February2026.pdf
6. Critical Minerals Strategy 2023–2030 | Department of Industry, Science and Resources. <https://www.industry.gov.au/publications/critical-minerals-strategy-2023-2030>
7. Critical minerals geopolitics in 2026: risks, supply chains and global power shifts. ODI. <https://odi.org/en/insights/critical-minerals-geopolitics-in-2026-risks-supply-chains-and-global-power-shifts/>
8. The US is merely the latest to join the global rush to hoard critical minerals. The Guardian. <https://www.theguardian.com/environment/2026/feb/16/critical-minerals-shortages-jd-vance-trading-bloc-analysis>
9. 2026 Critical Minerals Ministerial – United States Department of State. <https://www.state.gov/releases/office-of-the-spokesperson/2026/02/2026-critical-minerals-ministerial>
10. The US wants to remake the critical minerals supply chain. Society of Chemical Industry. <https://www.soci.org/news/2026/2/the-us-wants-to-remake-the-critical-minerals-supply-chain>
11. The Quad Critical Minerals Initiative. <https://www.foreignminister.gov.au/minister/penny-wong/media-release/joint-statement-quad-foreign-ministers-meeting-washington>
12. Alger, J., Green, J.F., Neville, K.J., Park, S., VanDeveer, S.D., & Webster, D.G. The false promise of deep-sea mining. *npj Ocean Sustainability* 4, 21 (2025). <https://doi.org/10.1038/s44183-025-00127-4>.

Critical Minerals and Materials Pillar and Network Members

The Critical Minerals and Materials Pillar and Network brings together researchers to support collaboration across the sector.





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