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Critical Minerals and the Clean Energy Transition: The Role of Innovation Across the Supply Chain*

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Abstract

The clean energy transition depends on a narrow set of critical minerals with highly concentrated and environmentally intensive supply chains. This paper reviews how innovation across the full value chain—from exploration, mining, and processing to manufacturing, use, reuse, and recycling—can reduce these vulnerabilities. A simple framework maps technological, digital, and organisational innovations, complemented by indicators such as patents, venture capital, industrial restructuring, circularity metrics, and traceability tools. The paper synthesises evidence on core drivers and barriers, including price volatility, industrial policy, environmental regulation, firm strategies, market size, and rising demand from AI and defence. Three focus areas—mining technologies, rare-earth magnets, and batteries—illustrate concrete pathways for reducing primary demand, diversifying supply, and improving circularity. Finally, we identify an urgent need for research on how emerging policy mechanisms, such as price stabilisation and digital traceability, can coordinate with technological progress to support supply security and climate goals.

Keywords: Critical minerals; Innovation; Clean energy transition; Supply chain; Mining; Rare earth elements; Batteries; Industrial policy; Circular economy.

JEL Classification: O31, Q55, L72.

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1 Introduction

The clean energy transition is increasingly defined by a paradox: while global efforts to decarbonise energy systems are accelerating, they hinge on a new form of dependence—a dependence on a narrow set of critical minerals (CMs)[1] sourced and processed in a handful of countries. Just as oil once shaped geopolitics and macroeconomic stability, materials like lithium, cobalt, nickel, copper, and rare earth elements now underpin the deployment of low-carbon technologies central to climate action.

Achieving net-zero emissions by mid-century, a goal endorsed by dozens of countries, will require the rapid and massive deployment of clean energy systems. According to the International Energy Agency (IEA), global renewable power capacity must triple between 2022 and 2030 (IEA 2024b). Electric vehicle (EV) sales are projected to continue their meteoric rise from 14 million in 2023 (IEA 2023b), while clean hydrogen, battery storage, and electrified industrial processes will all contribute to a sharp increase in demand for minerals essential to their manufacture (Miller et al. 2023; Naegler et al. 2025). Modern EVs rely on lithium, nickel, manganese, rare earths, graphite, aluminium, and copper. Solar photovoltaics require cadmium, indium, silicon, and tellurium, while wind turbines use rare-earth magnets and substantial amounts of copper. Meanwhile, grid infrastructure depends heavily on copper, gallium and vanadium.[2]

However, the raw material foundation of this transition is far from assured. First, many CM supply chains are characterised by high concentration. Over 90% of battery-grade graphite and more than 77% of refined rare earth elements are processed in China (IEA 2024b). The Democratic Republic of the Congo dominates cobalt extraction, while Indonesia and the Philippines are leading producers of nickel. These supply chains are vulnerable to political, environmental, or economic shocks. The 2010 rare earths dispute between China and Japan highlighted how trade tensions can disrupt supply (Donnan and Politi 2014; Evenett and Fritz 2023); the recent wave of export restrictions imposed by major producers suggests these risks are not theoretical (AfricaNews 2022; Lakshmi and Hodgson 2025). The IEA's 2024 Outlook warns that if supply from the largest producer of any major CM were cut off, only half of global demand could be met (IEA 2025b).

Second, the stakes extend beyond supply reliability to macroeconomic consequences. A study by Boer et al. (2024) found that, in a net-zero scenario, the value of global metals production could quadruple, reaching an accumulated US $11 trillion over two decades—a value comparable to global oil production over the same period under the scenario. They show that short-term supply elasticities are low for most CMs, meaning prices could spike sharply. Third, environmental and social concerns surrounding the mining and processing of CMs could drive up production costs and, consequently, prices. Prolonged high prices would have ripple effects[3]: delaying the deployment of clean technologies, reversing the long-standing trend

1. Throughout this paper, we use the term critical minerals (CMs) broadly to include certain raw materials deemed critical to the clean energy transition, even if they are not technically minerals—for example, graphite.

2. See Table 1 in United Nations Environment Programme (2024) for a more exhaustive overview.

3. We should emphasise, however, that such pricing effects may differ between metals depending on their characteristics, market structure, end-uses within energy transitions, and sensitivity to social and geopolitical disturbances. See Liu et al. (2025).

of falling costs in solar, wind, and battery systems, and increasing the cost of capital for green investments.

Yet the future is not fixed. Innovation can substantially reshape the elasticity of both supply and demand. On the supply side, technological advances in extraction, processing, and recycling can improve responsiveness. On the demand side, innovation can drive substitution away from scarce or politically sensitive materials, as in the rise of lithium-iron-phosphate (LFP) batteries or efforts to design permanent-magnet-free wind turbines. Smart product design, modularisation and traceability technologies schemes offer further levers. IEA modelling suggests that a strategic mix of battery downsizing, chemistry switching, and circularity could reduce lithium demand by up to 25% by 2030 (IEA 2024b).

This review aims to chart the landscape of innovation that can mitigate the critical minerals challenge. We focus on particular applications that are central to the clean energy transition, such as renewable energy systems and electric vehicles, rather than a specific subset of materials. Our scope spans the value chain—from mining and processing, to manufacturing, usage, reuse, and recycling. Our objectives are threefold:

1. To map the current innovation landscape in CMs, identifying key technologies and gaps across the CM value chain: from mining and processing to manufacturing, re-use and recycling;
2. To showcase real-world examples of innovations that reduce primary demand or expand the supply of CM. While we aim to cover a range of innovation types (some technical, some organizational), we do not address broader shifts in mobility patterns and consumer behaviour that could also reduce demand for cars and, by extension, batteries.
3. To assess emerging policy challenges and opportunities for governments, particularly in OECD countries, to foster innovation across the CM value chain.

In doing so, we seek to inform not only debates on energy security and industrial policy but also the design of climate strategies that are resilient to material constraints, as well as the role of innovation in minimizing environmental impact. While the clean transition has historically promised both climate and energy security benefits, the reliance on a small set of minerals may introduce new trade-offs (Kim et al. 2025). Innovation will be key to navigating them.

2 Mapping the Innovation Landscape for Critical Minerals

2.1 A Simple Conceptual Framework

To make sense of the rapidly evolving innovation landscape around critical minerals (CMs), we introduce a simple conceptual framework that structures innovation across the supply chain. The goal is not to be comprehensive, but to offer an organising lens for mapping different types of innovation, understanding their

		Mining & Processing	Manufacturing	Use & Re-use	Recycling
	Overall Innovation Goals	• Increase & diversify supply • Cost reduction • Lower environmental & social footprint	• Design with fewer / alternative CMs • Design for recyclability & longevity	• Lower demand • Optimise use for longevity	• Decrease recycling cost • Increase yield & purity
Examples	**Technical / Hardware Innovations**	Low-impact mining (in-situ)	Alt. chemistries (e.g. sodium-ion); modular design	Smart sensors & real-time tracking	Hydrogen magnet recycling for rare-earths
Examples	**Digital / Software Innovations**	AI-integration for geological mapping	AI-driven combinatorial R&D	AI-based predictive maintenance; product passports	Blockchain tokens certifying recycled minerals
Examples	**Organisational / Business-Model Innovations**	Blockchain Certification-as-a-Service for ESG finance	Upstream vertical integration / "mine-to-Gigafactory"	Product-as-a-Service / shared ownership	Recycling-as-a-Service + take-back credits

Figure 1: Illustrative innovation typology across the CM value-chain.

interactions, and identifying policy-relevant patterns. The framework takes the form of a two-dimensional matrix. One axis follows the physical life cycle of CMs—from upstream extraction to downstream recycling. The other categorises innovations into three types: technological (hardware), digital (software), and organisational (including business models and finance). Together, these axes allow us to classify diverse efforts into a manageable typology and relate them to core policy goals: supply security, cost competitiveness, environmental sustainability, and social performance.

The value-chain axis begins with mining and processing, encompassing exploration, extraction, refining, and transportation. This is where innovation targets the front end of supply chains, typically aiming to increase availability and reduce costs. Innovation in more productive drilling machines, in optimizing bulk transport (within mines but also in international maritime transport), and in processing and refining plants illustrate this step. Innovation also aims to reduce environmental harm. Techniques like in-situ leaching and bioleaching allow recovery from lower-grade ores with smaller footprints. AI-assisted geological mapping, using satellite imagery and machine learning, accelerates discovery and reduces risk. Blockchain certification-as-a-service informs investors, allowing them to de-risk early-stage projects and ease capital constraints.

The next stage, manufacturing, is where raw materials are turned into components or final products like batteries, motors, or wind turbines. Here, innovation often focuses on reducing dependence on critical inputs, either through improved efficiency or material substitution. Sodium-ion batteries and low-nickel chemistries illustrate this shift. AI is increasingly used to accelerate materials discovery, cutting down on costly experimentation. Meanwhile, vertical integration—linking mining and manufacturing within a single firm—can improve supply coordination and promote the use of recyclable product designs.

The third stage covers use, reuse, and in-use optimisation. Innovation at this point focuses not just on the materials embedded in products, but on how products are operated and maintained. Sensors and digital twins, for instance, allow real-time monitoring of performance and degradation in EVs or wind turbines, enabling predictive maintenance and longer useful lives. Blockchain-based product passports, which track composition and ownership over time, support better sorting and recovery at end-of-life. Business models like battery leasing keep material control with manufacturers, reinforcing circularity and improving recovery rates.

Finally, the recycling stage closes the loop. Here, the goal is to recover valuable materials and reduce reliance on virgin extraction. Hydrogen-based recycling of rare-earth magnets, for example, achieves high recovery rates with lower energy use. Digital tools also play a role by verifying recycled content, enabling new market mechanisms such as traceable tokens. Recycling-as-a-service models shift logistical and regulatory burdens away from manufacturers, raising collection rates, especially where formal take-back systems are weak.

The second axis of the framework groups innovations by their dominant mode. Technological innovations improve the physical transformation of materials through new chemistries, processes, or equipment. Digital innovations apply data and computation to improve efficiency and coordination. Organisational innovations reshape incentives and value capture through new financing models, ownership structures, or contractual arrangements. In practice, many high-impact solutions combine these elements. A low-impact mine might couple novel leaching processes with autonomous monitoring and ESG-linked finance. These bundled approaches tend to outperform isolated technical fixes.

Viewed through this framework, it becomes easier to see how innovations relate to specific outcomes. Upstream advances improve supply security and reduce environmental damage. Midstream innovations in materials design and manufacturing efficiency lower costs and make products easier to recycle. Downstream, digital tracking and service-based models extend product lifetimes and tighten material loops. These links are rarely linear or one-directional. Trade-offs emerge—for instance, moving away from cobalt may reduce geopolitical risk but increase material weight. Vertical integration can enhance resilience but also raise competition concerns. Effective policy must take these dynamics into account to expand the overall innovation frontier rather than shift bottlenecks from one part of the chain to another.

This framework serves not only as a map of current activity but also as a diagnostic tool for guiding future innovation and policy. In the sections that follow, we use this matrix to structure our discussion of how innovation in critical minerals is measured, what drives or hinders it, how it supports broader reforms, and how it interacts with shifting geopolitical and technological trends.

Box 1: The Battery Passport — A Digital Backbone for Circularity

The battery passport is a digital record designed to travel with a battery throughout its entire lifecycle. It brings together detailed information about the battery's composition, production, use, and end-of-life status into a structured and traceable format. Typically envisioned as a QR code physically attached to the battery or as a cloud-linked digital identity, the passport contains data on material content (including critical minerals and their country of origin), manufacturing details (producer, location, and date), technical performance and degradation over time (e.g. charging cycles), and the chain of ownership and custody (Rizos and Urban 2024).

From a critical minerals perspective, battery passports play a pivotal role. They help determine whether a battery is best reused, repurposed (e.g. for stationary storage), or recycled—decisions that depend on accurate knowledge of battery condition and embedded materials. This is especially important for optimising recovery of high-value elements like cobalt and lithium. Real-time monitoring also allows for predictive maintenance, extending battery life and reducing waste (Weng et al. 2023).

The EU's Batteries Regulation mandates battery passports for all large-format batteries by 2027, with layered access rights and interoperability requirements. In parallel, the Global Battery Alliance has piloted a standardised passport prototype with automakers and miners (Global Battery Alliance 2025). These efforts aim to improve traceability, harmonise data sharing, and enhance ESG accountability across global supply chains (Rizos and Urban 2024).

However, implementation faces hurdles. There is no global standard for data formats, and actors remain cautious about sharing sensitive information. Smaller or distributed battery systems (e.g. e-bikes, tools) are not yet fully covered, and responsibilities for updating passport data after reuse or recycling remain unclear.

While not a silver bullet, the battery passport is a crucial enabler of transparency, safety, and resource recovery. Its effectiveness will depend on harmonised policy, technological interoperability, and trust across the battery value chain.

2.2 How to Measure Critical Mineral Innovation

Measuring innovation across the critical minerals supply chain is essential for understanding where progress is occurring, where it is stalling, and how policy can help. Without reliable indicators, it is difficult to track the development and diffusion of new technologies, assess the maturity of emerging solutions, or compare innovation performance across countries or sectors. Measurement turns scattered signals into actionable insight.

We build on the framework introduced in Section 2.1, which maps innovation by value-chain stage and type. Different points in this matrix correspond to different kinds of observable activity. Early-stage R&D

in refining may show up in patents or publications, while business-model innovation in recycling might be visible through traceability systems or circular-economy metrics.

This section organises indicators into five categories: knowledge generation (e.g. patents, publications), commercialisation (e.g. VC deals), industrial dynamics (e.g. M&A, vertical integration), circularity outcomes (e.g. secondary-market activity), and traceability (e.g. adoption of digital passports). Each offers a partial view of the innovation landscape; taken together, they allow us to assess where momentum is building and where gaps remain.

Knowledge Generation One of the most direct ways to measure innovation in critical minerals is through indicators of knowledge generation, such as R&D expenditures, but also particularly patents. Patents offer a structured and internationally comparable source of information on emerging technologies, their geographic distribution, and the institutional landscape of innovation. The IEA's global patent report on batteries provides one of the most detailed mappings of technological trajectories in this space to date, showing how international patent families can be used to track developments across chemistries, components, and applications—including battery recycling, solid-state designs, and emerging cathode materials—using harmonised patent classification codes (IEA 2020). Similarly, the *WIPO Mining Database* provides a mapping of patents related to mining exploration, extraction, processing and refining, transport and environmental patents (see Section 3. Andersen and Noailly (2022) explore further patents aimed at reducing the environmental footprint of mining, particularly in water treatment, soil remediation, waste management, and mineral and metal processing.

Beyond these foundational studies, a growing number of patent landscape analyses have explored particular segments of the critical minerals and battery value chain, including work on cathode chemistry trends, nanomaterial-based storage systems, and recycling processes. These studies collectively confirm the usefulness of patent data for capturing commercially oriented innovation across a wide range of technological niches. Additional patent landscaping studies have looked at generic technologies such as AI, automation, and remote sensing that are increasingly relevant for parts of the CM value chain (Hossain et al. 2024; Metzger et al. 2023; Tong and Zhu 2025; WIPO 2019; Yang and Mu 2023).

By contrast, we are not aware of any attempts to systematically track scientific publications on critical minerals innovation. This is a notable gap, given the central role of fundamental research in the early stages of technology development, particularly in materials science, where new compounds or processes are often first documented in the academic literature before being embodied in a specific, patentable invention. A structured mapping of publications, using topic modelling or keyword sets, would be a worthwhile complement to the existing patent-based evidence, especially for identifying upstream shifts in the scientific knowledge base.

Commercialisation Commercialisation indicators help assess whether innovation in critical minerals is moving beyond the lab and attracting serious market interest. Among these, venture capital (VC) and start-up activity offer particularly valuable early signals of which technologies investors view as scalable and commercially promising.

Start-up funding data from platforms like Crunchbase, Dealroom, and PitchBook can be used to track the number and value of disclosed deals across different stages—seed, early, and growth—providing a rough proxy for the maturity of innovation in specific parts of the supply chain. Deal-level analysis can also offer insights into which segments—such as direct lithium extraction, rare-earth separation, or battery recycling—are emerging as hotspots of entrepreneurial activity.

Although data are dispersed and classification is often inconsistent, the IEA's Global Critical Minerals Outlook 2025 has begun to map out the VC landscape (IEA 2025b). It shows that investment activity in the critical minerals space surged between 2020 and 2023, especially in lithium extraction and battery recycling. Start-ups like Redwood Materials and Kobold Metals exemplify the growing investor interest in circular-economy and AI-driven mineral exploration technologies (Matousek 2025; Nextsprints Team 2025). However, the report also notes that funding has become more selective, with macroeconomic conditions and regulatory uncertainty creating barriers for companies trying to scale.

At present, there is no comprehensive or systematic dataset that captures VC and start-up activity across the full range of critical minerals technologies. Most available evidence comes from general-purpose investment databases or industry reports, offering only partial glimpses of the broader commercialisation landscape. A more structured effort to track capital flows into mining, refining, recycling, and substitution technologies would fill an important gap in the current innovation metrics toolkit.

Industrial Dynamics Innovation in critical minerals is not only about new technologies—it also involves how firms restructure supply chains and redeploy capabilities. Three types of corporate behaviour are particularly revealing: mergers and acquisitions (M&A), diversification, and vertical integration. Each offers insight into how incumbents respond to technological shifts and supply risks.

M&A activity provides a direct signal of where firms see strategic value or technical bottlenecks. M&A activity provides a direct signal of where firms see strategic value or technical bottlenecks. Deal data from platforms like LSEG (formerly Refinitiv) or S&P Capital IQ Pro can be used to explore trends by target activity and acquirer type. For example, a rise in the acquisition of recycling firms or lithium refiners suggests that these capabilities are increasingly viewed as core assets. Tracking changes in deal volume, size, and geography helps map where the innovation frontier is being redrawn.

Diversification—firms expanding into adjacent technological or market domains—can be analysed using patent data, segment revenues, and public disclosures. Moves such as mining firms investing in cathode-active materials or chemical companies exploring direct lithium extraction indicate where cross-sectoral capabilities are becoming valuable. Ideally, data linking firms to their suppliers (e.g., major mining firms to their equipment suppliers) would provide insights into diversification strategies.

Vertical integration is especially common in response to raw material constraints. Automakers have increasingly taken equity stakes or signed long-term offtake agreements with upstream mining and refining projects. These deals, while not always captured in M&A databases, signal a growing urgency among downstream firms to secure supply and reduce exposure to volatility.

These indicators complement patent and VC metrics by showing where firms are putting serious capital to work. However, data remain fragmented—many deals are private, classifications vary, and no unified source covers the full CM supply chain. Developing shared taxonomies and linking available datasets would greatly improve our ability to track industrial transformation in this space.

Circular-Economy Indicators Measuring progress in circularity is crucial for understanding how innovation in critical minerals is helping reduce pressure on primary extraction. Unlike patents or VC funding, circular-economy indicators speak to the deployment and scaling of new business models, particularly those that extend product life, recover materials, or reduce material demand altogether.

One important indicator is the volume of secondary markets for end-of-life (EoL) components, especially EV batteries. Data on repurposed batteries, for example, can reveal how much capacity is being redirected to second-life applications such as stationary storage. This can be measured in gigawatt-hours of repurposed capacity, or as a share of EoL battery volume. While datasets remain fragmented, initiatives such as RMI's Battery Circular Economy Initiative or the Global Battery Alliance are starting to provide relevant figures (Alliance 2025; Institute 2024).

Another useful proxy is the degree of sharing-economy penetration in transport. Car sharing, e-scooter fleets, and vehicle-as-a-service platforms reduce total vehicle demand per kilometre travelled, and thus lower aggregate demand for critical minerals. Indicators here could include the share of passenger-kilometres accounted for by shared modes, the fleet size of shared electric vehicles, or the number of active users per platform. These data are typically available from transport authorities, mobility platforms, or surveys.

While these indicators do not directly capture technological innovation, they reflect the adoption and diffusion of innovations that help decouple economic activity from material throughput. Monitoring them alongside upstream metrics—such as patents and investment—provides a fuller picture of how innovation contributes to system-level change. However, consistent tracking remains a challenge, and more granular, internationally comparable data on reuse, refurbishment, and product lifetime extension are needed.

Traceability Metrics As sustainability, human rights, and circularity rise on the policy agenda, traceability has become a critical dimension of innovation in critical minerals. Technologies such as digital product passports and blockchain-based certification systems enable firms to verify provenance[4], environmental and

4. It is vital to emphasise that one of the most significant challenges to the efficacy of these digital technologies is the difficulty of physical traceability of minerals. This is exemplified by the fact that very few metals are delivered with a certificate of provenance or origin, which may reflect the lack of an established international standard or authorised organisation to issue such certifications.

social standards, and recycled content across increasingly complex supply chains. Tracking the adoption and coverage of these systems offers a way to measure innovation not in the materials themselves, but in the infrastructure of accountability and trust.

One emerging indicator is the adoption rate of digital product passports—for example, as mandated under the EU Battery Regulation (See Box 1 for more details). These passports encode information about a product's origin, composition, and lifecycle, and can be used to facilitate end-of-life recovery, verify ESG compliance, and support sustainable procurement. Coverage can be measured in terms of the number of compliant products or firms, the extent of supply-chain tiers included, or the share of a given market (e.g. EV batteries) that is traceable through such systems.

Another metric is the deployment of blockchain or distributed ledger technologies for ensuring the integrity of information in relation to raw material traceability. These systems are being piloted in cobalt, lithium, and rare earths supply chains, sometimes led by industry consortia or third-party certification platforms (Cecilia Jamasmie 2021; Mugurusi and Ahishakiye 2022). Quantitative indicators include the number of certified kilogrammes tracked, the number of nodes in the network, or the volume of transactions logged. While many of these systems remain proprietary or pilot-scale, their expansion is an indicator of how seriously firms and regulators are investing in supply-chain transparency.

Together, these metrics help assess the extent to which digital infrastructure is enabling more transparent and accountable supply chains. While traceability systems do not replace innovation in extraction, processing, or recycling, they are increasingly a prerequisite for their legitimacy and market acceptance, especially in jurisdictions with tightening regulatory requirements. Developing more standardised and open datasets in this area would substantially improve the evidence base for policy and investment decisions.

2.3 General Drivers and Barriers of Innovation for Critical Minerals

Innovation in critical minerals responds to a mix of market signals, policy choices, and firm strategies. Price volatility, policy uncertainty, and fragmented supply chains can all slow investment, while well-designed industrial or environmental policies, large downstream markets, and supply-chain integration can accelerate it. This section reviews key drivers and barriers—ranging from prices to market structure—and highlights measurable indicators that can help track their effects.

2.3.1 Prices and Volatility

Prices are among the most powerful signals shaping innovation incentives in resource-intensive sectors, and critical minerals are no exception. Higher prices can increase the expected returns from investing in new extraction, processing, or substitution technologies. In the energy sector, for instance, a growing body of research has shown that higher fossil fuel prices stimulate innovation in clean alternatives, including renewables and energy efficiency technologies (Aghion et al. 2016; Dugoua and Gerarden 2025; Popp 2002).

A similar result is confirmed by Valacchi et al. (2023) who find that high commodity prices stimulate innovation in the mining sector (see Section 3. This basic logic is well established across multiple domains.

However, it is not only the level of prices that matters—volatility plays a key role as well. Recent events have made this clear. In March 2022, nickel prices surged by 270% over three trading days in response to Russia's invasion of Ukraine, prompting the London Metal Exchange to suspend trading (Oliver Wyman 2023). As Miller and Martinez (2025) note, this extreme volatility was driven not only by geopolitical shocks but also by pre-existing market tightness, growing demand from electric vehicles, and concentrated hedging positions that reduced market liquidity. More broadly, they argue that demand shocks are the dominant structural factor shaping metal price formation, while supply shocks tend to be more short-lived in their effects.

The IEA's Global Critical Minerals Outlook 2025 echoes this view, showing that many critical minerals now exhibit higher price volatility than oil—and in some cases, even natural gas (IEA 2025b). Price swings are amplified by a combination of long project lead times, highly concentrated supply (often in one or two countries), and demand surges triggered by policy shifts such as new EV mandates. Thin futures markets and limited stockpiling capacity further restrict producers' and consumers' ability to hedge, leaving spot prices more sensitive to short-term shocks.

This volatility creates particular challenges for diversification efforts. High-cost producers outside the dominant supplier countries often struggle to compete when prices fall, making investment in new supply highly sensitive to short-term market shifts. Volatility increases financing costs, raises the perceived risk of long-term capital projects, and creates uncertainty about the returns to innovation.

Uncertainty also interacts with macroeconomic dynamics in ways that amplify its impact. As shown by Reboredo and Ugolini (2024), uncertainty shocks in energy-transition metal markets can disrupt investment cycles, lower productivity, and deepen recessions—effects that are consistent with broader macroeconomic findings on the role of uncertainty in slowing innovation and capital formation (Bloom 2007; Bloom et al. 2007).

Given these challenges, there is growing interest in policy mechanisms that can mitigate downside risk and stabilise incentives. The IEA outlines the potential role of cap-and-floor mechanisms or contracts for difference (CfDs), which guarantee a minimum revenue (the floor) while limiting windfall profits (the cap) (IEA 2025b). These mechanisms, already used in the context of renewable energy, are now being explored for mineral projects (Allan 2025; Beiter et al. 2023; Kitzing et al. 2024; Savelli et al. 2022; Trupp 2025). They offer a way to reduce revenue uncertainty while preserving some degree of market exposure, avoiding excessive fiscal commitments, and maintaining flexibility under volatile conditions. However, their effectiveness depends heavily on the calibration of reference prices and the transparency of underlying market data.

In sum, while high prices can incentivise innovation, excessive volatility and uncertainty can do the opposite, especially in capital-intensive sectors like critical minerals. Well-designed policies that stabilise investment conditions may be essential not just for unlocking supply but also for enabling the kinds of innovation needed to make supply more secure, sustainable, and resilient.

2.3.2 Industrial Policy and Supply Diversification

Over the past few years, a growing number of governments have embraced industrial policy as a central tool for securing critical mineral supply chains. The shift is notable not just for its intensity but also for its breadth. What began as a focus on securing upstream extraction has expanded into coordinated strategies that span refining, manufacturing, recycling, skills development, and trade policy. As documented in the IEA's Global Critical Minerals Outlook 2025, the scope of country-level interventions is striking, ranging from fast-tracked permitting to equity investments in strategic projects and the introduction of digital product passport schemes (IEA 2025b). In parallel, national governments have begun to coordinate across ministries, create public–private task forces, and align infrastructure, environmental, and industrial policies under unified critical minerals strategies. This wave of policymaking marks a clear departure from a market-led approach to one in which governments seek to shape the direction and structure of supply chains. Although public policies frequently strive for quick responses to interventions, it is critical for the public policy agenda to be effectively aligned with market dynamics, given the enormous time required to build new value chains.

Financial Support A common feature of these national strategies is the provision of direct public support to early-stage or high-risk projects. These include grants, concessional loans, tax credits, and equity stakes. The EU Critical Raw Materials Act, for instance, introduces the concept of "Strategic Projects," which benefit from accelerated permitting and can receive EU-level financial support (European Commission 2025). The regulation also outlines plans for a European Raw Materials Fund to provide equity injections into domestic mining, refining, and recycling ventures. In the United States, both the Infrastructure Investment and Jobs Act and the Inflation Reduction Act (IRA) have allocated substantial funding for domestic battery materials and processing capabilities (Bistline et al. 2023). These efforts have already catalysed tens of billions in announced private-sector investment (Bermel et al. 2024; IEA 2023b). France, Canada and Australia have launched similar initiatives, often combining public co-financing with other measures such as export credits, sovereign guarantees, tax credit, and private equity (IEA 2023a).

This type of financial support, possibly also in the form of blended finance, is important for de-risking investment in countries where costs are higher, permitting processes are more complex, or supply chains are less mature. It also helps unlock innovation. By lowering the cost of capital for first-of-a-kind plants, these measures allow firms to experiment with new refining chemistries, recycling technologies, or modular processing systems that might otherwise struggle to attract private financing.

However, rapid shifts in battery chemistries and uncertain future scrap/feedstock composition create technology and throughput risk for capital-intensive refining and recycling assets. To mitigate this, industrial policy should complement cost-of-capital support with credible demand signals—such as transparent recycled-content trajectories, or advance market commitments—to align innovation with investment certainty.

Preferential Access and Regulatory Levers In addition to direct support, governments are using regulatory and market-access tools to steer investment and innovation. Local content requirements—particularly in the United States—are a prominent example. The IRA ties consumer tax credits for electric vehicles to critical mineral content thresholds (Bistline et al. 2023). To qualify, a growing share of minerals must be extracted or processed in the U.S. or its free-trade-agreement partners. These rules are already prompting automakers and battery firms to reconfigure their sourcing strategies and accelerate domestic supply-chain development. These policies can also help foster technology transfers from foreign firms to local ones.

The EU, for its part, is leveraging sustainability requirements. Under the Critical Raw Materials Act and the new Battery Regulation, manufacturers must meet recycled-content thresholds for certain critical materials. For example, by 2030, batteries sold in the EU will be required to contain a minimum share of recycled lithium, cobalt, and nickel (Rizos and Urban 2024). These mandates create a guaranteed market for secondary materials and are already encouraging innovation in collection, sorting, and high-yield recycling technologies. These obligations are already spurring innovation in traceability systems, high-purity recovery methods, and second-life repurposing.

Export bans are also on the rise. Countries like Indonesia and Zimbabwe have prohibited the export of unprocessed nickel, lithium, and other ores in an effort to capture more value-added activity domestically (AfricaNews 2022; Lakshmi and Hodgson 2025). While such measures may succeed in attracting refining investment, they also reduce global supply flexibility and can trigger retaliatory responses or discourage foreign capital.

These regulatory instruments have strong implications for innovation. Local content rules and recycled-content mandates effectively create new technical constraints, prompting firms to invest in substitute materials, redesign supply chains, or develop traceability systems.

Gaps and Risks Despite a rapid expansion of policy activity, major gaps remain. Most planned capacity expansions—especially in refining—are still concentrated in a handful of countries, particularly China. And while policies such as local content mandates and export restrictions aim to reorient global supply chains, they also carry real economic and technical risks.

Raising localisation requirements, for example, often raises costs. This can make end-use products like EVs or solar panels more expensive, potentially slowing deployment and reducing the net climate benefit. Newcomer countries may also lack the institutional, regulatory, or human-capital foundations needed to develop competitive industries from scratch.

The collapse of Northvolt is a powerful illustration of these challenges. Once hailed as Europe's future battery champion, the Swedish start-up raised more than USD 15 billion in equity, debt, and public funds, with backing from Volkswagen, Goldman Sachs, and the European Investment Bank. Yet in early 2025, Northvolt filed for bankruptcy after failing to secure another USD 1 billion to keep its Skellefteå gigafactory operational (Financial Times 2025a). While the full causes remain under investigation, contributing factors appear to include overly rapid expansion—attempting to build as many as six facilities at once—alongside internal management issues, over-reliance on Chinese machinery, and a lack of sustained public subsidies in Sweden. Broader market dynamics, including global overcapacity in NMC cell production and weaker-than-expected demand, likely exacerbated the firm's financial strain (Financial Times 2025b). The episode serves as a warning: even well-capitalised industrial policy bets can falter if ambition outpaces institutional and technical readiness.

More broadly, poorly calibrated industrial policies can contribute to uncertainty rather than resolve it. When targets are unrealistic or when rules change too frequently, firms may treat them as non-credible, undermining the very investment and innovation the policies are meant to stimulate. Calibrating the scope, timing, and credibility of government intervention is therefore crucial. Effective industrial policy should provide clear, stable signals without overpromising or overreaching. It is not only the presence of state support that matters, but the quality of its design and delivery.

2.3.3 Firm-level Strategies: Securing Inputs, Shaping Innovation

As critical minerals become central to industrial competitiveness and climate goals, downstream firms—particularly in the automotive and battery sectors—are no longer leaving sourcing to market forces. Instead, they are adopting increasingly proactive strategies to secure supply, manage risk, and align inputs with their technological and regulatory requirements. These strategies have direct implications for innovation: they can create stronger incentives to invest in new technologies, but they also carry risks that may constrain experimentation or delay adoption.

A key development is the trend toward vertical integration. Some firms are acquiring or developing upstream assets in mining, refining, or recycling in order to secure access to essential inputs and gain greater control over their supply chains (IEA 2023a). For example, Ford partnered with Vale and Huayou to build a nickel processing plant in Indonesia (Rani 2023). This can facilitate innovation by tightening feedback loops between product design and material availability. Firms that control their own raw material supply are better positioned to adapt chemistries or processing methods in-house and to invest in refining routes tailored to their specifications. However, integration also increases capital costs and operational complexity, which may deter smaller firms or lock incumbents into legacy technologies if markets evolve quickly.

Others pursue strategic partnerships or joint ventures, often with specialised upstream firms. This allows for shared investment in innovation while avoiding the risks of full ownership. Partnerships can accelerate technology transfer, align R&D efforts across the chain, and ease entry into sectors with high regulatory or technical barriers. In contrast, firms relying solely on arm's-length sourcing may have less influence over upstream innovation and may struggle to guarantee material inputs that meet evolving design or sustainability requirements.

But these strategies are not without limits. The shift toward supply-chain control requires firms to develop new capabilities—navigating environmental permitting, mastering refining processes, or coordinating logistics at scale. These are non-trivial organisational shifts, and failure to build the right internal capacity can lead to costly delays or failed projects. Moreover, the concentration of effort around particular chemistries or sourcing arrangements can create path dependency: firms heavily invested in today's inputs may be slower to switch to more sustainable or efficient alternatives as they emerge.

Ultimately, firm-level strategies can powerfully shape the direction and speed of innovation. Those that successfully integrate upstream control with downstream design often create the conditions for more targeted, responsive, and scalable technological development. But if integration is poorly sequenced, too narrow, or driven by defensive risk management alone, it may inhibit rather than enable meaningful innovation.

2.3.4 Market Size, New or Niche Markets

Market size plays a central role in shaping incentives for innovation. Larger markets tend to offer higher expected returns on R&D by enabling economies of scale, accelerating learning-by-doing, and providing a broader customer base to amortise upfront fixed costs. These dynamics are well-documented across a range of sectors. For instance, studies in pharmaceuticals and clean energy have shown that market expansion—whether due to demographic trends, regulatory change, or policy shifts—can spur significant increases in innovation activity (Acemoglu and Linn 2004; Aghion et al. 2024).

In the context of critical minerals, downstream demand for batteries, electric vehicles, and renewable energy technologies generates strong pull signals for upstream innovation. The rapid growth of the EV market, in particular, has helped mobilise investment in new refining techniques, material substitutes[5], and recycling solutions. This is a clear example of how anticipated demand growth lowers commercial risk for early-stage technologies and incentivises innovation across the supply chain.

At the same time, niche markets play a distinctive and complementary role. Though smaller in volume, these segments often offer more stable and predictable demand. This can be attractive for firms developing specialised technologies that might not yet be ready for mass deployment. One example is stationary storage, where performance requirements and cost structures differ substantially from those in mobile applications. Niche markets also function as testing grounds for emerging chemistries and system architectures. By demonstrating technical viability and generating performance data, they help de-risk new technologies and

5. This might, however, depend on the relative metal composition of products and the prospect for development, especially at the early stages of innovation when a "new" metal is used. For example, PEM technology relies on a platinum/iridium catalyst containing two to four times more iridium than platinum, while in ores, iridium is ten times less abundant – or even more – than platinum. When enough ore is extracted to create the required iridium, platinum is overproduced, which lowers its price and puts the mine's profitability at risk. Additionally, the method becomes expensive if iridium dominates the total cost.

prepare them for potential scale-up—a process well recognised in the literature on evolutionary technical change (Schot and Geels 2007).

Some niche players have even driven significant innovation spillovers. For instance, so-called "hidden champions"—often highly specialised firms serving narrow markets—have been shown to punch above their weight in terms of patenting activity, particularly when located in diverse industrial clusters (Lehmann et al. 2025). This suggests that even modest market segments can support vibrant innovation ecosystems, provided the firms within them maintain high absorptive capacity and access to relevant knowledge networks.

That said, niche strategies are not without risk. Small markets may not justify ongoing investment in process innovation, and firms may become overly reliant on customer-specific solutions. Investors, too, may discount future growth potential if the niche appears isolated from broader trends. For these reasons, some firms adopt hybrid strategies, designing modular "platform" chemistries or processes that can serve both niche and high-volume applications.

Alongside these firm strategies, policy can play a critical role in shaping credible demand signals—particularly during scale-up phases. Demand-pull tools such as public procurement, offtake agreements, and fleet or content mandates can help emerging firms navigate the "valley of death" by securing predictable market volumes and reducing commercial uncertainty.

In sum, both market scale and segmentation matter for innovation in critical minerals. Large, fast-growing markets draw investment into scalable, cost-reducing innovations. Smaller, specialised markets support differentiated performance and incremental learning. A diversified market landscape—backed by credible demand signals—helps ensure that innovation progresses not just in quantity, but in direction.

2.3.5 Environmental Policies: Innovation Driver or Diversification Constraint?

Environmental regulations are often framed as drivers of innovation, and indeed, a growing body of evidence supports this view. Policies targeting air pollution, water quality, waste management, and land use can push firms toward cleaner, more efficient processes—especially when designed with clear rules and predictable timelines. Recent empirical work, for instance, shows that well-calibrated environmental policies accelerated green innovation in sectors ranging from pollution standards to ozone-depleting substances (Dugoua 2025; Popp 2019; Rozendaal and Vollebergh 2025). This echoes findings from the broader literature on the Porter Hypothesis, which argues that environmental regulation can, under the right conditions, enhance not only environmental performance but firm productivity and technological upgrading (Ambec et al. 2013). While evidence is mixed on the productivity channel, there is strong support for the idea that environmental policies spur green innovation even without improving overall efficiency. Andersen and Noailly (2022) provide a first analysis for the mining sector, showing that environmental regulations are positively associated with innovations aiming to reduce the environmental footprint of mining (see Section 3.3.2).

Yet in the context of critical minerals, this optimistic view collides with a more difficult reality. Mining and refining are inherently material-, water- and energy-intensive processes. Stricter regulations on water use, biodiversity impact, hazardous-waste handling, carbon emissions, and land rehabilitation—particularly in regions like the EU—raise the compliance burden and capital cost of operating within these jurisdictions. While these rules may induce innovation at the margin, they can also render projects economically unviable. This creates a structural tension: the very countries seeking to diversify their supply of critical minerals often place the highest environmental barriers on domestic production, undermining their own strategic goals.

This misalignment has clear implications. If mining and refining activities are pushed to countries with weaker environmental standards, global emissions and ecosystem impacts may rise, even as local indicators improve. Moreover, the innovation-forcing effects of regulation depend on where production actually occurs. Relocation to less-regulated jurisdictions limits firms' exposure to high standards and erodes the domestic incentive to invest in cleaner technologies. This dynamic is well captured in the literature on the pollution haven hypothesis, which documents mixed evidence for how stringent environmental regulation in high-income countries may displace polluting industries to jurisdictions with laxer standards, leading to net global harm (Copeland 2008; Duan et al. 2021).

Policies that aim to raise environmental performance across the supply chain must therefore navigate a delicate trade-off. On one hand, overly lax regulation risks locking in dirty technologies and undermining long-term sustainability. On the other, overly stringent or poorly timed rules may drive critical activities offshore—diluting innovation incentives and concentrating environmental harms elsewhere. This trade-off is especially acute in refining and recycling, where permitting delays, site constraints, and infrastructure gaps can make innovation-driven facilities difficult to site in the regions with the strongest policy ambitions.

The challenge, then, is one of calibration and coordination. For environmental policy to function as an effective driver of innovation in critical minerals, it must be designed with an awareness of both global supply dynamics and domestic institutional capacity. Sequencing matters. So does enforcement credibility. Without this, high standards may produce more offshoring than innovation, and more fragmentation than diversification.

2.4 How Innovation Can Help Speed the Reforms Required to Create Greener and More Secure Supply Chains

Innovation is not just a long-term outcome of reform—it can also act as an essential enabler. Many of the policy and political challenges that slow efforts to build greener and more secure critical mineral supply chains stem from high costs, limited enforcement capacity, and local resistance to new extraction. Targeted innovation in materials, processes, and digital infrastructure can ease these constraints, making regulatory reform more credible, scalable, and politically feasible.

One of the most powerful levers is substitution. Advances in material science are reducing reliance on supply-constrained or geopolitically sensitive inputs. Sodium-ion batteries, cobalt-lean cathodes, and

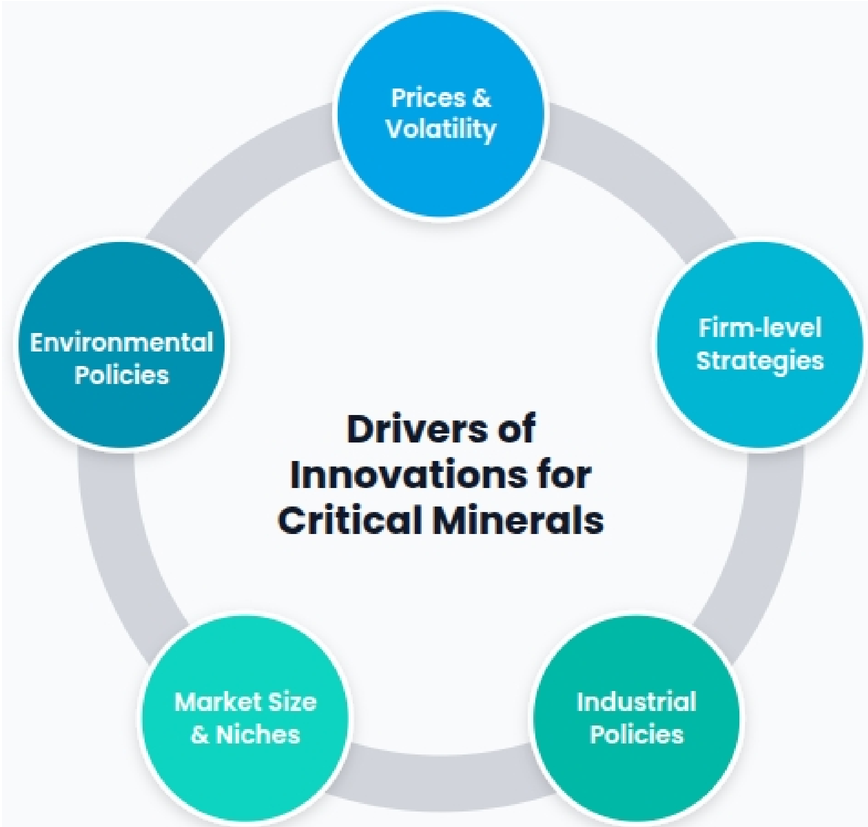

Figure 2: General Drivers and Barriers of Innovation for Critical Minerals.

rare-earth-free motor designs offer credible alternatives for key technologies, although they may also use a lot of copper that must be energized. As substitutes become cheaper and more competitive, governments can rely less on costly industrial policy to manage supply risk. Put differently, when materials are less critical, regulatory and political reform becomes less risky, although we also acknowledge the countervailing risk posed by the so-called "rebound effect"[6] which suggests that switching to a new high-energy efficient technology could transform a non-critical metal into a critical one, particularly in specific circumstances such as limited supply conditions.

Innovation also plays a central role in reducing overall demand intensity. Improvements in material efficiency, modular design, and predictive maintenance stretch the service life of products and reduce the amount of raw material required per unit of output. For example, lighter EV designs and reuse-oriented battery formats reduce the need for new extraction and ease pressure on recycling infrastructure. This, in turn, allows for more ambitious regulation on mining and waste, because the volume of material passing through the system shrinks.

A major bottleneck for supply-chain reform is weak enforcement and traceability, especially in transnational contexts. But digital innovation is beginning to change this. Blockchain-based ledgers, battery passports, and material-tracking sensors are lowering the cost of monitoring compliance with ESG standards, recycled content mandates, and origin-based trade rules. These systems build trust with consumers

6. see Freire-González and Vivanco (2017).

and investors, enabling reforms that depend on credible certification to function effectively.

Finally, innovation in low-impact mining and processing helps overcome one of the most politically sensitive barriers to reform: local resistance. Techniques such as in-situ leaching, dry-stack tailings, and electrified refining reduce the visible and ecological footprint of critical mineral operations. As these technologies become more affordable and scalable, they make environmental regulation of mining activities less economically burdensome and more politically palatable, both for policymakers and industry. In doing so, technological progress lowers resistance from economic actors and helps accelerate permitting timelines, ultimately reinforcing environmental ambition.

In sum, innovation reduces the cost—economic, social, and political—of reform. It allows governments to align their goals for supply security and environmental protection, rather than trading one off against the other. The faster low-impact, substitute, and traceable technologies become viable, the easier it becomes to implement the rules, incentives, and safeguards required to rewire global supply chains.

2.5 Crowding-in vs. Crowding-out with the AI and Defence Boom

The clean-energy transition is no longer the only major driver of critical mineral demand. A powerful combination of defence rearmament and artificial intelligence (AI) infrastructure deployment is reshaping global material markets, creating potential tensions with climate goals. Military and data-centre hardware rely on many of the same minerals that underpin wind turbines, electric vehicles, and solar photovoltaics. Whether this overlapping demand will crowd out clean-energy deployment or instead help catalyse supply-chain expansion is now a central question for industrial and innovation policy.

Global military expenditure reached an all-time high of USD 2.7 trillion in 2024—a 9% year-on-year increase, with particularly sharp rises in Europe, the Middle East, and East Asia (Liang et al. 2025). In parallel, the AI boom is driving unprecedented growth in demand for data-centre capacity and high-performance computing. In the United States alone, AI-related capital investment reached USD 67 billion in 2023, and the International Energy Agency projects that by 2030, data-centre growth could account for over 10% of current global gallium demand, and material shares above 2% for high-purity silicon, copper, and select rare earths (IEA 2025a; Zentner 2025).

The mineral overlap between these sectors is significant. AI hardware relies on gallium, germanium, tellurium, and high-purity silicon for chips, photonics, and power management (IEA 2025a). Defence systems—from precision-guided missiles to radar and electrified platforms—are intensive users of rare earth magnets (especially dysprosium and terbium), gallium-based semiconductors, titanium alloys, and tungsten (Clavilier 2025). These are not hypothetical risks: in 2024, the U.S. Department of Defence renewed funding to expand domestic rare earth separation capacity (IEA 2025b), and NATO's new supply-chain roadmap identifies stockpiling and recycling of critical materials as a strategic priority (North Atlantic Treaty Organization 2025).

The risk of crowding out is threefold. First, there is the price and availability channel: increased demand from sectors with higher willingness to pay could raise prices and tighten supply for clean-energy firms (other things being equal), especially in thin markets like gallium or heavy rare earths. Second, there is the allocation channel: defence procurement often secures long-term supply contracts or strategic reserves, absorbing capacity before civilian buyers enter the market. Third, there is the policy channel: export controls and national-security carve-outs—such as China's restrictions on gallium and germanium—can create segmented markets that raise transaction costs and limit supply-chain coordination.

But there are also pathways for crowding in. High-value, state-backed demand can reduce risk and improve project bankability, unlocking investment in refining and recycling infrastructure. Defence procurement and AI server demand are already driving non-Chinese rare earth and gallium processing projects in the U.S., Australia, and the EU (North Atlantic Treaty Organization 2023). Technological spillovers also matter: gallium nitride (GaN) chips developed for military radar are now used to improve efficiency in EV inverters (Oncea 2025; Rahman et al. 2024). Similarly, defence logistics chains—often required to maintain traceability—can pioneer data standards and recovery systems that are later applied to civilian recycling efforts.

Whether the AI and defence booms end up crowding out or crowding in clean-energy supply chains depends not just on how much demand they generate, but on how that demand intersects with existing supply constraints and policy choices. Materials like gallium, dysprosium, and high-purity silicon are already under pressure due to limited refining capacity and geographic concentration, particularly in China, making them highly susceptible to bottlenecks. Others, such as lithium, are less affected because they are not heavily used in AI or defence applications.

The implications for innovation are complex but potentially positive. Strategic defence and AI investments can catalyse process innovation, help scale substitute materials, and create stable offtake for refining and recycling capacity. But unmanaged, they also risk diverting scarce inputs, raising prices, and slowing energy transition deployment. Monitoring and governance of cross-sector material flows—particularly for gallium, dysprosium, terbium, high-purity silicon, and cobalt—will be crucial in the years ahead. The challenge is not just to expand supply, but to ensure it flows toward technologies that meet both climate and security goals. Ultimately, policy coordination will determine whether this overlapping demand leads to competition or complementarity. Joint procurement mechanisms, shared refining infrastructure, and clear reserve-release protocols could help ensure that new supply benefits multiple sectors, including clean energy, rather than being locked into siloed or security-first channels.

3 Focus Area: Mining Exploration and Mining Operations

Meeting future demand for CMs implies increasing the supply of minerals. Technological innovation is key 1) to increase the volume of extracted minerals by either discovering new deposits, opening new mines, and reducing the costs of mining production, but also 2) to limit supply disruptions induced by accidents, natural hazards, and increasing regulations on environmental and social issues. In this section, we discuss innovation along the first part of the CM value chain: Mining and Processing, which encompasses the stages of exploration, extraction, processing and refining and transportation.

3.1 Characteristics of Innovation in the Mining Industry

Although economically smaller than the oil and gas industry, the mining industry[7] is a large and global industry. It is often perceived as a conservative sector, sharing more similarities with low-tech manufacturing industries (such as textiles) than with high-tech sectors like pharmaceuticals or ICT. While research on technological innovation in mining remains limited, a number of key characteristics have been identified (Calzada Olvera 2022; Filippou and King 2011; Humphreys 2020; Sánchez and Hartlieb 2020).

First, minerals are homogeneous commodities – zinc, copper, etc – offering little scope for product differentiation. As a result, most innovation in the mining industry is aimed at reducing operational costs. Second, innovation in mining is characterised by long time-lags, implying that technological change tends to be more incremental than disruptive. Exploration and permit processing are lengthy processes, and it is difficult to retrofit and upgrade existing mines once they are in operation. Technological change is typically implemented when new mines come into operation (Filippou and King 2011). Third, innovation fluctuates with commodity prices super-cycles affecting profitability.[8] Mining companies are price-takers[9] and commodity prices reflect global supply and demand traded on international exchanges (e.g NYMEX or the London Metal Exchange). Using patent data over 1991-2015, Valacchi et al. (2023) find that high commodity prices during boom periods stimulate innovation in the mining sector, while downturns are associated with reduced patenting activity, with long-term price cycles exerting a stronger influence than short-term fluctuations. They also find that countries with a large mining sector (e.g. Australia, South Africa) innovate a lot but tend to be less reactive to commodity price variations, possibly due to the larger role of the government in the mining industry in these countries.

A fourth characteristic of innovation in the mining industry is the diversity of actors involved. Exploration activities are typically undertaken by small specialised companies – so-called 'juniors' (ca 2'500 firms worldwide) – whose principal activity is to prospect and assess the feasibility of mineral deposits. These companies typically work together with universities and public research laboratories via consortia and public-private partnerships. Next to juniors, the core of the industry is the hands of 150 global 'majors' companies whose main activity is mining production focused on extraction and processing at the mining

7. When describing the mining industry, we focus on the exploration and extraction of 'hard' non-energy minerals, which excludes the oil and gas industry, as well as coal and uranium extraction.

8. Commodity prices are highly volatile and characterised by "super-cycles", i.e. long-term cycles where long 'booms' during which commodity prices rise above their long-time trend for 10-30 years alternate with long 'busts' of low prices. Upcycles are driven by structural changes affecting the demand for minerals (e.g. industrialisation of China). The high prices are sustained over long periods as it takes time before supply via the opening of new mines can be ramped up to meet the rising demand. By the time mining production has sufficiently expanded, demand growth may already be slowing, leading to overcapacity and long periods of lower prices.

9. By contrast to the fossil fuel industry, they do not typically hold a significant enough market share of the global supply to be able to influence prices.

site.[10] Since the 1990s, large mining corporations have become increasingly prone to innovate through the adoption of technologies developed by third parties, rather than to develop in-house solutions (Daly et al. 2019; Humphreys 2020; Sánchez and Hartlieb 2020). This explains that today, the most important actors along the innovation mining supply chain are the so-called 'Mining Equipment Technology and Services' (METS) companies, which supply the major companies with innovative technologies. As these firms are very diversified, the size of the METS sector is difficult to assess. Finally, and also due to the increasing role of METS firms, although mines tend to be located in developing countries, firms' R&D laboratories are situated in developed countries.

These characteristics help to inform the development of metrics aiming to assess technological innovation in mining. Accordingly, focusing only on innovation from the large majors or from mining countries would tend to underestimate the technological intensity of the sector. Indeed, only 0.4% of mining firms file patents and the industry spends only 0.5% of total revenues on R&D expenditures (compared to respectively 6% and 25% for the pharmaceutical and ICT sectors) (Daly et al. 2019; Sánchez and Hartlieb 2020). Avoiding this caveat, the *WIPO Mining Dataset* is to our knowledge the only database aiming to measure innovation in mining using patents along the various steps of the mining supply chain (Daly et al. 2019; Valacchi et al. 2023).[11] Descriptive analysis on the *WIPO Mining Dataset* shows that over the 1991-2015 period, innovation in mining technologies accounted for about 2% of total patents worldwide. After declining over the 1990s and early 2000s, the share of mining patents almost doubled between 2004 and 2013, with a slight fall since 2013. Mining extraction, exploration and refining are the largest subsectors of mining technologies, representing respectively 31%, 25% and 19% of all mining patents. Other subsectors include patents related to environmental issues (12%), transport (6%), processing (5%), metallurgy (1%), blasting (0.6%) and automation (0.2%). Analysing the geography of patenting activities of mining firms, the data show – as expected – no overlap between the distribution of countries active in mining technologies and typical mining production countries. China and the US, and to a smaller extent Australia and Canada, are leading countries in both mining innovation and production. The Russian Federation, Brazil, Chile or South Africa, on the contrary, are relatively strong in mining production, but file relatively small numbers of patents. Japan, the Republic of Korea and European countries such as Switzerland and Germany, finally, score relatively high in mining patenting activities despite not being active in mining operations (Daly et al. 2022; Valacchi et al. 2023).

10. Next to these majors, there are also a large number of smaller companies and artisanal and small scale miners (ASMs) operating on a much smaller scale (i.e. a single mine or a specific commodity) but these tend to be low-tech operators that represent only a very small share of global mineral production.

11. The methodology combines a patent search based on both[12] 1) technological information from patents, relying on IPC classes (e.g. including the 'E21'(Earth or rock drilling; Mining) IPC or CPC class, but also excluding other IPC classes in pharmaceutical or defense (see Appendix E in (Daly et al. 2019)) combined with a specific set of keywords (see Appendix D in (Daly et al. 2019)), 2) a list of mining and most importantly METS firms borrowed from patent offices in Chile, Brazil, Australia, Canada and the US and from the Orbis database.

3.2 Innovations in Mining Exploration

CMs are not physically scarce, and there is evidence that these minerals are abundant in the Earth's crust in various parts of the world beyond current extraction sites (Meinert et al. 2016). Yet, not all deposits have been discovered and among known deposits not all are economically viable.[13] Hence, the first stage of the mining process is exploration and discovery. Exploration activities consist in identifying relevant geological deposits, analysing geophysical surveys, undertaking initial on-the-ground chemical analyses, drill testing and feasibility studies (Jébrak 2012). Exploration activities are not typically included in R&D expenditures, despite being risky and knowledge-intensive and thus sharing many similarities with R&D processes (Upstill and Hall 2006). Data on exploration expenditures exist, but are not ideal, as these also include non-innovation expenditures. Progress in exploration research can best be assessed via scientific publications, number of research partnerships and consortia, announcements of new deposits discovery, and venture capital data and funding raised by junior companies.[14]

The exploration of new CMs deposits is confronted with an increasing number of challenges. As the easy deposits have already been depleted, mineral exploration is increasingly shifting to more challenging environments where rocks may be more deeply buried or in newly unexplored areas (e.g. deep-sea, space, Arctic), requiring specific technologies. There is also evidence that the productivity of exploration spending is declining over time – e.g. the cost of discovering a tone of base metals has doubled since the 1980s[16]). There is thus much hope that novel advanced technologies in mining exploration able to target and assess deposits in challenging environments but also to organize the exploration in cost-effective ways can help alleviate some of these concerns. The following technological areas will be particularly important for the exploration of new CMs deposits.

Big Data and AI for Improved Geological Modelling Discovering new deposits typically involves analysing and integrating large volumes of geological data into advanced geological models. Over the last decade, the increasing availability of geological, geochemical and geophysical data is transforming mining exploration towards the big data domain (Yang et al. 2024). Recent advancements in data processing and 3D visualisation, enabled by artificial intelligence (AI), offer particularly promising opportunities. AI integration can enhance geological mapping beyond the capabilities of current GIS systems by enabling the interpretation of complex, multi-scale geological structures. Machine learning algorithms make it possible to automatically uncover hidden patterns in geological data and to improve the classification of mineral structures, thereby advancing Mineral Prospectivity Mapping (MPM) — the prediction of the location and potential scale of mineral deposits. In addition, core logging (the systematic analysis of drill core samples) can benefit from AI-driven automation, improving both the speed, efficiency and consistency of

13. In natural resources economics, the concept of 'reserves' is used for known resources that can be profitably extracted at current prices. Reserves are thus not finite and evolve over time depending on price fluctuations.

14. As banks do not typically lend to risky exploration activities of juniors, exploration companies typically have to raise finance in stock markets (mostly in Toronto, Sydney and London stock exchanges) and via venture capital finance. [15]

16. https://www.bcg.com/publications/2015/metals-mining-sustainability-tackling-the-crisis-in-mineral-exploration

data interpretation.[17]

Deep Exploration Techniques There is an increasing interest in 'deep' exploration techniques, i.e. with the ability to 'see' more deeply into the Earth's crust or through opaque layers, providing data on rock type and structure. There are several broad categories of methods typically used for deep exploration and reviewed in detail in Durrheim et al. (2022):

- Magnetic method. This method is commonly used for geological mapping, as ore bodies have magnetic signatures which can be captured by airborne or ground surveys.
- Gravity method. This method is used to map the density contrast in rocks and structures using satellite, airborne and regional ground surveys.
- Induced polarisation (IP) methods. These methods are used to explore for conductive minerals using electrodes that inject current into the earth; hence, surveys are conducted on the ground or in boreholes.
- Seismic and magnetotelluric (MT) methods. These methods are used to map gross geological structure and explore for conductive minerals using signals from seismic energy and electrical fields.

Once identified, deposits need to be evaluated. This requires rock sampling, core drilling and testing for geophysical and geochemical properties. Testing can be done in situ or in the laboratory. A number of public-private consortia, such as the EU Smart Exploration consortia or Australia's Deep Earth Imaging Future Science Platform, have been recently created to develop further deep exploration (Durrheim et al. 2022). These innovative methods will also be used in the new Inventory of France's Subsurface Mineral Resources (IRM - Inventaire des Ressources Minérales), which is overseen by the French Geological Survey [Bureau de recherches géologiques et minières, BRGM] and will span five regions in metropolitan France and French Guiana over the course of a five-year program valued at €53 million[18].

Remote Sensing Technologies The deep exploration methods previously mentioned can greatly benefit from advances in remote sensing technologies, making it increasingly easier to map rugged or difficult-to-access terrain. Remote sensing technologies present the additional advantage of being labour-saving thanks to unmanned operation, e.g. unmanned aerial vehicle (UAV)-based exploration. Shirmard et al. (2022) review the improvement of remote sensing data acquired from satellites, airborne- and ground-based instruments for exploration activities. Optical sensors and radar sensing systems measure the intensity of the electromagnetic spectrum. Airborne data are collected using aeroplanes and drones with improved sensors. On the ground, specialised cameras and scanners can be used for capturing pictures of very high resolution, capturing real-time conditions, for instance, under different solar lights.

17. While several studies have sought to measure AI- and big-data-related innovation through patent analysis (Andres et al. 2022; Van Roy et al. 2019; WIPO 2019), the patent classification system used by Daly et al. (2019) for mining exploration would need to be refined to distinguish patents related to these technologies.

18. See: https://www.brgm.fr/en/news/press-release/new-programme-identify-french-mineral-resources

Unexplored Areas: Deep-sea, Arctic, Space Future rising demand for minerals may require exploration of new challenging environments, such as deep-sea, the Arctic or even space. Guo et al. (2023) presents the potential provided by deep-sea minerals, with many exploration areas of polymetallic nodules in the Eastern Pacific, Peruvian Basin and the Northern Indian Ocean Centre. Cobalt deposits instead are concentrated in the West and Central Pacific, while polymetallic sulfides are around mid-ocean ridges and volcanic zones. At present, deep-seabed mining remains in the exploratory stage. Although initial trials of deep-sea mineral exploration began in the late 1970s, interest in the field has grown significantly over the past decade, as reflected in the increasing number of scientific publications on the subject (Guo et al. 2023). While many of the technologies for exploration are similar to on the ground exploration for identification of deposits (using gravity, seismic, magnetic, and electrical exploration) and evaluation of the deposits (in-situ testing, laboratory testing), they require to be adapted to the challenges of the maritime environment including high-pressure, low temperature and complex marine geology (Guo et al. 2023; Shipping 2020). Other challenging environments such as the Artic or space (Fleming et al. 2023) will also require specific technologies. In all cases, the role of autonomous equipment and remote sensing technologies with limited human intervention will be particularly important for the exploration of these harsh environments. Finally, more research is needed to better understand the potential environmental impacts of deep-sea mining.

Digitisation Technologies to Improve the Organisation of Exploration At last, digitisation and ICT technologies can help improve the efficiency of the organisation of the exploration. There is hope that data-driven approaches can help speed up and facilitate the administration of mining claims, as well as the collection and processing of information related to the granting of permits. Innovations in exploration organisations remain, however, poorly documented.

3.3 Innovations in Mining Operations

3.3.1 Innovations to Increase the Productivity of Mining Operations

After the exploration phase, the next steps involve planning the mining site, securing the necessary authorisations and permits, and preparing for the start of production. Once the mine becomes operational, mining production proceeds through several key stages: extraction, transportation, processing, and refining of minerals. Because the final product is typically highly uniform, most technological advancements focus on reducing costs and increasing productivity —- measured as the output per unit of input—at each stage of production. Yet, there is evidence that the productivity of mining has recently been decreasing possibly induced by a combination of factors (Humphreys 2020) including 1) the decline in the quality of ore grades[19], 2) limits in scale economies as mines are reaching their maximum operation limits and it will be difficult to further extend existing mine sites and 3) increasing disruptions in mining operation due to labor strikes, accidents and natural hazards (earthquakes, flooding). There is much hope that innovation can contribute

19. Over the last 25 years, ore grades of copper and gold have declined globally by 20 and 15% respectively[20])

to reverse the currently observed decreasing productivity of mining and enhance efficiency by lowering the use of expensive inputs (capital, labour, energy and water), recovering more minerals from mined material (e.g. mine tailings) and limiting supply disruptions at the mining site.

Patent data from the *WIPO Mining Database* indicate that since the 1990s, technological innovations in exploration, extraction, and transport have steadily increased, while innovations in processing and refining have declined. Specifically, the share of mining patents related to processing and refining fell from 25% in the early 1990s to 19% by 2015 (Valacchi et al. 2023). This trend may be partly driven by the declining quality of ore grades, which has made expanded exploration more economically attractive. Simultaneously, advances in transport technologies have reduced the costs of accessing more remote mining sites. Yet, processing and refining technologies are likely to gain increasing importance in the coming years. China currently dominates this stage of the mineral value chain, having invested heavily over recent decades in large-scale refining facilities strategically located near port infrastructure. Many countries now ship minerals to China for low-cost refining and China refines 68% of global nickel, 40% of copper, 59% of lithium and 73% of cobalt (Brookings Institution 2022). Geopolitical concerns could thus make improvements in processing and refining more profitable in the future. Moreover, as processing and refining are highly polluting activities, further innovation will be essential to mitigate their environmental impact and to lower the costs associated with increasingly stringent environmental regulations (see Section 3.3.2).

Incremental Innovation in Mining Operations Incremental innovation in mining technologies has been an important factor behind the surge in mineral production over the last century. Making mining machinery and processes more efficient allows for savings on input costs. We briefly describe below examples of incremental innovation for each stage of mining production.

- *Extraction technologies*: Extraction involves technologies related to drilling, blasting, excavation and tunnelling. These technologies vary significantly depending on the type of mine, surface or underground, and continuous incremental innovations have played a major role in improving mining productivity. Drilling technologies, for example, have seen remarkable progress over the past century, with drilling speeds increasing from just 3–5 meters per hour in 1900 to 450 meters per hour by 2005 (Humphreys 2020).

- *Transportation technologies:* Transport of minerals takes place both within the mining area – via conveyor belts or road transport from the mine surface to a storage or processing area – and outside the mine using road, rail and sea transport to the destination country. While the largest hauling truck for mining had a carrying capacity of 27 tons in the 1960s, the largest truck today can carry more than 500 tons of raw materials (Humphreys 2020). A main goal of transport innovation in the mining sector is to raise efficiency through cost reduction, increased operation (e.g. allowing 24/7 operations) or distance reduction (e.g new building techniques for viaducts allowing higher loads) (Dionori and

Zehtabchi 2022). The share of transport innovation in total mining patents rose from 2% in the early 1990s to 6% today, likely induced by the high commodity price cycle since the early 2000s and the rise of ICT technologies (Dionori and Zehtabchi 2022).

- *Processing and refining:* After leaving the mine surface, ores must undergo a process of separating the grains of ore minerals from worthless gangue, which aims to increase the ore concentration and remove impurities. Such processing and refining is needed to increase the final fraction of concentration of the desired mineral.[21] This typically involves three major steps (Balasubramanian 2015):

  1. Comminution: size reduction using crushers and grinding equipment to reduce large rocks into fine particles. Key machinery includes, for instance, high-pressure grinding rolls or vertical roller mills.
  2. Beneficiation (physical separation): This separation takes place through processes of gravity separation, froth flotation, magnetic separation, or electrostatic separation.
  3. Chemical treatment (leaching): Processes of hydrometallurgical treatment and leaching operations help increase the final concentration of the mineral through the use of chemical solvents.

  Productivity increases can be gained by advancing innovation to improve each of these processes. Examples include advanced ore sorting, crushing and grinding or the reduced use of expensive chemicals and solvents.

Intelligent and Smart Mining There is much hope that the advent of 'Intelligent and Smart mining' through the deployment of digitisation and autonomous machinery and vehicles will help to boost productivity in the mining sector (Humphreys 2020). ICT and digital solutions can be applied to a large range of mining operations. Examples include wireless initiating systems for blasting, 3D software to predict blast movement, digital solutions to monitor haul roads and improve transport logistics, optimisation of processing flows, monitoring and optimisation of close-loop systems (e.g. transport, water recovery), etc. Innovation in automation and robotics is expected to increasingly contribute to reducing labour and safety costs. Automated machines, autonomous haulage trucks, and driverless trains are all technologies that reduce the need for on-site personnel, which presents the advantage of lower labour costs and fewer disruptions induced by workers' accidents and strikes. Sensors, drones, and cameras can facilitate remote monitoring and site inspections, reducing health and safety risks and thus enhancing the social performance of mines (see Section 3.3.2. Future developments in AI-integration and Internet of Things (IoT) will help integrate digital data with automation and provide opportunities to further optimise mining operations (Corrigan and Ikonnikova 2024).

21. Not all steps of processing and refining take place at the mining site. Minerals can be shipped internationally for further processing and chemical refining, transforming the minerals into fine particles with high purity levels to make them suitable for use in manufactured products.

Innovations in Natural Hazard and Climate Risk Management Natural hazards (e.g. earthquakes) and extreme events induced by climate change (droughts, wildfires, flooding, hurricanes) can disrupt extraction activities and increase the costs of mining operations (Odell et al. 2018). Several types of innovation can help alleviate these concerns, such as monitoring technologies – sensors, weather and climate data to better assess potential risks – and structural innovations including reinforced tailings dams and climate adaptation technologies (e.g. ventilation and cooling systems against heat-stress in underground mining operation, water management systems) (International Council on Mining and Metals (ICMM) 2019).

Recovery and Reprocessing of Mine Tailings Increasing demand for minerals in energy technologies has led to a re-evaluation of the financial feasibility of recovering minerals from mine tailings as a potential new source of supply (IEA 2025b). Tailings are typical mining waste that are composed of a mixture of non-economical crushed rock and other fluids generated during mineral processing. Processing mine tailings presents specific challenges due to the variety of particle sizes, but also due to exposure to weather, which can cause significant oxidation of minerals. Hence, while the various processing steps remain similar to those of ores, the types of technologies used within each of the sub-processes may be different. Whitworth et al. (2022) reviews in particular the role of advanced attrition-based comminution (critical for surface cleaning and improved flotation), modern classification techniques for better separation, emerging flotation technologies extending the range of particle sizes that can be processed, and cost-effective gravity and magnetic separation technologies.

3.3.2 Innovations to Improve the Environmental and Social Performance of Mining Operations

There is mounting evidence on the adverse impacts of mining on the local environment. The extraction of minerals is associated with various environmental issues such as air pollution, local contamination by toxic chemicals, landscape disruption, biodiversity loss and waste generation (Sengupta 2021). The excavation, grinding of ore and transport of material by large diesel trucks is land-, energy- and emissions-intensive, and mining waste and tailings may cause contamination of local water and soil, leading to adverse health effects for the exposed population. In addition, mining activities are associated with a host of negative social and governance impacts with severe implications for the livelihoods of communities in the vicinity of mines, including violation of labor and safety rights, displacement of local population due to contamination and land degradation, violation of indigeneous people lands rights, and contribution to armed conflicts. Rising concerns about the adverse impacts of mining may lead to increasing environmental and cleanup costs for the mining industry, faced with increasingly stringent environmental and social regulations. These issues highlight the importance of responsible mining (Maier et al. 2014) and the potential role of innovation in achieving it (Fernández et al. 2025).

The *WIPO Mining Database* provides a classification of mining technologies aiming to mitigate environmental impacts. Using classifications for patents in clean technologies (Y02) developed by the European Patent Office, the WIPO database identifies the subset of 'clean' mining patents at the intersection of these two search strategies combining IPC/CPC classifications with keywords in the patents title and abstract.[22] Accordingly, these patents cover the following categories: 1) reclamation of mining areas, 2) treatment of wastewater, 3) treatment of soil, 4) waste disposal, 5) clean technologies related to mineral and metal processing, 6) protection against radiation, and 7) other general environmental patents.[23]. Accordingly, patents related to clean mining technologies account for about 15% of all mining patents; this share has been relatively stable over the 1990-2015 period. Interestingly, top-inventor countries are Japan, South Korea and Austria, which are not major mining countries. This reflects the important role of METS companies supplying major mining companies. Australia, Brazil and Canada do appear in the top-10 innovative countries.

Environmental and social regulations imposed by the government drive innovations aimed at improving the environmental and social performance of mining operations. There is a lot of empirical evidence in the literature on how well-designed environmental policies can contribute to fostering clean innovation, as measured by patents, in a large range of sectors. For the mining industry, Andersen and Noailly (2022) estimate how the stringency of environmental regulations is associated with patents in clean mining technologies at the country level, controlling for GDP, mining exports, mineral rents and mineral prices. They find that a 1% increase in the growth rate of the OECD Environmental Policy Stringency (EPS) index is associated with a 0.3-0.45 percent increase in clean mining patents, with environmental standards having a larger impact that market-based instruments. Yet, the analysis relates patents to domestic environmental regulations, while in practice, mining activities tend to be concentrated in developing countries with weak environmental and social institutions. More likely, foreign METS firms are important technology providers to domestic mining corporations, and future empirical analysis should aim to identify the links between major companies and their suppliers.

Environmental and social impacts are present at each stage of mining operations, from mine planning, extraction, transport, processing and refining of minerals, but also mine closure. We classify technologies based on the environmental and social concerns that they aim to address.

Innovations to Mitigate Land Use Impacts Mining activities often take place on large areas, putting pressure on local ecosystems and disrupting landscapes. This can result in deforestation and biodiversity loss through habitat destruction, fragmentation and pollution. In addition, the indirect impact of mining infrastructure (roads, pipelines) can lead to broader ecological damages beyond the mining site (Sonter et al. 2018). Technologies related to biodiversity mapping and improved integration of geospatial, soil measurement, and biodiversity data can help improve modelling techniques for Environmental Impact

22. For the detailed patent classification, see Table 6.1 in Andersen and Noailly (2022)

23. Some of the patent classifications for clean mining in Andersen and Noailly (2022) are very broad (e.g. other general environmental patents) and a more refined analysis of the full text of patents could provide more refined and granular data and help to disentangle specific (e.g. energy or water-saving) technologies.

Assessments used to predict mining impacts. In addition, remote sensing technologies can help identify areas most at risk of biodiversity loss, and could be used to monitor habitat and land-use change over time, for instance via cameras, sensors, drones and satellite imagery.

Landscape disruption from waste disposal is an additional major concern from extractive activities generating open pits, mine tailings and waste rock. A key technology to minimise surface impacts is in-situ leaching, which consists of injecting chemical solutions to dissolve minerals underground, although this runs the risk of contamination of groundwater if not properly managed. The technology avoids open-pit or underground mines, leading to energy savings, lower emissions and reduced water consumption. Other technologies can help to reduce surface mine tailings by storing them underground.

Innovations to Reduce Air, Soil and Water Pollution Mining is one of the most energy-intensive industries, and primary metal and mineral production is responsible for about 10% of global energy-related GHG. Hence, integrating renewable energy into mining operations is critical (Igogo et al. 2021). Currently, most of the exploration, extraction, transport, processing and refining rely on fossil fuel, such as diesel, heavy oils and coal. Solar PV, wind, hydropower, geothermal, and battery storage systems can help reduce emissions from, for instance, drilling machines, heat processing, ventilation systems and electrochemical processes. Hydrogen can also have many uses in the mining industry to generate high-temperature heat, power, fuel for transportation and energy storage. Yet, scaling up renewable energy technologies for electrifying mining operations faces important challenges, notably due to the remoteness of mining sites, high capital costs and lower performance due to intermittency issues. A major source of air pollution and GHG emissions comes from mining haul trucks. Potential innovative solutions include battery-electric trucks and hydrogen fuel-cell vehicles, which are at the commercial stage. Yet, major challenges remain to create the appropriate on-site infrastructure, including charging infrastructure (with a need to standardise components so that haul trucks from different suppliers can use the same charging stations). Some of these developments have now reached the pilot plan stages.

Finally, refining is the most energy/electricity-intensive segment of mineral production, leading to high levels of GHG, and several innovations have the potential to reduce the energy use of refining. Examples include novel synthetic graphite, which uses the resistance of the carbon material itself to convert electric energy into heat energy, helping to substantially reduce energy consumption. Induction furnaces could also be used to refine graphite in shorter times than regular furnaces (IEA 2025b).

Soil and water pollution are pervasive in extraction processes, resulting in acid mine drainage and the use of toxic chemicals for processing and refining. Innovation in bio-leaching (using microorganisms to extract metal from ores) can help reduce both the amount of chemical pollution and energy consumption. Technologies to reprocess mine wastes could also mitigate environmental risks from acid mine drainage, while technologies such as phytomining and phytoremediatation -– which consists in using plants with specific properties for metal accumulation – could reduce the need for chemically intensive extraction of some metals, improve biodiversity and facilitate rehabilitation of mine sites, although challenges are currently associated with upscaling these technologies (Sonter et al. 2018). Finally, technologies for wastewater treatment and closed-loop water systems to minimise contaminated discharges help address water pollution issues. Dry stack tailings, consisting of dewatering mine tailings, help both to save on water consumption and to avoid water contamination.

Improving Livelihoods around Mining Sites Mining communities often face environmental degradation and economic dependency on a single industry. These problems can lead to social unrest and loss of livelihoods. Community-based business models can diversify the economy and create sustainable job opportunities. The development of stonemeal technology can help link the mining and neighbouring agricultural sectors, thereby improving the livelihood of nearby communities. This technology uses mineral sources (crushed rock) to remineralise leached agricultural soil, so that by-products generated by mining can be used for agricultural purposes. These soil reminilizers are compatible with agroecology and organic farming, offering an alternative to chemical practices (Theodoro et al. 2022).

Internet of Things (IoT) for Environmental and Safety Monitoring As discussed previously, future developments in IoT-related technologies can improve the monitoring and inspection of mining sites to track environmental, safety and health-related risks (Pincheira et al. 2022). Measures and observations carried out with remote sensing technologies can be automatically transferred to an IT system to obtain the inspection result. Integration within a blockchain system can also improve the transparency and traceability of the measurement.

Blockchain-enabled Certification for Sustainable Mining Environmental and social challenges in the mining industry create inherent investment risks that are closely scrutinised by investors and policymakers. In response, the industry has become increasingly proactive in developing and implementing innovative practices to improve Environmental, Social, and Governance (ESG) performance across CM supply chains.

One emerging solution is blockchain-enabled certification, which enhances transparency and data integrity for ESG reporting. Blockchain technology is a type of distributed ledger technology (DLT) where data on environmental and social governance is recorded at various stages of the supply chain. Sealed containers of minerals are marked with a unique identifier (ID), which includes details such as mineral quality, composition and environmental and social considerations. This ID is linked to a unique digital token recorded on the blockchain, allowing the minerals to be digitally tracked throughout the supply chain, with updates entered manually at key points. Recording ESG performance data on a blockchain provides a high degree of transparency and security, which is particularly valuable in regions with weak governance and limited regulatory enforcement.

Blockchain-enabled certification is being piloted in the mining industry through various projects and industry initiatives. New business models are emerging from startup companies offering "certification-as-a-service" through blockchain platforms. However, challenges remain in scaling these solutions and ensuring verification, interoperability, standardisation of blockchain platforms, and managing their environmental impacts (Onifade et al. 2024).

In summary, a large range of technologies and new types of business models are needed to reduce the environmental and social footprint of mining activities. Most innovation in this domain is still in early stages of development. Yet, it will be particularly challenging to open mines that meet the current environmental and safety standards of developed economies, without massive investments in innovation.

4 Focus Area: Rare-Earths (REs) Magnets for Electric Motors and Generators

Rare earth elements (REEs)—particularly neodymium, praseodymium, and dysprosium—are essential to the development of high-efficiency clean energy technologies. REs comprise the group of 17 lanthanide metals and are divided into light RE (LREEs) and heavy RE (HREEs). These elements are critical in producing neodymium-iron-boron (NdFeB) permanent magnets, which are widely used in motors and generators for electric vehicle (EV) and wind turbines.[24] Under the net-zero emission scenario from the International Energy Agency, RE demand from clean energy will rise sevenfold between 2020 and 2040 (IEA 2024a). The global demand for NdFeB magnets (125'000 tons/year in 2019) is predicted to double by 2030. US imports for neodymium-iron-boron (NdFeB) magnets have already increased by over 400% between 2000 and 2021 (Gagarin and Eggert 2023).

However, global access to REs is currently constrained by extreme geographic concentration as China dominates every stage of the supply chain. China produces about 60% of mined rare earths and controls nearly 90% of global separation and refining capacity of rare earths. Even in countries with domestic mining activity, such as the United States and Australia, intermediate processing and refining depend on Chinese facilities. China is also a leading manufacturer of alloy and magnet manufacturing, accounting for over 90% of permanent magnet production (Smith et al. 2022). At last, China also holds a dominant position in downstream technologies such as EVs and wind turbines, reinforcing its strategic position through vertical integration.

This concentration creates significant supply chain vulnerabilities, especially for countries that rely heavily on imports. These risks are exacerbated by China's history of using rare earth exports as a geopolitical tool. In 2010, a maritime dispute led to a temporary halt in RE exports to Japan, which severely impacted Japanese manufacturers such as Hitachi and Mitsubishi. RE prices increased by over 3000% in 2010-2011 following the announcement of drastically reduced Chinese export quotas, prompting widespread concern

24. Beyond energy technologies, RE magnets are also used in products like hard disk drives, electric bicycles, air conditioning systems, and audio equipment.

among Western nations (Smith and Eggert 2018). More recently, in December 2023, China imposed new restrictions on the export of RE magnet manufacturing technologies, including those related to ore separation and high-purity processing.[25] Despite growing efforts to diversify sourcing and scale up domestic capabilities, alternative supply chains remain underdeveloped. This section maps the innovation landscape for the RE supply chain, ranging from technologies for RE extraction and processing, to innovation aiming at substituting the use of RE in permanent magnets, or into substituting wind and EV components, but also at finding ways to recover RE through re-use and recycling.

4.1 Innovations to improve REs Extraction and Processing

The extraction and processing of RE present specific challenges due to their complex mineralogy, chemical properties and small particle sizes. We review key emerging innovations for processing and sourcing REs.

Novel RE processing technologies Suli et al. (2017) provides an overview of the specific processing and refining technologies used for REs, including ion exchange, but also emerging techniques such as supercritical fluid extraction, electrowinning and biosorption. A main challenge specific to RE is that separating individual RE is rendered difficult by their occurrence as a mixture of elements with mineral deposits, and especially due to their similar chemical properties. Solvent extraction is the predominant commercial process but it uses a lot of energy, creates significant waste (particularly in the absence of specific recycling of the aqueous and organic phases), leading to significant environmental and health risks. A few novel approaches are emerging, such as selective precipitation, selective crystallisation, selective dissolution, the application of efficient N-heterocycle-based extractants in solvent extraction processes, and dual-ligand separation systems (IEA 2025b). Yet, there is a need to bridge the gap between fundamental and applied research by implementing larger-scale demonstration projects.

Ionic Adsorption Clay A promising and cost-effective approach to rare-earth extraction is the development of Ionic Adsorption Clay (IAC) deposits, where recovery of rare earth elements is expected to be simpler, less energy-intensive, and more economical compared to extraction from deeper hard rock deposits. In situ leaching is typically used for IACs in Southern China. In recent years, there has been a steady stream of announcements regarding IAC discoveries outside China, particularly in Australia, Brazil, and Uganda. However, it remains uncertain whether these deposits can be developed at commercial scale (IEA 2025b).

Unconventional RE sources New technologies may help recover REs from other unconventional sources. REs could be recovered from mine tailings as these elements are often a by-product from other mined minerals. The US Department of Energy recently issued a call for bids for a Rare Earth Demonstration Facility for the extraction of REs from unconventional sources such as mine waste. Other sources of REs that

25. https://asia.nikkei.com/Economy/Trade/China-bans-exports-of-rare-earth-magnet-technologies

could be further exploited are extraction from coal combustion residues, geothermal fluids used for energy production and red mud (bauxite residue) generated from the production of alumina (Smith et al. 2022). To date, most of R&D on RE recovery from unconventional sources is at the stage of pilot plants. The US Department of Energy has recently started pilot-scale projects for the recovery of rare earths from coal and coal byproducts. In Europe, the Horizon 2020 program financed a recent project on extracting RE from fertiliser production processes, as phosphate rocks used to make fertiliser contain a small concentration of RE.

4.2 Innovations in Permanent Magnets

Permanent magnets – and in particular neodymium-iron-boron (NdFeB) magnets – are key to the production of wind turbines and EV motors. Discovered in 1984, NdFeB magnets are composed of the light rare earth elements (LREEs) neodymium (Nd) and praseodymium (Pr), along with heavy rare earth elements (HREEs) such as dysprosium (Dy) and terbium (Tb), which are added to enhance thermal resistance. NdFeB magnets offer a range of advantageous features for electric motors and generators: they deliver strong magnetic performance with high reliability (and thus low maintenance costs); they are efficient even at low or partial load conditions (e.g. low wind speeds); and they provide compact and lightweight design, which is ideal where space and weight are critical such as in EVs and offshore wind applications.

4.2.1 Material Efficiency

Improving material efficiency is a key strategy to reduce the rare earth content of NdFeB magnets. Some modern NdFeB magnets now contain around 20% rare earth elements by weight, down from approximately 30% in 2010–2012. Considerable effort has gone into reducing neodymium and praseodymium content while maintaining equivalent magnetic performance (Pavel et al. 2017; Pavel et al. 2016). Much of this efficiency has been achieved through microstructural optimisation. A central technology in this regard is grain boundary diffusion (GBD), which improves resistance to demagnetisation by modifying the grain boundaries of the magnet. This method gained widespread adoption after the 2010–2011 rare earth price spike, particularly to reduce the required amount of expensive HREEs like dysprosium (Smith and Eggert 2018). Although originally developed by Sumitomo Special Metals in 2002, GBD became commercially viable only after rare earth prices surged, providing strong incentives to save on dysprosium.

A second approach to reducing critical rare earth usage is substitution — developing alloys that replace scarce elements with more abundant or lower-cost alternatives. One such strategy involves increasing the proportion of praseodymium, which is chemically similar to neodymium but typically less expensive. Further technical advances have explored the substitution of Nd with more abundant rare-earth elements such as cerium (Ce) and lanthanum (La). While magnets based on these substitutions are approaching commercialisation, they currently exhibit lower magnetic performance compared to standard NdFeB. Research on substitution strategies involving Ce and La has been largely driven by Chinese research groups, as indicated by the volume of related scientific publications (Delette 2023).

Efforts have also focused on substituting HREEs, especially dysprosium (Dy), with alternative materials. Approaches include alloying Dy with iron (DyFe) or replacing Dy partially with terbium (Tb) to reduce its usage. These substitution efforts have been supported by advances in powder refinement technologies, which use finer grain sizes to enhance magnetic properties, and the Multi Main Phase (MMP) method, which involves designing magnets with several strong magnetic materials combined together to optimise performance and resource efficiency.

4.2.2 Magnets Substitution

Besides NdFeB magnets, another type of RE-based magnets is samarium-cobalt (SmCo), containing samarium, praseodymium and gadolinium, a main advantage being that they do not contain either neodymium or dysprosium. These SmCo magnets excel at extreme temperatures but have lower magnetic strength and are less strong than NdFeB magnets. Ultimately, developing magnets that are fully rare-earth free (RE-free) could significantly reduce the geopolitical risks associated with China's dominance in the rare-earth element supply chain. Currently, there are two commercially established types of RE-free permanent magnets: 1) ferrites (ceramic magnets made primarily of strontium iron oxide) and 2) Alnico magnets (composed of aluminium, nickel, cobalt, iron, copper, and titanium). However, these alternatives do not yet match the performance of NdFeB magnets—ferrites have lower magnetic strength, while Alnico magnets are more susceptible to demagnetisation. In recent years, research has increasingly focused on manganese-based alloy magnets as a promising RE-free option. While these materials show potential, their development is still in the early stages, with significant challenges (Cui et al. 2018).

4.3 Innovation in Wind Generators

Wind turbines typically consist of blades, a rotor, a gearbox to increase rotation speed (in some designs), and a generator that converts mechanical energy into electricity. In offshore wind turbines, the leading generator technology is the Direct-Drive Permanent Magnet Synchronous Generator (DD-PMSG). Those generators present the advantages of being used in direct-drive systems, which eliminate the need for a gearbox. This is possible thanks to the use of NdFeB magnets, which enable the generator to operate efficiently at low rotational speeds. The use of NdFeB magnets also contributes to a lighter, more compact, and reliable system with low maintenance costs. In 2020, almost all offshore wind turbines in the EU and approximately 72% of the globally deployed offshore wind turbines utilised generators with rare earth permanent magnets (Joint Research Centre 2023).[26] In the following, we only discuss turbine technologies relevant for future development in offshore applications.[27]

26. For onshore turbines installed in 2020, around 13% in the EU and 22% worldwide use permanent magnets.
27. We use the classification in Table 1 in Carrara et al. (2020)

4.3.1 Incremental Innovation in DD-PMSGs

Incremental innovations in the design of direct-drive permanent magnet synchronous generators (DD-PMSGs) can help reduce the reliance on rare earth elements. For example, optimising the cooling system can lower the operating temperature of the turbine, allowing the use of smaller or less rare-earth-intensive magnets. In 2017, Siemens introduced a heavy, rare-earth-free generator by redesigning the permanent magnets: although the new design required more neodymium, it eliminated the use of dysprosium and terbium (Pavel et al. 2017).

New technologies based on hybrid generator systems also offer potential reductions in rare-earth usage. By coupling a gearbox with a smaller permanent magnet generator, hybrid turbines require significantly less magnetic material. On average, hybrid-drive generators use permanent magnets that are approximately one-third the mass of those used in direct-drive systems. Direct-drive generators typically require around 17 t/GW of dysprosium and 180 t/GW of neodymium, whereas hybrid systems reduce these figures to 6 t/GW and 51 t/GW, respectively (Carrara et al. 2020). Although hybrid systems have lower manufacturing costs, they tend to incur higher maintenance costs compared to direct-drive configurations (Carrara et al. 2020).

4.3.2 Generators Substitution

Alternative technologies to Permanent Magnet Synchronous Generators (PMSGs) that use reduced amounts of rare earth elements, or none at all, are available. However, only a limited number are currently viable for offshore wind applications, where material costs and maintenance requirements are major concerns (Pavel et al. 2017). Notable options include Double-Fed Induction Generators (DFIGs), Squirrel Cage Induction Generators (SCIGs) with full converters, and direct-drive turbines utilising high-temperature superconductors (HTS).

Double-fed induction generators The double-fed induction generator is a well-established, rare-earth-free technology. However, it relies on a gearbox, which makes it less suited to offshore deployment due to higher maintenance demands. DFIGs are generally used in turbines with capacities ranging from 2 MW to 6 MW. While the technology is mature, its future offshore market potential will likely depend on the price trends of rare earth materials (Pavel et al. 2017).

Squirrel-cage induction generators SCIGs have been in use since the 1990s, and new designs with the introduction of a full converter between the electricity generator and transformer (e.g. Siemens NetConverter®) allow the SCIG to rotate freely at any speed (through a gearbox). Although SCIGs are less efficient than PMSGs, they offer the advantage of low maintenance and full rare-earth independence. A notable example is Siemens' 3.6 MW rare-earth-free offshore wind turbine, introduced in 2005. Current research aims to develop larger SCIG-based turbines suitable for offshore deployment.

Direct-drive turbines based on High-temperature superconductors (HTS) High-temperature superconductors are advanced materials capable of generating stronger magnetic fields than conventional permanent magnets, offering the potential for high-performance, lighter, and more compact wind turbine generators. This approach could significantly reduce or eliminate the need for rare earth elements like neodymium and dysprosium. However, HTS-based generators are still in the early stages of research and development and are not yet commercially viable.

4.4 Innovations in EV Motors

Another use of magnets is in motors. In this case, electrical energy is transformed into mechanical energy through a rotor, creating torque (rotational force). An important advantage of using permanent magnets in motors is that the very strong magnetic field allows for a light and compact motor design. This is important to reduce the weight of electric vehicles and is especially advantageous for hybrid models, with space restrictions to introduce two separate driving trains. There is also no need to use additional electricity to generate a magnetic field in the rotor. The rise of battery electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV) and hybrid vehicle vehicles (HEV) has led to the large deployment of the highly efficient Permanent Magnet Synchronous-traction Motor (PMSM) technology.

4.4.1 Incremental Innovation in PMSMs

There is some room for optimising PMSMs so that less magnetic materials are used. Successful approaches have tended to focus on hybrid motors such as Permanent Magnet-assisted Synchronous Reluctance Motors (PMSynRM), which tend to be more suited for mini and small electric cars (range lower than 299km) (Katona and Orosz 2024). An example of this type of motor technology is used in the BMW i3 electric vehicle, which uses about 30% less rare earths compared to PMSM (Pavel et al. 2016; Widmer et al. 2015). PMSM with low-cost magnets, such as ferrite or Alnico magnets, are still at the prototype stage. Software systems and improved motor designs have been essential to managing the trade-offs between minimal magnet material and motor performance.

4.4.2 Alternative motors

While there are alternatives to PMSMs, they all tend to be less efficient than PMSMs. Only a few have reached the stage of commercialisation, while others still face R&D challenges (Pavel et al. 2016; Podmiljšak et al. 2024). Even then, these solutions frequently require a lot of copper in the face of significant market pressures.

Asynchronous motors (ASM) - induction motors Asynchronous (Induction) motors contain no permanent magnets and work on the principle of induction, where electrical currents are induced in the rotor. A main disadvantage is that they are less efficient (92% efficiency compared to 96% for PMSMs

(Pavel 2016)), larger, heavier than PMSM and may become overheated (Pavel et al. 2016; Podmiljšak et al. 2024; Widmer et al. 2015). While these motors have reached commercialisation and were common in early Tesla models (Tesla S), they have become less adopted in modern EVs and are more used for specific industrial applications. Future research aiming to develop ASM with high rpm could be more promising once it passes the prototype stage.

Externally excited synchronous motor (EESM) motors EESM only differ from PSM in their rotor designs, as they use field windings rather than permanent magnets. The Renault Zoe is an example of a vehicle with an EESM. While these motors do not rely on rare earth, they tend to require more space and provide lower power density than PMSM. They have reached commercialisation stage.

Synchronous Reluctance Motors (SynRMs) Synchronous Reluctance Motors (SynRMs) in their version without permanent magnets (by contrast to PM-SynRMs) are an emerging promising solution, although they still face challenges in terms of dynamic performance (speed control) (Podmiljšak et al. 2024). They have reached early commercialisation stage.

Switched Reluctance Motors (SRMs) SRM rare earths free motors could be an alternative for PMSM, but more R&D is needed to increase efficiency and reduce acoustic noise before it could become widespread in EV production (Pavel et al. 2016; Podmiljšak et al. 2024).

Advanced designs While conventional motors are radial flux motors, new advanced motor designs consider changing the axis of the flux of the magnetic field, which can provide advantages in terms of cooling and material costs. The transversal flux motors (TFMs) or axial flux motor are emerging electric motor technologies which are still at early R&D stage (Pavel et al. 2016; Podmiljšak et al. 2024). Some of these designs are rare-earth free. Based on the engineering literature and above discussion, Table 1 summarises the various EV motor types, their dependence on REEs, performance trade-offs and stages of development, illustrating the current dominance of PMSM technologies over alternative designs.

4.5 Innovations in Re-use and Recycling of RE materials

Current recycling rates are very low (1% globally, 6-7% in Europe) (Filippas et al. 2021) and it is believed to be only a partial bridge in the supply gap. Recycling processes are at the development stage and have not yet been scaled up to meet industrial demand. Reusing and recycling RE material is key to reducing dependence on rare earth mining. Yet, recycling of RE products is complicated by the fact that only a small quantity of RE is incorporated in most recyclable or reusable materials, and the processes are energy-intensive and complex. There are also coatings and adhesives on magnets that complicate the recycling processes. Both wind generators and electric motors rely on sintered Nd-Fe-B magnets, where the magnetic powder is heated to fuse the particles together, making it difficult to extract and reuse without loss in

Table 1: Comparison of Electric Motor Types and Their Characteristics

Motor Type	**Rare Earths**	**Advantages and Trade-Offs**	**Stage of Development**
Permanent Magnet Synchronous Motor (PMSM)	Yes	Highest efficiency and power density	Fully commercialized
PM-Assisted Synchronous Reluctance Motor (PM-SynRM)	Limited	High efficiency	Commercial stage
Induction Motor (IM)	No	Lower efficiency	Fully commercialized
Electrically Excited Synchronous Motor (EESM)	No	Low efficiency, heavy	Commercialized in some EVs and industrial drives
Synchronous Reluctance Motor (SynRM)	No	Potentially good efficiency, low dynamic performance	Early commercial stage
Switched Reluctance Motor (SRM)	No	Good efficiency, high noise	Developmental stage
Advanced Designs	Limited	High performance through design flexibility and improved cooling. Design complexity	R&D stage

performance. Next to techniques available to recycle NdFeB magnets, there is also some scope for recycling motor components (Podmiljšak et al. 2024).

Remelting of magnets A major difficulty is that NdFeB magnets have a much higher oxygen content than virgin magnets, and ideally this oxide phase should be removed for proper recycling. Traditional methods for RE recycling are the pyrometallurgical route or the hydrometallurgical route (e.g leaching, solvent extraction methods), but both come at high energy and environmental costs (Y. Zhang et al. 2020). Pyrometallurgical methods rely on melting alloys and liquid metal extraction, which cannot be used for oxidised magnets. Hydrometallurgical methods are applicable to all magnets and use the same processing steps as those for the extraction of rare-earth from primary ones, consuming a large amount of chemicals and water. A recently emerging method is Hydrogen Processing of Magnet Scrap, consisting of separating mechanically the alloys in a rotating hydrogen reactor, developed by the University of Birmingham. Currently, a few pilot plants in Europe are investigating the HPMS route. Finally, the French Alternative Energies and Atomic Energy Commission (CEA) has also developed a process based on hydrogen decrepitation[28].

Waste reduction Manufacturing processes based on Net Shape Production allow for the reduction of waste during the magnet production and thus for the recovery of costly material. Several methods are promising, such as Spark Plasma Sintering (SPS) technologies, which can be used to construct complex-shaped alloys, and Additive Manufacturing technologies, based on 3D-printing techniques, which can support circularity by improving the customisation of magnet shapes during production and improving reuse and recyclability.

28. See Bacchetta et al. (2022).

Reuse of End-of-Life magnets Reusing without changing the magnetic structure of the magnet is currently the most economically viable route. This is used for generators and motors in wind turbines and EVs/HEVs, but it is more challenging to use magnets from other industrial uses (e.g hard-disk drive or air-conditioners) as magnets have a specific share and properties that are only useful for similar applications. Recycling of magnets would be facilitated by improved classification systems using a standardised grading system and labelling system for easy recyclability. A main challenge is that the amount of scrap available today is not likely to meet future demand.

Recycling Motors and Generators Several EU initiatives advocate for circular motor systems that are more traceable, repairable, and recyclable. However, these efforts are often hindered by limited information regarding the condition and availability of returned components. Demonstration projects and emerging technologies are now focusing on developing prototype motors with modular designs build specifically for the circular economy, aiming to address these challenges and enable more efficient reuse and recycling of motor parts.

To sum up, this section made clear that technological innovation provides many opportunities to reduce vulnerabilities at many segments of the RE supply chain, from exploring new RE sources and deposits, to substituting RE into magnets and components, and to improve re-use and circularity. Major questions remain regarding which segment of the value chain to prioritise, given the dominant position of China at many stages of the value chain. For now, the concentration of RE processing appears as a major concern. Recently, many countries have intensified their efforts to reduce reliance on China. In the US, the IRA includes a tax credit of 10 per cent of the production cost for 'critical components', which includes rare earths and the US Department of Defense awarded a US$35 million contract to MP Materials Corporation to build the country's first HREE processing and separation plant at the Mountain Pass mine, and funded Lynas to build a separation plant in Texas. Canada, Australia and the European Union are following the US in making substantial investments in mining and processing capacity. Efforts to promote RE processing in developed countries will require long-term innovation incentives to reduce capital costs and improve the environmental performance of RE processing plants. Regarding components, while European automakers are exploring NdFeB recycling and alternative motor designs to reduce reliance on Chinese magnets, further innovation to reduce dependencies will depend on market conditions, supply disruption and supportive policies.

5 Focus Area: Batteries

5.1 Innovations in Battery Chemistry

Introduction Innovation in battery chemistry is a critical driver of progress in electrification and energy storage, underpinning global efforts to decarbonise transport, industry, and the power sector. Almost 90% of patents in energy storage in fact concern electrochemical inventions (IEA 2020). While lithium-ion (Li-ion) technologies continue to dominate commercial markets—especially in electric vehicles (EVs)—there is growing pressure to diversify chemistry pathways in response to three converging challenges: the rising cost of critical minerals, environmental and ethical concerns over extraction, and the need for performance gains in emerging applications.

This section explores current and emerging innovations across four dimensions: (1) incremental improvements within established Li-ion technologies, including high-nickel cathodes and silicon-based anodes; (2) frontier battery chemistries such as sodium-ion, solid-state, and lithium–sulfur; (3) new approaches for long-duration, stationary storage; and (4) the accelerating role of artificial intelligence (AI) in battery materials discovery and optimisation.

To help situate these innovations within a broader strategic context, Figure 3 summarises a range of battery technologies by their material composition, mineral criticality, application domains, innovation maturity, and risk-reduction potential. This table provides a comparative view of how different chemistries align with critical mineral constraints and technology readiness, and serves as a reference throughout the discussion.

Battery Type	Key Materials	Main Applications	Critical Minerals Intensity	Stage of Maturity
Lithium-ion (NMC/NCA)	Li, Ni, Co, Graphite	EVs (high-performance)	High	Commercial
LFP (Lithium Iron Phosphate)	Li, Fe, Phosphate, Graphite	EVs (low-cost), Storage	Moderate	Commercial
Sodium-ion	Na, Mn, Fe, Carbon	Micromobility, Stationary	Low	Emerging
Solid-state	Li, Solid Electrolytes (e.g., La, Ta)	Next-gen EVs	High	Prototype / Pre-commercial
Lithium–Sulfur	Li, Sulfur	Aerospace, future EVs	Moderate	Early-stage R&D
Redox Flow	Vanadium, Iron, Zinc	Stationary Storage	Variable	Commercial (niche)
Zinc-Air / Iron-Air	Zinc or Iron, Air	Long-duration Storage	Low	Prototype / Demonstration

Figure 3: Battery Chemistries and Critical Mineral Implications.

5.1.1 Incremental Innovation within Lithium-ion Technologies

The first generation of mass-produced electric vehicles (EVs), launched just over a decade ago, relied on battery chemistries originally developed for consumer electronics—chiefly lithium cobalt oxide (LCO) and lithium manganese oxide (LMO). These early cathodes prioritised energy density and stability, but were also cobalt-intensive. As EV deployment expanded, battery development shifted focus toward improving specific energy (energy per unit mass), durability, power output, charge/discharge speed, and recyclability—while also addressing the rising cost and ethical concerns surrounding critical minerals, particularly cobalt (IEA 2020).

This evolution has led to the widespread adoption of alternative chemistries such as lithium nickel manganese cobalt oxide (NMC), lithium iron phosphate (LFP), and, more recently, lithium nickel cobalt aluminium oxide (NCA)—the latter of which, while developed earlier, has seen a resurgence in market share in recent years due to its high energy density and growing use in premium EV segments. Alongside these cathode developments, the progressive substitution of graphite with silicon in anodes has also gained momentum. Together, these shifts reflect three dominant trends in contemporary battery design: reducing cobalt through high-nickel chemistries, reviving cobalt- and nickel-free LFP, and siliconising the anode to ease graphite dependency.

High-nickel, low-cobalt cathodes Over the past decade, a central trend in lithium-ion battery innovation has been the shift toward high-nickel, low-cobalt cathode chemistries, particularly within the class of layered oxide cathodes known as NMC — short for nickel–manganese–cobalt oxides. These materials are typically denoted by three numbers indicating the molar ratio of each metal. For example:

- NMC 111 contains equal parts nickel, manganese, and cobalt (1:1:1).
- NMC 622 increases the nickel content to 60%, with 20% each of manganese and cobalt.
- NMC 811 pushes nickel to 80%, reducing cobalt to just 10%.

This progressive increase in nickel content is often referred to as the "cathode road-map", where manufacturers evolve from NMC 111 → 532 → 622 → 721 or 811, with each step lowering cobalt content and increasing nickel to improve energy density (how much energy a battery can store per unit weight or volume).

This evolution has been motivated not just by energy performance but by economic and geopolitical concerns. In early 2022, cobalt prices surged past USD 70,000 per tonne, driven by tight supply and growing demand (Benchmark Mineral Intelligence 2023). Meanwhile, 70% of global cobalt mining output continued to originate from the Democratic Republic of Congo, a country repeatedly scrutinised for human rights violations and labour abuses in its artisanal mining sector, and ongoing resource-related conflicts (IEA 2023a).

Given these pressures, battery manufacturers have opted to invest in more complex processing steps and advanced materials in order to reduce dependency on cobalt, even at the cost of added production complexity and increased need for quality control.

According to the IEA Global EV Outlook 2023, global electric vehicle (EV) sales rose from around 2 million in 2018 to over 10 million in 2022. This rapid growth has been accompanied by a steep increase in battery demand: total demand for lithium-ion batteries in the automotive sector grew by approximately 65% in a single year, rising from 330 GWh in 2021 to 550 GWh in 2022. Alongside this surge, the material composition of EV batteries has evolved. In 2018, a substantial share of batteries still relied on mid-nickel chemistries such as NMC 622. By 2022, more than half had shifted to high-nickel formulations like NMC 721, NMC 811, and nickel–cobalt–aluminium oxide (NCA) (IEA 2023b).

This transition has significantly reduced cobalt demand per kilowatt-hour of battery storage. While an NMC 622 cathode might require around 170 grams of cobalt per kWh, newer high-nickel versions like NMC 811 use approximately 80 grams, a reduction of more than 50% (U.S. Department of Energy 2023). However, this shift comes with engineering challenges and safety trade-offs. Nickel-rich materials tend to be less thermally stable, meaning they are more prone to thermal runaway — an uncontrollable rise in temperature that can lead to battery fires or explosions. The materials are more energy-dense but also more sensitive to heat, mechanical abuse, or overcharging (W. Zhang et al. 2024).

The rise of high-nickel cathode chemistries—particularly NCM and NCA—has been clearly reflected in patenting trends. Between 2015 and 2022, the number of international patent families related to these two materials more than tripled, reaching approximately 2,300 families by 2022 (Yang and Mu 2023). While the data do not disaggregate patents by precise nickel content, Yang and Mu (2023) notes a growing focus on Ni-rich variants to boost energy density and reduce cobalt dependency. This trend has spurred substantial innovation in addressing the stability challenges of high-nickel materials.

Yang and Mu (2023) highlight that extending the cycle life of Ni-rich cathodes has become a major research priority, driving work on surface coatings, grain-boundary engineering, and electrolyte modification strategies. Scientists are developing several process and material-level adaptations. For example, a thermal treatment step during synthesis to ensure uniform distribution of transition metals in the cathode particles could improve structural stability and reduce localised hot spots that can lead to degradation (Z. Wu et al., n.d.). Or, a combination of lithium salts in the electrolyte could enhance the formation of a more robust interphase between the electrode and the electrolyte, reducing degradation under high-voltage operation (Wang et al. 2021).

LFP Resurgence Lithium iron phosphate (LFP) batteries are a cobalt- and nickel-free lithium-ion chemistry that relies on abundant materials: lithium, iron, and phosphate. First developed in the 1990s, LFP was widely used in early electric buses and low-speed EVs but fell out of favour by the mid-2010s as automakers shifted to higher-energy-density NMC and NCA chemistries. However, since around 2020, LFP has experienced a striking resurgence.

Globally, the market share of LFP in electric cars rose from under 10% in 2017 to just under 30% in 2022 (IEA 2023a). By 2024, it had nearly doubled again, approaching 50% of the global EV market (IEA 2025b). While high-nickel variants of NMC and NCA still dominate in Europe and North America, LFP has become the standard in China: in 2022, 95% of battery electric vehicles produced in China used LFP cells (IEA 2023b).

LFP's main historical disadvantage was its lower energy density: on average, pack-level energy density is about 20% lower by mass (Wh/kg) and roughly 30% lower by volume (Wh/L) compared to high-nickel NMC chemistries (IEA 2025b). This typically translates into a shorter driving range. However, this is partially offset by LFP's tolerance for full charging cycles: unlike NMC, which is often capped at 80% SOC to prolong battery life, LFP cells can safely charge to 100% without rapid degradation.

Importantly, the energy density of LFP has improved in recent years. Through innovations in electrode structure, cell format (e.g., CATL's cell-to-pack technology), and materials engineering, LFP batteries now offer fast charging and competitive range performance in some applications (CATL 2025; News 2025).

This technological momentum is reflected in the surge of innovation activity focused on LFP. Chinese firms in particular dominate patents for advanced LFP materials that support fast-charging and higher energy density, often embedding these innovations into proprietary battery pack-level designs such as cell-to-pack configurations (IEA 2025b; Yang and Mu 2023).

LFP batteries are approximately 30% cheaper per kWh than high-nickel NMC batteries (IEA 2025b). The cost advantage, combined with lower thermal runaway risk and greater durability, has made LFP the preferred choice for entry-level EVs, urban buses, delivery fleets, and stationary storage. GM and Toyota, for instance, launched behind-the-meter energy storage systems using LFP in 2022 (IEA 2023a).

LFP's growth was catalysed by high cobalt and nickel prices in 2021–2022, but its momentum has persisted even as prices fell. This suggests that cost competitiveness alone no longer explains its rise: improved performance and intense competition in the EV market have consolidated its commercial position (IEA 2025b).

While LFP offers an alternative to nickel and cobalt materials associated with ethical sourcing issues and concentrated supply chains, it creates new dependencies. Phosphorus is abundant, but purified battery-grade phosphoric acid is not. In 2024, China produced around 75% of global battery-grade phosphoric acid and 98% of LFP cathodes (IEA 2025b). According to the IEA, planned production projects outside China also currently appear insufficient to meet anticipated LFP demand by 2030. Furthermore, in January 2025, China announced potential export controls on LFP-related technology and materials, highlighting geopolitical exposure (Blois 2025).

Another potential concern is that the increased use of phosphate in batteries may eventually compete with agricultural demand. The IEA estimated that if all EVs in 2023 had used LFP batteries, global phosphate demand would have increased by around 1% — small, but potentially meaningful as EV adoption grows (IEA 2023b).

LFP's resurgence illustrates how continuous incremental innovation in a seemingly mature chemistry, coupled with favourable cost dynamics, durability, and geopolitical factors, can significantly reshape global battery markets.

Anode Pathways Beyond Pure Graphite Graphite has long been the dominant material used in lithium-ion battery anodes, valued for its low cost, stability, and decent energy density. However, it is now increasingly regarded as a critical mineral due to its extreme supply concentration. In 2024, China accounted for more than 80% of global graphite mining and over 90% of battery-grade graphite processing. This geographic concentration presents a growing vulnerability for global battery supply chains, particularly as demand for graphite surges in tandem with electric vehicle and stationary storage deployment (IEA 2025b).

In response, battery manufacturers are increasingly turning to silicon as a partial substitute in anode materials. The appeal lies in silicon's much higher theoretical capacity — the maximum charge it can store per gram under ideal conditions. While graphite's theoretical capacity is about 372mAh/g, that of silicon is ten times higher, meaning it can hold nearly five times more lithium per unit of weight (Hossain et al. 2024). This matters because higher capacity at the material level translates into greater energy density at the cell level, enabling longer driving ranges or smaller, lighter batteries for the same performance.

Even modest additions of silicon, typically blended with graphite to preserve cycling stability, can yield substantial gains. Industry-wide, anodes containing around 10% silicon have grown from virtually 0% of the EV market in 2019 to over 10% by 2024 (IEA 2025b). These silicon–graphite hybrids can significantly improve cell-level energy density (Kwade et al. 2018), while also reducing the mass of graphite needed per kilowatt-hour. This improves performance and helps diversify supply chains away from a single critical input.

However, this comes with a major challenge: lithiation — the process where lithium ions enter the silicon structure during charging — causes the material to expand by more than 300% in volume. Such extreme swelling leads to mechanical cracking and breakdown of the solid electrolyte interphase, a protective film that forms on the anode surface. When the interphase fractures and reforms repeatedly, it consumes active lithium and degrades battery performance over time (Hossain et al. 2024).

To manage silicon's severe volume expansion and associated degradation, innovation efforts have increasingly centred on nanostructured anode designs. Patent filings and academic studies reveal three prominent approaches: (1) encapsulating silicon nanoparticles in yolk–shell architectures that buffer expansion without mechanical rupture; (2) embedding nano-porous silicon within carbon matrices to provide structural cushioning and improved electronic conductivity; and (3) using fluorine-rich electrolyte additives to form more stable and elastic solid–electrolyte interphase layers that can withstand repeated cycling without fracturing (Amici et al. 2022; Hossain et al. 2024).

According to the IEA and EPO, patent activity in this space has grown rapidly since 2018, focusing on such silicon–carbon composite innovations, particularly from leading firms like Panasonic and Sila Nanotechnologies (Hossain et al. 2024; IEA 2020).

While full-silicon anodes are not yet mainstream, the gradual incorporation of silicon into commercial cells represents a strategically important evolution. It allows manufacturers to improve performance while diversifying away from graphite — a shift with both technical and geopolitical advantages.

5.1.2 Frontier Chemistries with Transformative Potential

Sodium-ion batteries Sodium-ion (Na-ion) batteries are emerging as a promising, low-cost, lithium-free alternative in the battery innovation landscape, particularly for applications in stationary storage and low-range electric vehicles (EVs). While sodium-ion technologies have long lagged behind lithium-ion (Li-ion) in terms of commercial readiness, recent developments have rapidly accelerated their maturation. According to IEA estimates, Na-ion batteries have progressed from Technology Readiness Level (TRL) 3–4 in 2021 to TRL 8–9 by 2023–24, underscoring their potential near-term deployment in commercial markets (IEA 2023b).

A key innovation advantage of Na-ion batteries lies in their reduced reliance on critical minerals. Unlike conventional Li-ion chemistries that depend on lithium, cobalt, and nickel, sodium-ion batteries can operate using abundant and widely available materials. The leading Na-ion chemistries contain no lithium, cobalt, or graphite, and in many cases, they use aluminium rather than copper as the anode current collector, substantially lowering both cost and supply chain risks. Cathode materials typically include layered oxides (such as sodium nickel manganese oxides) or Prussian white, depending on the performance target. Furthermore, the upstream supply chains for sodium—including soda ash, caustic soda, and hard carbon from biomass—are relatively diversified, with active roles played by the United States and Europe, even though the downstream cell and cathode production remains highly concentrated in China (IEA 2025b).

Despite a lower energy density compared to LFP or NMC batteries, Na-ion batteries are still viable for specific market segments. They are especially suited for urban mobility, micro-mobility (e.g. e-scooters and three-wheelers), and stationary storage, where high range and fast charging are less critical. Chinese battery giants like CATL and BYD are already producing Na-ion cells for budget EV models[29], such as the BYD Seagull, which offers a range of about 300 km at a price point around \$11,600, with broader adoption planned across all models priced below \$29,000 (IEA 2023b).

In sum, sodium-ion batteries may not displace lithium-ion at the high-performance end of the market, but they represent a strategically significant innovation path. By reducing dependence on lithium, nickel, and cobalt and enabling a more geographically diversified supply chain, Na-ion technologies contribute to both cost-effective decarbonisation and critical mineral risk mitigation—an increasingly important objective in a geopolitically fragmented world. Their rapid commercialisation illustrates how innovation can open new technological frontiers while easing pressure on mineral-intensive clean energy transitions.

Solid-state batteries Solid-state batteries (SSBs) promise significant gains in energy density and safety, and are moving closer to commercialisation as companies like Toyota, CATL, Samsung SDI and QuantumScape target limited production by 2027–2028 (IEA 2025b). While early models are likely to use semi-solid or hybrid electrolytes to ease manufacturing and cost constraints, full-scale deployment remains a challenge due to high defect rates, complex production processes, and critical mineral requirements.

Compared to conventional lithium-ion batteries, SSBs depend on a distinct and in some cases riskier mix of materials. Lithium metal anodes—key to their performance advantage—are costly and difficult to produce at scale, with over 90% of global battery-grade lithium metal capacity expected to be in China

29. Chinese battery giant CATL also recently launched a new sodium-ion battery with a range of around 1,000 km. See https://www.france24.com/en/live-news/20250421-china-s-catl-launches-new-ev-sodium-battery

by 2025. Sulphide-based electrolytes rely on lithium sulphide and phosphorus, putting additional strain on phosphate supply chains. Oxide-based variants use lanthanum and zirconium, both currently by-products of other sectors but heavily geographically concentrated (IEA 2025b).

Despite these emerging material challenges, SSBs may play a crucial role in decarbonising hard-to-abate sectors such as long-haul electric trucks or short-haul boats and planes—applications where high energy density is essential and conventional lithium-ion batteries fall short (IEA 2023c). Their deployment could also reduce demand for cobalt or nickel. But the shift in mineral requirements underlines the need for early policy planning to diversify supply, promote recycling innovation, and closely track evolving technology pathways.

Lithium-sulfur and lithium-air Among the most ambitious battery innovations under development are lithium-sulfur (Li-S) and lithium-air (LiO_2) systems. Both promise ultra-high energy densities while eliminating the need for cobalt and nickel, potentially offering dramatic reductions in critical mineral demand. Li-S batteries use elemental sulfur, a by-product of petroleum refining, which is cheap and abundant. With a theoretical specific energy nearly five times that of today's lithium-ion cells, Li-S could radically extend EV range and reduce cathode costs (IEA 2023c).

Early commercial interest is growing: Lyten has announced the first Li-S gigafactory, and Stellantis plans to bring the technology to market by 2030 (IEA 2023c). However, serious hurdles remain, including short cycle life due to the "polysulfide shuttle" effect, and the insulating nature of sulfur, which limits performance without complex carbon matrices. These challenges place large-scale deployment beyond 2030, though the technology shows promise for long-haul transport and aviation, where weight savings are critical (EUROBAT 2024).

Even further from commercialisation is lithium-air, a chemistry that uses ambient oxygen as the cathode reactant and offers the highest theoretical energy density of any rechargeable battery, potentially rivalling gasoline. However, Li-air remains in the lab, plagued by electrolyte instability, poor reversibility, and extremely short lifetimes. It is unlikely to reach the market before 2030 (EUROBAT 2024; IEA 2020).

Both systems would remove cobalt and nickel from the supply chain, but they face formidable materials and engineering challenges—chiefly electrode degradation and dendrite-free lithium cycling—that must be solved before scale-up.

Taken together, these frontier chemistries illustrate the trade-offs ahead: Na-ion prioritises cost and resource security; SSBs chase safety and higher energy while reshuffling mineral demand; Li-S and Li-air target ultra-high energy with minimalist critical-mineral content but require major leaps in basic science and manufacturing know-how.

5.1.3 New Storage Solutions for Stationary Applications

Redox-Flow Batteries Redox flow batteries (RFBs) are emerging as a promising technology for long-duration, grid-scale energy storage, offering a fundamentally different architecture from lithium-ion systems. In RFBs, energy is stored in liquid electrolytes that circulate through electrochemical cells during charging and discharging. This decouples energy capacity (determined by the volume of electrolyte) from power output (determined by the size of the cell stack), enabling flexible system sizing and relatively easy capacity scaling. Flow batteries are especially well-suited to applications where space and weight constraints are less important, such as utility-scale renewables integration, peak shaving, or backup storage for remote grids (Metzger et al. 2023).

Among the various chemistries, vanadium redox flow batteries (VRFBs) are the most mature, thanks to their stability and long cycle life. VRFBs use vanadium ions in different oxidation states in both the positive and negative electrolyte tanks. This single-metal system avoids the problem of cross-contamination between electrolytes, offering high reversibility and a long operational life (IEA 2020; U.S. Department of Energy 2023).

Importantly, because they do not rely on lithium, cobalt, or nickel, RFBs offer a pathway to relieve pressure on lithium-ion supply chains, particularly for long-duration storage needs where high energy density is less critical. However, vanadium's price volatility and geographic concentration—with a large share of supply coming from China, Russia, and South Africa—pose supply chain concerns (World Bank 2023). While vanadium is often recovered as a by-product of steelmaking, this limits the ability to flexibly ramp up supply in response to energy storage demand.

Research is underway on alternative flow battery chemistries using iron, zinc, or organic molecules to reduce cost and material risk, but these systems currently lag VRFBs in terms of performance, stability, and commercial readiness (Simas et al. 2022).

Metal-Air and Other Long-Duration Options Metal–air batteries, such as zinc–air or iron–air, are attracting attention for long-duration storage due to their potential for very low cost and high energy density. These systems use abundant metals as the anode and oxygen from the air as the cathode reactant, significantly reducing material needs and enabling simpler designs. Companies like Form Energy are developing iron–air batteries targeting 100+ hours of discharge—ideal for balancing variable renewables over multi-day periods ("Battery Technology" 2021). While energy efficiency is lower than in lithium-ion systems, the extremely low materials cost and long lifespans make them promising for grid-scale storage, particularly in regions with constrained mineral supply chains.

Beyond metal–air, other emerging long-duration technologies include thermal energy storage, gravity-based systems, and hydrogen-based solutions. These approaches often bypass electrochemical storage entirely and may offer regional advantages, especially where space, geological features, or industrial waste heat are available. While most are still at early deployment stages, they are increasingly seen as critical complements to batteries—filling the gap between daily cycling and seasonal balancing, and reducing long-term dependence on lithium, cobalt, and vanadium in stationary applications.

5.1.4 AI-Accelerated Discovery Pathways

Artificial intelligence (AI) is increasingly being recognised as a powerful enabler of accelerated innovation across the energy technology landscape, including batteries and other energy storage systems. In particular, AI can compress discovery timelines and reduce development costs for new chemistries that might substitute or reduce reliance on critical minerals such as cobalt, nickel, and lithium.

AI for Chemical Design and Materials Discovery

Battery innovation has historically been a slow and empirical process. For example, the typical lead time from fundamental materials discovery to large-scale deployment can take 10–20 years. AI promises to dramatically shorten this cycle by guiding researchers toward promising compounds with predictive models trained on massive datasets of material properties, thermodynamics, and performance metrics (IEA 2025a).

In battery research, machine learning is used to screen billions of candidate materials for electrodes and electrolytes by predicting characteristics like voltage windows, stability under cycling, ionic conductivity, abundance and criticality of precursor minerals. In one illustrative example, AI-driven high-throughput screening reduced a candidate set of over 100,000 hypothetical battery materials down to a few hundred viable contenders, cutting initial discovery efforts from years to weeks (Dave et al. 2022).

Degradation Modelling and Lifecycle Prediction AI is also being applied to battery ageing and failure prediction, helping to understand how and why materials degrade under different conditions. Conventional degradation testing requires thousands of hours of cycling; in contrast, AI models can forecast degradation patterns from just a few early charge/discharge cycles, enabling faster evaluation of new chemistries and designs.

These models rely on large training datasets from real-world battery usage and test benches and have been shown to predict cycle life within 9% accuracy after only the first 100–150 cycles — an enormous advantage for early-stage material screening (Severson et al. 2019).

Robotic Experimentation and Autonomous Labs Another key breakthrough is the use of AI-integrated robotic platforms that automate materials synthesis and testing. These “self-driving labs” can: 1) run dozens of experiments in parallel, 2) modify hypotheses in real-time, 3) learn from failed trials, and 4) optimise toward target properties without human intervention.

For instance, automated labs have demonstrated AI-guided workflows that independently selected and synthesised new solid-state electrolyte formulations, evaluating ionic conductivity and mechanical strength across thousands of samples in just weeks (Chen et al. 2024; Yik et al. 2025).

These platforms represent a shift from traditional ”trial-and-error” approaches toward closed-loop optimisation — a critical leap for frontier chemistries such as lithium–sulfur or sodium–metal.

Conclusion Battery chemistry is no longer evolving along a single trajectory; instead, we are witnessing a branching innovation landscape where performance, sustainability, and critical mineral constraints intersect. Within the Li-ion family, modest compositional shifts — such as cobalt-reduction or partial graphite substitution — already generate large aggregate effects due to the scale of deployment. Meanwhile, emerging chemistries like sodium-ion and solid-state batteries offer the potential to decouple performance gains from material scarcity, though most remain several years from widespread commercialisation.

For stationary storage, where volumetric energy density is less important, a new class of low-cost, long-duration solutions is gaining traction, potentially alleviating pressure on lithium and other high-demand materials. Across all fronts, AI-enabled discovery and optimisation is proving essential to compress development timelines, navigate material trade-offs, and identify alternatives to geopolitically sensitive minerals.

In sum, battery chemistry innovation is not only about making better batteries — it is also about making batteries differently, with new materials, tools, and design principles that align with long-term goals of climate resilience, resource security, and global equity.

5.2 Innovations in Use, Re-Use and Recycling of Batteries

As attention shifts from battery production to what happens during and after use, new strategies are emerging to reduce the demand for raw materials. These include making batteries last longer, repurposing them after their initial use, and recovering critical materials through advanced recycling. This section examines each of these approaches in turn.

5.2.1 Use Phase: Stretching First Life

Extending battery first-life is one of the fastest ways to reduce demand for lithium, nickel, cobalt and other critical minerals. Broader shifts—such as reducing car use, increasing shared mobility, or shifting to public transport—are also essential to long-term demand reduction, though they tend to unfold over longer timescales and involve more complex behavioural and systemic change. A reduction of car ownership and extending the lifetime of EV batteries by five years could reduce annual battery mineral demand by 10% to 20% between 2030 and 2040, and potentially up to half of the annual demand by 2050, when compared to a baseline scenario (Simas et al. 2022). Three strategies stand out: better design for long life, smarter charging and grid use, and business models that reward durability. These are already delivering results and starting to shape new policies.

Design for longevity Data from around 92,000 battery patent families show a sharp rise in mentions of "battery management system" (BMS) between 2000 and 2019, reflecting growing focus on software that controls voltage, temperature, and depth-of-discharge (Metzger et al. 2023). Modern BMS limit charging to a 10–80% state-of-charge window, which can reduce battery ageing by around 15% compared to unmanaged systems (IEA 2020).

At the same time, many EVs are fitted with oversized batteries, especially large SUVs used mostly for short trips. Battery for SUVs can be two to three times larger (IEA 2023a). This adds to mineral demand without necessarily extending product use. The upcoming EU Battery Regulation addresses the problem of oversizing by introducing requirements to better align battery design with how vehicles are actually used. It calls for reporting and, in some cases, minimum thresholds on metrics like energy consumption per kilometre and battery durability (Rizos and Urban 2024). This pushes manufacturers to consider not just range, but also how efficiently a battery delivers that range in everyday driving.

In response, automakers are offering more tailored battery options rather than defaulting to the largest possible pack. For example, VW's MEB platform (used in models like the ID.3 and ID.4) offers both 45 kWh and 77 kWh battery variants ("Modular Electric Drive Matrix (MEB)" 2025). In theory, this allows buyers to choose a pack size that fits their typical driving needs—shorter daily commutes versus long-distance travel—without unnecessary material use. Such modular offerings could help reduce the average battery size across the fleet, lowering demand for critical minerals without compromising functionality. It would be valuable to see future research evaluating how consumers respond to these options and how battery usage patterns evolve under different ownership and leasing arrangements.

Design improvements at the battery system level can also extend first-life performance. One important shift is the move from traditional cell–module–pack architectures to cell-to-pack (CTP) designs (Froese 2024). By eliminating the intermediate module layer, CTP systems significantly reduce the amount of inactive material (e.g., casing, connectors, cooling channels). This not only improves energy density, but also allows for more even heat distribution across the pack, which helps slow down the uneven ageing of cells—a common cause of early battery degradation.

Looking ahead, solid-state batteries represent a promising next step. Solid-state cells currently in pilot testing are projected to achieve over 300 full-depth charge cycles while retaining 80% of their original capacity—about twice the typical lifespan of today's lithium-ion batteries (Khollam 2025).

Smart charging & vehicle-to-grid (V2G) Smart charging strategies and advanced battery management systems (BMS) can substantially extend battery life by reducing degradation. A modern BMS not only balances charge across cells and regulates temperature to prevent overheating, but also adjusts charging parameters in real time to minimise wear, extending cell life by up to 17.5% (IEA 2020). Avoiding ultra-fast charging is also critical, as excessive heat and lithium plating can accelerate degradation and pose safety risks. When integrated with smart charging infrastructure, BMS can enable flexible, low-emission charging aligned with grid needs and renewable energy availability.

Vehicle-to-grid (V2G) systems offer additional potential to extend system value — provided discharging is limited to shallow cycles (e.g., less than 10% of capacity) to preserve battery health (IEA 2023c).

In parallel, new high-power charging standards such as CharIN's Megawatt Charging System (MCS) include thermal management features designed to minimise battery wear during rapid charging (Tolbert et al. 2024). Policy is also pushing in this direction. The EU Battery Regulation will require the publication of durability data, encouraging manufacturers to implement adaptive charging and discharging strategies.

Emerging electric car-sharing models, especially when combined with smart charging and vehicle-to-grid (V2G) services, offer additional potential to reduce overall vehicle numbers, extend battery life, and unlock new system-level value streams.

Business models that reward long life Commercial EV fleets—such as those used for ride-hailing and logistics—often exceed 200,000 km within four years (Slanger 2023), generating detailed battery health data that simplifies grading for second-life applications or warranty claims. Business models like Battery-as-a-Service (BaaS) and leasing, where manufacturers or specialised asset managers retain ownership, align revenues with the battery's lifetime energy throughput rather than upfront sales.

NIO's BaaS platform exemplifies this approach. As of November 2023, NIO had established a total of 30 battery-swapping stations across 5 European markets and over 2,200 stations worldwide, completing nearly 33 million battery swaps ("NIO Reaches 30 Power Swap Stations in Europe and Over 2,200 Worldwide" 2025). This model allows for optimised battery utilisation and lifecycle management, as NIO maintains control over battery performance and health data.

In Europe, Renault pioneered large-scale battery leasing for models like the *ZOE* and *Kangoo Z.E.*, with over 100,000 battery rentals recorded by 2017 ("Renault Reaches Milestone of 100,000 E.V. Batteries Leased" 2017). These leased batteries remain under OEM monitoring, providing high-quality degradation data and facilitating planned transitions to second-life applications, such as stationary storage projects managed by Mobilize Power Solutions.

Regulatory frameworks are reinforcing these business models. The EU Battery Regulation mandates traceability and durability disclosures across the battery lifecycle, effectively monetising longer first-life performance. Similarly, the U.S. Inflation Reduction Act provides tax credits for EVs that meet specific criteria for battery component sourcing and durability, incentivising manufacturers to adopt practices that extend battery life (Bistline et al. 2023).

5.2.2 Reuse and Second-Life Applications

As more electric vehicle (EV) batteries reach the end of their first life, they represent a growing pool of potential energy storage assets. EV packs are typically retired after around 10 years of use, once their capacity has declined by 20–30% (Kastanaki and Giannis 2023; Zhu et al. 2021). At this stage—usually around 70–80% of original capacity—batteries may no longer meet automotive performance standards but still exceed the capabilities of many stationary storage systems, including new lead–acid or LFP units (Harper et al. 2019).

Realising this residual value depends on three main factors: (i) robust traceability and diagnostic tools to assess battery health; (ii) stationary applications where second-life batteries provide clear climate and economic benefits; and (iii) standardised processes to manage technical variation, liability, and financing challenges.

Battery passports as enablers of safe reuse As outlined in Box 1, the battery passport provides a structured digital record of each battery's composition, usage history, and performance over time. For second-life applications, this visibility is essential. It enables accurate, non-destructive grading of retired EV packs and helps identify which units are suitable for reuse, repurposing, or direct recycling.

Early pilot projects suggest that when state-of-health and usage metadata are available at the point of disassembly, diagnostic labour can be reduced by up to 40% (Weng et al. 2023). In addition, traceable records of ownership and repair events can lower liability barriers and support standardised repurposing workflows. Battery passports thus act as a foundation for more scalable and lower-risk reuse pathways, especially for OEM-monitored leasing fleets and high-throughput logistics applications.

Stationary storage, grid resilience and backup power Second-life electric vehicle (EV) batteries are increasingly being deployed in stationary applications such as behind-the-meter storage, where performance requirements are more flexible and cost sensitivity is paramount. Batteries retired from EV use typically retain 70–80% of their original capacity, making them viable for less demanding energy storage roles like residential backup, demand response, and microgrid support (Engel et al. 2019; Simas et al. 2022)

While economic viability remains context-specific, studies suggest that second-life batteries can reduce storage costs compared with new battery systems, especially where local labour and remanufacturing are cost-competitive (Engel et al. 2019; Zhao et al. 2021). Technical challenges include heterogeneous degradation profiles and the need for robust battery management systems to ensure reliability and safety (Simas et al. 2022; Sulzer et al. 2021)

Demonstration projects continue to emerge worldwide. For example, Nissan has formalised partnerships to reuse battery packs from its LEAF EVs for stationary storage, while Renault has deployed retired EV batteries in off-grid microgrids in Europe (Zhu et al. 2021). These systems have reported round-trip efficiencies in the range of 80–85%, with service lives of 5–10 additional years depending on operational conditions (Sulzer et al. 2021).

The potential supply of batteries for repurposing is expanding rapidly. Global second-life battery capacity is projected to reach over 200 GWh by 2030, enough to significantly supplement grid-scale storage in many regions (Engel et al. 2019; Zhao et al. 2021). However, bottlenecks in disassembly, diagnostics, and standardisation persist, particularly in the absence of common design and certification protocols (Gu et al. 2024; McCrossan and Shankaravelu 2021).

Climate benefits versus delayed material recovery Second-life use of EV batteries in stationary applications offers clear climate benefits. Life-cycle assessments suggest that reusing batteries can reduce greenhouse gas emissions by 30–70 kg CO_2e per kWh of storage capacity, primarily by offsetting the production of new battery systems and better utilising the energy and materials embedded in the original battery (Zhao et al. 2021; Zhu et al. 2021).

Yet these environmental gains come with a trade-off: prolonging battery use defers the recovery of critical minerals like cobalt, nickel, and lithium. This delay could become increasingly consequential as demand for these materials outpaces supply in the 2030s, particularly under accelerated electrification scenarios (IEA 2025b).

This creates a policy dilemma—whether to prioritise second-life applications for their immediate climate benefits, or expedite recycling to reintegrate critical materials into the supply chain. The EU Battery Regulation seeks to manage this tension by requiring a "take-back option" for second-life batteries. This means that producers or authorised third parties must ensure that batteries reused in a second-life application are eventually collected at end-of-life and returned for proper recycling. The regulation also sets binding material recovery targets: by 2031, at least 90% of cobalt and nickel and 50% of lithium must be recovered from spent batteries (Gu et al. 2024).

Technical and institutional hurdles Technical heterogeneity remains a core barrier to scaling second-life battery applications. Even within a single OEM's product line, rapid evolution in cell chemistries (e.g., from NCM111 to NCM811) and formats (e.g., prismatic to pouch) can result in dozens of unique battery configurations over a decade. This variation complicates automated disassembly, safety testing, and standardised repurposing procedures (Gu et al. 2024; Zhu et al. 2021).

Although recent standards define protocols for assessing safety and performance in second-life batteries, institutional misalignments remain. In particular, inconsistencies in national warranty and liability regimes hinder the development of cross-border markets for repurposed packs (Engel et al. 2019).

These uncertainties are reflected in insurance premiums, which remain higher for second-life systems compared to new ones. The lack of long-term performance data and clear liability allocation continues to limit investor and user confidence. However, emerging tools—such as standardised state-of-health metrics and digital battery passports—are expected to improve transparency, reduce transaction costs, and support the development of a more liquid and trusted second-life battery market over the coming decade (Gu et al. 2024; Sulzer et al. 2021).

5.2.3 Recycling: Recovering Critical Minerals

As the number of EV batteries reaching the end of their primary use (first life) increases, they create a significant and growing resource pool for materials recovery. This rise in end-of-life battery volume is driving the recycling industry into a crucial growth phase.

Today, two main industrial pathways dominate: pyrometallurgy, which smelts battery components at high temperatures, and hydrometallurgy, which uses chemical leaching to extract metals from shredded "black mass".

Thermal and chemical routes Pyrometallurgical processes are robust to feedstock variability and can recover more than 90% of copper and other high-value metals (Zhao et al. 2021). However, they are energy-intensive and often fail to recover lithium, which is lost to slag. Recent improvements in furnace design and flux chemistry have increased metal recovery rates and reduced energy use, but fundamental limitations remain.

Hydrometallurgical methods offer lower energy consumption and greater selectivity. Leaching and solvent extraction can achieve high-purity separation of cobalt, nickel, and lithium from black mass (Makuza et al. 2021). Newer approaches use greener agents—such as ammonium carbonate or organic acids—in place of concentrated sulphuric acid. One NSF-funded method, for example, extracts cobalt and nickel from e-waste with 99% purity using ammonia and carbonate (Zheng et al. 2024).

In both Europe and North America, most recycled input still comes from manufacturing scrap, not end-of-life EVs—reflecting the lag in battery retirements (IEA 2023b).

Direct recycling and closed-loop recovery "Direct" or "value-retention" recycling aims to preserve the structure of cathode materials (e.g. NCM powders) rather than reducing them to raw elements. Processes include mechanical dismantling, electrolyte removal, flotation, relithiation, and surface recoating. Lab-scale trials show 80–90% yield for NCM811, with 60–70% lower energy demand than conventional hydro/pyro routes (J. Wu et al. 2023). Commercial projects (e.g. Redwood, Li-Cycle, GEM) are targeting 10–25 kta plants, but these depend on chemistry-specific sorting—mixing LFP and NCM powder degrades regenerated cathode quality. Here, the forthcoming EU *battery passport* is critical: composition and manufacturing data can support automated routing to the correct recovery line.

Emerging chemistries and biological pathways Different battery types pose distinct challenges. LFP batteries, which contain no cobalt or nickel, are unsuitable for high-temperature pyrometallurgy. Developers are exploring low-temperature hydrometallurgical routes (e.g. hydrochlorination) or molten-salt electrolysis to recover lithium and phosphate streams.

Solid-state batteries introduce other risks, including H_2S emissions from sulphide electrolytes and unstable lithium-aluminium alloys. Pilot lines at Umicore (Belgium) and JFE (Japan) are testing cryo-milling followed by lithium sublimation and hydrometallurgical treatment.

Biological methods also show promise. Microbes such as Aspergillus niger produce organic acids that can leach metals from e-waste, while biomass-based materials can adsorb critical minerals from solution (Dar et al. 2025; Ferreira-Filipe et al. 2025; Joshi et al. 2025). These approaches offer low-impact, flexible alternatives, though scale-up and reaction speed remain key challenges.

Recycling policy and the push for circularity Battery recycling policy is evolving rapidly in major EV markets as governments aim to reduce dependence on primary critical mineral extraction and secure more resilient supply chains. China leads the global recycling landscape, with over 80% of global capacity for both pre-treatment and material recovery (IEA 2025b). Its regulatory framework mandates producer responsibility, requiring EV manufacturers to establish dedicated recycling channels and embed unique identifiers in battery packs to enable traceability throughout their lifecycle (Gu et al. 2024). Policies are reinforced through subsidies, gate fees, and integration with national digital infrastructure, including efforts to implement blockchain-based tracking. Beyond extended producer responsibility schemes, additional policy support—such as investment tax credits, concessional finance, or public-private partnerships—may be needed to overcome financial frictions that hinder the development and deployment of large-scale recycling infrastructure. Industrial coordination is also strong: leading recyclers like Brunp (a CATL subsidiary) operate close to battery production facilities, reducing logistical costs and environmental impacts.

The EU and the United States are also strengthening circularity requirements. The EU Battery Regulation introduces targets for material recovery and mandates minimum recycled content in new batteries starting in 2030 (Rizos and Urban 2024). A cornerstone of the regulation is the Digital Battery Passport, legally required by 2027, which will track origin, chemistry, performance, and due diligence across each battery's life. Extended Producer Responsibility schemes place the financial burden of recycling on manufacturers, while collection and reuse are prioritised over disposal. In the U.S., the Inflation Reduction Act indirectly promotes domestic recycling by linking tax credits for EVs and mineral processing to North American content, including recycled sources (IEA 2023b). These policy efforts reflect a broader global trend: embedding circular economy principles at every stage of the battery value chain, while addressing the technical and economic challenges of recycling diverse and evolving battery chemistries.

6 Conclusion

This review has shown that innovation, technological, organisational, and policy-based, is central to reconciling the growing demand for critical minerals with climate, economic, and geopolitical imperatives. As the energy transition accelerates, the challenge is not simply to secure more materials but to build a system that is more resilient, circular, and adaptive.

First, cost declines for clean technologies are no longer guaranteed. Volatile mineral prices, sharp post-boom corrections, and high concentration risks are dampening investment and threatening long-run learning curves. Policy tools like contracts-for-difference, cap-and-floor schemes, and strategic offtake agreements could help reduce revenue risk and enable more exploration, but remain underused in this sector.

Second, diversification is expensive and slow. Mining and refining projects outside dominant producer countries often face capital costs up to 50% higher, plus long permitting and construction timelines. Technological upgrades typically occur only at mine opening, making first-generation design decisions critical. Even accelerated permitting will not fully overcome these long lags. Public-private pilot projects—automated, renewables-powered, ESG-certified—can serve as testing grounds for new models and technologies.

Third, while recycling and substitution are essential, they will not eliminate risk. Scrap supply will be limited in the near term. Rare earth recycling from hard disks and industrial equipment poses technical challenges. New battery chemistries like LFP, sodium-ion, and manganese-rich lithium-ion may reduce reliance on cobalt or lithium, but shift attention to other potentially constrained materials like phosphoric acid and manganese sulphate.

Fourth, data and design are foundational to circularity. Digital product passports and traceability systems are crucial for enabling second-life and recycling markets. Furthermore, since some primary mining activities cannot be conducted in some jurisdictions due to a lack of transparency and traceability, traceability beyond second life and recycling may become crucial. Standards for modular design and material labelling can lower disassembly and separation costs. Clear regulation of end-of-life EV flows—currently inconsistent across jurisdictions—is also needed to unlock material recovery at scale.

Given these challenges, potential areas for policy action going forward include: (1) introducing price or revenue stabilisation mechanisms to reduce the impact of price volatility; (2) developing national strategies to de-risk and financial support early-stage investment (e.g. grants, tax credits, but also developing blended finance); (3) embedding circularity in design and regulation to ensure that products are durable, repairable, remanufacturable and recyclable (for instance by using product passports); and (4) building interoperable, open-access data systems for reserves, trade, ESG metrics and material flows.

Outstanding research questions include: How far can substitution scale without introducing new bottlenecks? Which policy instruments reduce financing costs most effectively for greenfield projects? Can AI-driven exploration meaningfully raise discovery rates? And how might rising demand from defence and AI sectors reshape mineral markets, and should countries coordinate procurement in response?

The criticality of minerals is not a fixed constraint—it is a policy and innovation challenge. With the right combination of finance, standards, policies, and open data, governments can turn today's material risks into tomorrow's enabling conditions for clean energy.

Future work should further complement this initial mapping of the CM innovation landscape by extending the range of innovation indicators. Examples include tracking early-stage scientific publications on CRM innovation, identifying key minerals using Natural Language Processing techniques, collecting data on venture capital deals or on the number of companies developing circular CM solutions. This would allow identifying knowledge gaps tied to specific CMs, with potential bottlenecks or choke points along the innovation value chain. Future avenues of research should also consider empirical evaluations of the impact of public policies on CM related innovation. Furthermore, there scope for more work to deepen our understanding of the linkage between ESG frameworks and technological traceability, which may be particularly useful in the Global South contexts where technology adaptation may be uniquely shaped by institutional, social, and territorial capacities. This could also inform the role of participatory governance in strengthening the social license to operate. Beyond innovation only, future work could aim to improve our understanding of how CM innovation diffuses across countries, in particular on the role of the regulatory framework in incentivizing technology transfers from foreign firms to local ones. Other technical analysis might provide comprehensive environmental assessments of emerging chemistries.

References

Acemoglu, Daron, and Joshua Linn. 2004. "Market Size in Innovation: Theory and Evidence from the Pharmaceutical Industry." *The Quarterly Journal of Economics* 119 (3): 1049–1090.

AfricaNews. 2022. "Zimbabwe Bans All Lithium Exports." *Africanews* (December 29). https://www.africanews.com/2022/12/29/zimbabwe-bans-all-lithium-exports/.

Aghion, Philippe, Antonin Bergeaud, Matthieu Lequien, and Marc J. Melitz. 2024. "The Heterogeneous Impact of Market Size on Innovation: Evidence from French Firm-level Exports." *Review of Economics and Statistics* 106 (3): 608–626.

Aghion, Philippe, Antoine Dechezleprêtre, David Hemous, Ralf Martin, and John Van Reenen. 2016. "Carbon Taxes, Path Dependency, and Directed Technical Change: Evidence from the Auto Industry." *The journal of political economy* 124 (1): 1–51.

Allan, Bentley B. 2025. "Establishing a Critical Minerals Club across North America." March 5. Accessed June 4, 2025.

Alliance, Global Battery. 2025. "Establishing a Sustainable and Responsible Battery Value Chain." Accessed June 4, 2025. https://www.globalbattery.org/.

Ambec, Stefan, Mark A Cohen, Stewart Elgie, and Paul Lanoie. 2013. "The Porter Hypothesis at 20: Can Environmental Regulation Enhance Innovation and Competitiveness?" *Review of Environmental Economics and Policy* 7 (1): 2–22.

Amici, Julia, Pietro Asinari, Elixabete Ayerbe, Philippe Barboux, Pascale Bayle-Guillemaud, R. Jürgen Behm, Maitane Berecibar, et al. 2022. "A Roadmap for Transforming Research to Invent the Batteries of the Future Designed within the European Large Scale Research Initiative Battery 2030+." *Advanced Energy Materials* 12 (17): 2102785.

Andersen, Mikael, and Joëlle Noailly. 2022. "Innovation and Environmental Policy in the Mining Sector." In *Global Challenges for Innovation in the Mining Industries,* edited by Alica Daly, David Humphreys, Julio Ruffo, and Giulia Valacchi. Cambridge: Cambridge University Press.

Andres, Pia, Eugenie Dugoua, and Marion Dumas. 2022. *Directed Technological Change and General Purpose Technologies: Can AI Accelerate Clean Energy Innovation?* Centre for Climate Change Economics, Policy; Grantham Research Institute on Climate Change, and the Environment.

Bacchetta, G, Cyril Rado, and Sorana Luca. 2022. "Short-loop recycling of sintered NdFeB magnets by Hydrogen Decrepitation." *World PM2022 Proceedings* (September 15): 5370650.

Balasubramanian, A. 2015. *Overview of Mineral Processing Methods.* Centre for Advanced Studies in Earth Sciences, University of Mysore, India.

"Battery Technology." 2021. July 22. Accessed June 3, 2025.

Beiter, P, Jérôme Guillet, Malte Jansen, Elizabeth J Wilson, and L Kitzing. 2023. "The Enduring Role of Contracts for Difference in Risk Management and Market Creation for Renewables." *Nature energy* 9 (December 5): 20–26.

Benchmark Mineral Intelligence. 2023. *Cobalt Market Report 2022.* Cobalt Institute, Guildford.

Bermel, L, R Cummings, B Deese, M Delgado, et al. 2024. "Clean Investment Monitor: Tallying the Two-year Impact of the Inflation Reduction Act."

Bistline, John, Neil R. Mehrotra, and Catherine Wolfram. 2023. *Economic Implications of the Climate Provisions of the Inflation Reduction Act.* National Bureau of Economic Research, Cambridge, MA.

Blois, Matt. 2025. "China Threatens to Stop Export of Iron-based Cathode Technology." Accessed June 3, 2025.

Bloom, Nick. 2007. "Uncertainty and the Dynamics of R&D." *American Economic Review* 97 (2): 250–255.

Bloom, Nick, Stephen Bond, and John Van Reenen. 2007. "Uncertainty and Investment Dynamics." *The Review of Economic Studies* 74 (2): 391–415.

Boer, Lukas, Andrea Pescatori, and Martin Stuermer. 2024. "Energy Transition Metals: Bottleneck for Net-zero Emissions?" *Journal of the European Economic Association* 22 (1): 200–229.

Brookings Institution. 2022. *China's Role in Supplying Critical Minerals for the Global Energy Transition: What Could the Future Hold?* LTRC Report.

Calzada Olvera, Beatriz. 2022. "Innovation in Mining: What Are the Challenges and Opportunities along the Value Chain for Latin American Suppliers?" *Mineral Economics* 35 (1): 35–51.

Carrara, Samuel, Patrícia Alves Dias, Beatrice Plazzotta, and Claudiu Pavel. 2020. *Raw Materials Demand for Wind and Solar Pv Technologies in the Transition Towards a Decarbonised Energy System.* EUR 30095 EN. Luxembourg: Publications Office of the European Union.

CATL. 2025. "CATL Unveils Shenxing PLUS, Enabling 1,000-km Range and 4C Superfast Charging." Accessed June 3, 2025.

Cecilia Jamasmie. 2021. "Tesla, Resource to Launch Final Pilot in DRC to Trace Cobalt from Mine to EVs." August 13. https://www.mining.com/tesla-resource-to-launch-final-pilot-in-drc-to-trace-cobalt-from-mine-to-evs/.

Chen, Chi, Dan Thien Nguyen, Shannon J Lee, Nathan A Baker, Ajay S Karakoti, Linda Lauw, Craig Owen, et al. 2024. "Accelerating Computational Materials Discovery with Machine Learning and Cloud High-performance Computing: From Large-scale Screening to Experimental Validation." *Journal of the American Chemical Society* 146 (29): 20009–20018. Accessed June 3, 2025.

Clavilier, James Hackett; Ester Sabatino; Matthew Bint; Dzaky Naradichiantama; Michael Gjerstad; Jonathan Bentham; Johannes Fischbach; Louis Bearn; Yurri. 2025. *Critical Raw Materials and European Defence.* The International Institute for Strategic Studies.

Copeland, B. 2008. "The Pollution Haven Hypothesis." *Handbook on Trade and the Environment* (December 28).

Corrigan, Caitlin C., and Svetlana A. Ikonnikova. 2024. "A Review of the Use of AI in the Mining Industry: Insights and Ethical Considerations for Multi-objective Optimization." *The Extractive Industries and Society* 17:101440.

Cui, Jun, Matthew Kramer, Lin Zhou, Fei Liu, Alexander Gabay, George Hadjipanayis, Balamurugan Balasubramanian, and David Sellmyer. 2018. "Current Progress and Future Challenges in Rare-earth-free Permanent Magnets." *Acta Materialia* 158:118–137.

Daly, Alica, David Humphreys, Julio Raffo, and Giulia Valacchi, eds. 2022. *Global Challenges for Innovation in Mining Industries.* Cambridge: Cambridge University Press.

Daly, Alica, Giulia Valacchi, and Julio D. Raffo. 2019. *Mining Patent Data: Measuring Innovation in the Mining Industry with Patents.* World Intellectual Property Organization, Geneva.

Dar, Afzal Ahmed, Zhi Chen, Gaixia Zhang, Jinguang Hu, Karim Zaghib, Sixu Deng, Xiaolei Wang, et al. 2025. "Sustainable Extraction of Critical Minerals from Waste Batteries: A Green Solvent Approach in Resource Recovery." *Batteries* 11 (2): 51.

Dave, Adarsh, Jared Mitchell, Sven Burke, Hongyi Lin, Jay Whitacre, and Venkatasubramanian Viswanathan. 2022. "Autonomous Optimization of Non-aqueous Li-ion Battery Electrolytes Via Robotic Experimentation and Machine Learning Coupling." *Nature Communications* 13 (1): 5454.

Delette, Gérard. 2023. "$Nd_2fe_{14}b$ Permanent Magnets Substituted with Non-critical Light Rare Earth Elements (ce, La): A Review." *Journal of Magnetism and Magnetic Materials* 577:170768.

Dionori, Francesco, and Maryam Zehtabchi. 2022. "The Role of Transport-related Innovation in the Mining Sector." In *Global Challenges for Innovation in the Mining Industries,* edited by Alica Daly, David Humphreys, Julio Ruffo, and Giulia Valacchi. Cambridge: Cambridge University Press.

Donnan, Shawn, and James Politi. 2014. "WTO Rules against China on 'rare Earths' Export Restrictions." *Financial Times* (March). https://www.ft.com/content/962a0ba4-b4e6-11e3-9166-00144feabdc0.

Duan, Yuwan, Ting Ji, Yi Lu, and Siying Wang. 2021. "Environmental Regulations and International Trade: A Quantitative Economic Analysis of World Pollution Emissions." *Journal of public economics* 203 (104521): 104521.

Dugoua, Eugenie. 2025. "Induced Innovation and International Environmental Agreements: Evidence from the Ozone Regime." *Review of Economics and Statistics.*

Dugoua, Eugenie, and Todd D Gerarden. 2025. "Induced Innovation, Inventors, and the Energy Transition." *American Economic Review: Insights* 7 (1): 90–106.

Durrheim, Raymond, Musa Manzi, Glen Nwaila, and Susan J. Webb. 2022. "Exploring for Deeply Buried Ore Deposits." In *Routledge Handbook of the Extractive Industries and Sustainable Development,* edited by Natalia Yakovleva and Edmund Nickless. Routledge Environment and Sustainability Handbooks. London, New York: Routledge.

Engel, Hauke, Patrick Hertzke, and Giulia Siccardo. 2019. *Second-life EV Batteries: The Newest Value Pool in Energy Storage,* April 30. Accessed June 4, 2025.

EUROBAT. 2024. *Battery Innovation Roadmap 2035.* EUROBAT.

European Commission. 2025. "Strategic Projects under the CRMA." Accessed June 4, 2025. https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/strategic-projects-under-crma_en.

Evenett, Simon, and Johannes Fritz. 2023. *Revisiting the China–Japan Rare Earths Dispute of 2010,* July 19. Accessed May 29, 2025.

Fernández, Paulina, Felipe Sánchez, Maria Mavroudi, Karin Ungerer, Philipp Hartlieb, and Michael Tost. 2025. "Research projects towards an innovative, digitalised, and responsible extractive industry: Examples from the Chair of Mining Engineering and Mineral Economics" [in en]. *BHM: Berg- und Huttenmannische Monatshefte* 170 (2): 81–87.

Ferreira-Filipe, Diogo A., Armando C. Duarte, Andrew S. Hursthouse, Teresa Rocha-Santos, and Ana L. Patrício Silva. 2025. "Biobased Strategies for E-waste Metal Recovery: A Critical Overview of Recent Advances." *Environments* 12 (1): 26.

Filippas, Alexandros, Georgios Sempros, and C. Sarafidis. 2021. "Critical Rare Earths: The Future of Nd & Dy and Prospects of End-of-life Product Recycling." *Materials Today: Proceedings* 37:4058–4063.

Filippou, Dimitrios, and Michael G. King. 2011. "R&D Prospects in the Mining and Metals Industry." *Resources Policy* 36 (3): 276–284.

Financial Times. 2025a. "Northvolt Files for Bankruptcy in Sweden." March 12. https://www.ft.com/content/21dbc9fa-2503-4a1d-a14c-7ac2b6f44303.

———. 2025b. "Northvolt's Fate Teaches Europe a Lesson: Stick to What You Are Good At." March 12. https://www.ft.com/content/70bb107b-ba69-4be6-9502-125f81e2afdd.

Fleming, Maxwell, Ian Lange, Sayeh Shojaeinia, and Martin Stuermer. 2023. "Mining in Space Could Spur Sustainable Growth." *Proceedings of the National Academy of Sciences* 120 (43): e2221345120.

Freire-González, Jaume, and David Vivanco. 2017. "The influence of energy efficiency on other natural resources use: An input-output perspective" [in en]. *Journal of cleaner production* 162 (September): 336–345.

Froese, Michelle. 2024. "How Cell-to-pack Transforms EV Battery Designs?" June 24. Accessed June 3, 2025.

Gagarin, Hannah, and Roderick G. Eggert. 2023. "Measuring Trade Flows of Sintered NdFeB Magnets and Li-ion Batteries: Reported Vs. Embedded US Imports." *Mineral Economics* 36 (4): 667–696.

Global Battery Alliance. 2025. "Battery Passport MVP Pilots." Accessed June 2, 2025. Accessed June 2, 2025. https://www.globalbattery.org/battery-passport-mvp-pilots/.

Gu, Xubo, Hanyu Bai, Xiaofan Cui, Juner Zhu, Weichao Zhuang, Zhaojian Li, Xiaosong Hu, and Ziyou Song. 2024. "Challenges and Opportunities for Second-life Batteries: Key Technologies and Economy." *Renewable and Sustainable Energy Reviews* 192 (114191): 114191.

Guo, Xingsen, Ning Fan, Yihan Liu, Xiaolei Liu, Zekun Wang, Xiaotian Xie, and Yonggang Jia. 2023. "Deep Seabed Mining: Frontiers in Engineering Geology and Environment." *International Journal of Coal Science & Technology* 10 (1): 1–31.

Harper, Gavin, Roberto Sommerville, Emma Kendrick, Laura Driscoll, Peter Slater, Rustam Stolkin, Allan Walton, et al. 2019. "Recycling Lithium-ion Batteries from Electric Vehicles." *Nature* 575:75–86.

Hossain, M. A. Motalib, Pin Jern Ker, Sieh Kiong Tiong, T. M. Indra Mahlia, and M. A. Hannan. 2024. "Recent Progress in Nanomaterials of Battery Energy Storage: A Patent Landscape Analysis, Technology Updates, and Future Prospects." *Nanotechnology Reviews* 13 (1): 20230215.

Humphreys, David. 2020. "Mining Productivity and the Fourth Industrial Revolution." *Mineral Economics* 33 (1-2): 115–125.

IEA. 2020. *Innovation in Batteries and Electricity Storage.* IEA, Paris.

———. 2023a. *Critical Minerals Market Review 2023.* IEA, Paris.

IEA. 2023b. *Global EV Outlook 2023.* IEA, Paris.

———. 2023c. *Global EV Outlook 2025.* IEA, Paris.

———. 2024a. *Energy Technology Perspectives 2024.* Paris: IEA.

———. 2024b. *Global Critical Minerals Outlook 2024.* Paris: IEA.

———. 2025a. *Energy and AI.* IEA, Paris.

———. 2025b. *Global Critical Mineral Outlook 2025.* IEA, Paris.

Igogo, Tsisilile, Kwame Awuah-Offei, Alexandra Newman, Travis Lowder, and Jill Engel-Cox. 2021. "Integrating Renewable Energy into Mining Operations: Opportunities, Challenges, and Enabling Approaches." *Applied Energy* 300:117375.

Institute, Rocky Mountain. 2024. "Battery Circular Economy Initiative - Dashboards." November 7. Accessed June 4, 2025. https://rmi.org/battery-circular-economy-initiative/resources/dashboards/?dashboard=2.

International Council on Mining and Metals (ICMM). 2019. *Adaptation to a Changing Climate: Building Resilience in the Mining and Metals Industry.* London.

Jébrak, Michel. 2012. *Innovations in Mineral Exploration: Targets, Methods and Organization since the First Globalization Period.* Working Paper. University of Quebec.

Joint Research Centre. 2023. *Clean Energy Technology Observatory, Wind Energy in the European Union: Status Report on Technology Development, Trends, Value Chains and Markets : 2023.* Technical report. European Union.

Joshi, Khyati, Sara Magdouli, and Satinder Kaur Brar. 2025. "Bioleaching for the Recovery of Rare Earth Elements from Industrial Waste: A Sustainable Approach." *Resources, Conservation, and Recycling* 215:108129.

Kastanaki, Eleni, and Apostolos Giannis. 2023. "Dynamic Estimation of End-of-life Electric Vehicle Batteries in the EU-27 Considering Reuse, Remanufacturing and Recycling Options." *Journal of Cleaner Production* 393:136349.

Katona, Mihály, and Tamás Orosz. 2024. "Circular Economy Aspects of Permanent Magnet Synchronous Reluctance Machine Design for Electric Vehicle Applications: A Review." *Energies* 17 (6): 1408.

Khollam, Aamir. 2025. "Solid-state EV Battery Breakthrough with Ni Cathode Retains 80% Capacity After 300 Cycles." March 6. Accessed June 3, 2025.

Kim, Jaden, Florence Jaumotte, Augustus J Panton, and Gregor Schwerhoff. 2025. "Energy Security and the Green Transition." *Energy Policy* 198:114409.

Kitzing, L, A Held, M Gephart, F Wagner, V Anatolitis, and C Klessmann. 2024. "Contracts-for-difference to Support Renewable Energy Technologies: Considerations for Design and Implementation."

Kwade, Arno, Wolfgang Haselrieder, Ruben Leithoff, Armin Modlinger, Franz Dietrich, and Klaus Droeder. 2018. "Current Status and Challenges for Automotive Battery Production Technologies." *Nature Energy* 3 (4): 290–300.

Lakshmi, A. Anantha, and Camilla Hodgson. 2025. ""the Opec of Nickel": Indonesia's Control of a Critical Metal." *Financial Times* (February). https://www.ft.com/content/0bbbe7c7-12a1-43ba-8bef-c5c546367a0e.

Lehmann, Erik E., Julian Schenkenhofer, and Silvio Vismara. 2025. "Hidden Champions and Knowledge Spillovers: Innovation-enhancing Agglomeration Effects and Niche Technology Specificity." *Small Business Economics* N/A (N/A): 1–21.

Liang, Xiao, Nan Tian, Diego Lopes da Silva, Lorenzo Scarazzato, Zubaida Karim, and Jade Guiberteau Ricard. 2025. *Trends in World Military, 2024.* Stockholm International Peace Research Institute.

Liu, Ling, Mehboob Ul Hassan, Moona Shamim, Ilma Sharif, and Syed Tehseen Jawaid. 2025. "How global supply chain pressure and economic policy uncertainty impact the prices of energy transition metals" [in en]. *Review of world economics* 161 (4): 1573–1597.

Maier, Raina M, Fernando Díaz-Barriga, James A Field, James Hopkins, Bern Klein, and Mary M Poulton. 2014. "Socially responsible mining: the relationship between mining and poverty, human health and the environment" [in en]. *Reviews on environmental health* 29 (1-2): 83–89.

Makuza, Brian, Qinghua Tian, Xueyi Guo, Kinnor Chattopadhyay, and Dawei Yu. 2021. "Pyrometallurgical Options for Recycling Spent Lithium-ion Batteries: A Comprehensive Review." *Journal of Power Sources* 491:229622.

Matousek, Mark. 2025. "Ai-powered Mining Firm Backed by Bill Gates and Jeff Bezos Is Now Worth $2.96 Billion As It Takes on Chinese Rivals." January. https://fortune.com/2025/01/02/kobold-mining-jeff-bezos-bill-gates-investment-round-copper-lithium/.

McCrossan, Conor, and Karthickeshwar Shankaravelu. 2021. "A Review of the Second Life Electric Vehicle Battery Landscape from a Business and Technology Perspective." In *2021 IEEE Green Technologies Conference (GreenTech),* 416–423. Denver, CO: IEEE.

Meinert, Lawrence D., Gilpin R. Robinson, and Nedal T. Nassar. 2016. "Mineral Resources: Reserves, Peak Production and the Future." *Resources* 5 (1): 14.

Metzger, Philipp, Sandro Mendonça, José A. Silva, and Bruno Damásio. 2023. "Battery Innovation and the Circular Economy: What Are Patents Revealing?" *Renewable Energy* 209:516–532.

Miller, Hugh, Simon Dikau, Romain Svartzman, and Stéphane Dees. 2023. *The Stumbling Block in 'the Race of Our Lives': Transition-critical Materials, Financial Risks and the NGFS Climate Scenarios.* Banque de France.

Miller, Hugh, and Juan-Pablo Martinez. 2025. *The Changing Dynamics in Global Metal Markets: How the Energy Transition and Geo-fragmentation May Disrupt Commodity Prices.* OECD Publishing, Paris.

"Modular Electric Drive Matrix (MEB)." 2025. Accessed June 3, 2025.

Mugurusi, Godfrey, and Emmanuel Ahishakiye. 2022. "Blockchain Technology Needs for Sustainable Mineral Supply Chains: A Framework for Responsible Sourcing of Cobalt." *Procedia Computer Science* 200:638–647.

Naegler, Tobias, Sebastian Rauner, Alois Dirnaichner, Patrick Jochem, Steffen Schlosser, and Gunnar Luderer. 2025. "Raw Material Demand and Geopolitical Risk in Carbon-neutral Futures." *Energy Policy* 204:114622.

News, AP. 2025. "China's BYD Launches EV Charging System It Says Works Nearly As Fast As a Fill Up." Accessed June 3, 2025.

Nextsprints Team. 2025. "Redwood Materials Product Strategy Guide — Circular Economy." February 1. https://nextsprints.com/guide/redwood-materials-product-strategy-guide.

"NIO Reaches 30 Power Swap Stations in Europe and Over 2,200 Worldwide." 2025. Accessed June 4. https://www.nio.com/news/NIO-reaches-30-Power-Swap-Stations-in-Europe..

North Atlantic Treaty Organization. 2023. *Securing the U.S. Aerospace and Defense Critical Minerals Supply Chain.* Aerospace Industry Association.

———. 2025. *Defence-critical Supply Chain Security Roadmap.* North Atlantic Treaty Organization.

Odell, Scott D., Anthony Bebbington, and Karen E. Frey. 2018. "Mining and Climate Change: A Review and Framework for Analysis." *The Extractive Industries and Society* 5 (1): 201–214.

Oliver Wyman. 2023. *Independent Review of Events in the Nickel Market in March 2022: Final Report.* London Metal Exchange, London.

Oncea, John. 2025. "How the Defense Industry Is Using GaN Technology." Accessed June 4. https://www.rfglobalnet.com/doc/how-the-defense-industry-is-using-gan-technology-0001.

Onifade, Moshood, John A. Adebisi, and Tawanda Zvarivadza. 2024. "Recent Advances in Blockchain Technology: Prospects, Applications and Constraints in the Minerals Industry." *International Journal of Mining, Reclamation and Environment* 38 (7): 497–533.

Pavel, Claudiu C., Roberto Lacal-Arántegui, Alain Marmier, Doris Schüler, Evangelos Tzimas, Matthias Buchert, Wolfgang Jenseit, and Darina Blagoeva. 2017. "Substitution Strategies for Reducing the Use of Rare Earths in Wind Turbines." *Resources Policy* 52:349–357.

Pavel, Claudiu C., Alain Marmier, Patrícia Alves Dias, Darina Blagoeva, Evangelos Tzimas, Doris Schüler, Tobias Schleicher, Wolfgang Jenseit, Stefanie Degreif, and Matthias Buchert. 2016. *Substitution of Critical Raw Materials in Low-carbon Technologies: Lighting, Wind Turbines and Electric Vehicles.* EUR 28152 EN. Luxembourg: Publications Office of the European Union.

Pincheira, Miguel, Mattia Antonini, and Massimo Vecchio. 2022. "Integrating the IoT and Blockchain Technology for the Next Generation of Mining Inspection Systems." *Sensors* 22 (3): 899.

Podmiljšak, Benjamin, Boris Saje, Petra Jenuš, Tomaž Tomše, Spomenka Kobe, Kristina Žužek, and Sašo Šturm. 2024. "The Future of Permanent-magnet-based Electric Motors: How Will Rare Earths Affect Electrification?" *Materials* 17 (4): 848.

Popp, David. 2002. "Induced Innovation and Energy Prices." *The American economic review:* 160–180.

———. 2019. "Environmental Policy and Innovation: A Decade of Research." *International Review of Environmental and Resource Economics* 13 (3-4): 265–337.

Rahman, Kazi Faridur, Shaili Falina, Mohamed Fauzi Packeer Mohamed, Hiroshi Kawarada, and Mohd Syamsul. 2024. "The Role of Gallium Nitride in the Evolution of Electric Vehicles: Energy Applications, Technology, and Challenges." *Applied physics reviews* 11 (3): 031322. Accessed June 4, 2025.

Rani, Archana. 2023. "Ford Partners with Vale and Huayou on $4.5bn Nickel Plant in Indonesia." March 31. Accessed June 4, 2025. https://www.mining-technology.com/news/ford-vale-nickel-indonesia/.

Reboredo, Juan C, and Andrea Ugolini. 2024. "The Impact of Uncertainty Shocks on Energy Transition Metal Prices." *Resources Policy* 95:105161.

"Renault Reaches Milestone of 100,000 E.V. Batteries Leased." 2017. March 21. Accessed June 4, 2025. https://media.renault.com/renault-reaches-milestone-of-100000-ev-batteries-leased/.

Rizos, Vasileios, and Patricia Urban. 2024. *Implementing the EU Digital Battery Passport: Opportunities and Challenges for Battery Circularity.* CEPS.

Rozendaal, Rik, and Herman Vollebergh. 2025. "Policy-induced Innovation in Clean Technologies: Evidence from the Car Market." *Journal of the Association of Environmental and Resource Economists* 12 (3): 565–598.

Sánchez, Felipe, and Philipp Hartlieb. 2020. "Innovation in the Mining Industry: Technological Trends and a Case Study of the Challenges of Disruptive Innovation." *Mining, Metallurgy & Exploration* 37 (5): 1385–1399.

Savelli, Iacopo, Jeffrey Hardy, C Hepburn, and Thomas Morstyn. 2022. "Putting Wind and Solar in Their Place: Internalising Congestion and Other System-wide Costs with Enhanced Contracts for Difference in Great Britain." *Energy economics* (August 1).

Schot, Johan, and Frank W. Geels. 2007. "Niches in Evolutionary Theories of Technical Change: A Critical Survey of the Literature." *Journal of Evolutionary Economics* 17 (4): 605–622.

Sengupta, Mritunjoy. 2021. *Environmental Impacts of Mining: Monitoring, Restoration, and Control.* CRC Press.

Severson, Kristen A, Peter M Attia, Norman Jin, Nicholas Perkins, Benben Jiang, Zi Yang, Michael H Chen, et al. 2019. "Data-driven Prediction of Battery Cycle Life before Capacity Degradation." *Nature energy* 4 (March 25): 383–391.

Shipping, American Bureau of. 2020. *Guide for Subsea Mining.*

Shirmard, Hojat, Ehsan Farahbakhsh, R. Dietmar Müller, and Rohitash Chandra. 2022. "A Review of Machine Learning in Processing Remote Sensing Data for Mineral Exploration." *Remote Sensing of Environment* 268:112750.

Simas, Moana, Fabian Rocha Aponte, and Kirsten Svenja Wiebe. 2022. *The Future Is Circular: Circular Economy and Critical Minerals for the Green Transition.* SINTEF akademisk forlag, Oslo.

Slanger, Dan. 2023. "Understanding the Clean Miles Standard Regulation for Ridehailing Companies." June 28. Accessed June 4, 2025. https://rmi.org/understanding-the-clean-miles-standard-regulation-for-ride-hailing-companies/.

Smith, Braeton, Matthew Riddle, Matthew Earlam, Chukwunwike Iloeje, and David Diamond. 2022. *Rare Earth Permanent Magnets: Supply Chain Deep Dive Assessment.* U.S. Department of Energy Response to Executive Order 14017, "America's Supply Chains". US Deparment of Energy.

Smith, Braeton J., and Roderick G. Eggert. 2018. "Costs, Substitution, and Material Use: The Case of Rare Earth Magnets." *Environmental Science & Technology* 52 (6): 3803–3811.

Sonter, Laura J., Saleem H. Ali, and James E. M. Watson. 2018. "Mining and Biodiversity: Key Issues and Research Needs in Conservation Science." *Proceedings of the Royal Society B: Biological Sciences* 285 (1892).

Suli, Liyananadirah Mat, Wan Hanisah Wan Ibrahim, Badhrulhisham Abdul Aziz, Mohd Rizauddin Deraman, and Nurul Ain Ismail. 2017. "A Review of Rare Earth Mineral Processing Technology." *Chemical Engineering Research Bulletin:* 20–35.

Sulzer, Valentin, Peyman Mohtat, Antti Aitio, Suhak Lee, Yen T Yeh, Frank Steinbacher, Muhammad Umer Khan, et al. 2021. "The Challenge and Opportunity of Battery Lifetime Prediction from Field Data." *Joule* 5 (8): 1934–1955.

Theodoro, Suzi Huff, David A. C. Manning, André Mundstock Xavier De Carvalho, Fabiane Rodrigues Ferrão, and Gustavo Rosa De Almeida. 2022. "Soil Remineralizer." In *Routledge Handbook of the Extractive Industries and Sustainable Development,* edited by Natalia Yakovleva and Edmund Nickless, 261–281. Routledge Environment and Sustainability Handbooks. London, New York: Routledge.

Tolbert, Isaac, Namrata Kogalur, Jonathan Martin, and Andrew Meintz. 2024. *Charin Megawatt Charging System: 4th Event Summary Report.* National Renewable Energy Laboratory.

Tong, Zhuoya, and Xiaobo Zhu. 2025. "A Patent Landscape Analysis on the Recycling of Lithium-ion Battery Positive Electrode Materials: Trends, Technologies, and the Future." *Batteries* 11 (3): 110.

Trupp, Addison. 2025. *Resources for Resources: Financing Critical Minerals Supply Chains.* SAFE, January 16. Accessed June 4, 2025.

U.S. Department of Energy. 2023. *2023 Critical Materials Assessment.* Advanced Materials & Manufacturing Technologies Office, Washington, D.C.

United Nations Environment Programme. 2024. *Critical Transitions: Circularity, Equity and Responsibility in the Quest for Energy Transition Minerals.* United Nations Environment Programme, Nairobi.

Upstill, Garrett, and Peter Hall. 2006. "Innovation in the Minerals Industry: Australia in a Global Context." *Resources Policy* 31 (3): 137–145.

Valacchi, Giulia, Julio Raffo, Alica Daly, and David Humphreys. 2023. "Mining Innovation and Economic Cycles: How Commodity Prices Affect Mining Related Patenting?" *Mineral Economics* 36 (3): 437–461.

Van Roy, Vincent, Daniel Vertesy, and Giacomo Damioli. 2019. *AI and Robotics Innovation: A Sectoral and Geographical Mapping Using Patent Data.* Global Labor Organization (GLO), Essen.

Wang, Xinyang, Siyuan Li, Weidong Zhang, Duo Wang, Zeyu Shen, Jieping Zheng, Houlong L. Zhuang, Yi He, and Yingying Lu. 2021. "Dual-salt-additive Electrolyte Enables High-voltage Lithium Metal Full Batteries Capable of Fast-charging Ability." *Nano Energy* 89:106353.

Weng, Andrew, Eric Dufek, and Anna Stefanopoulou. 2023. "Battery Passports for Promoting Electric Vehicle Resale and Repurposing." *Joule* 7 (5): 837–842.

Whitworth, Anne J., Elizaveta Forbes, Isabella Verster, Vladimir Jokovic, Bellson Awatey, and Anita Parbhakar-Fox. 2022. "Review on Advances in Mineral Processing Technologies Suitable for Critical Metal Recovery from Mining and Processing Wastes." *Cleaner Engineering and Technology* 7:100451.

Widmer, James D., Richard Martin, and Mohammed Kimiabeigi. 2015. "Electric Vehicle Traction Motors without Rare Earth Magnets." *Sustainable Materials and Technologies* 3:7–13.

WIPO. 2019. *WIPO Technology Trends 2019: Artificial Intelligence.* World Intellectual Property Organization, Geneva.

World Bank. 2023. *Circular Business Model for Vanadium Use in Energy Storage.* World Bank.

Wu, Jiawei, Mengting Zheng, Tiefeng Liu, Yao Wang, Yujing Liu, Jianwei Nai, Liang Zhang, Shanqing Zhang, and Xinyong Tao. 2023. "Direct Recovery: A Sustainable Recycling Technology for Spent Lithium-ion Battery." *Energy Storage Materials* 54:120–134.

Wu, Zhenzhen, Cheng Zhang, Fangfang Yuan, Miaoqiang Lyu, Pan Yang, Lei Zhang, Ming Zhou, Liang Wang, Shanqing Zhang, and Lianzhou Wang. n.d. "Ni-rich Cathode Materials for Stable High-energy Lithium-ion Batteries." *Nano Energy* 126 (109620): 109620.

Yang, Chen, and Xin-Yu Mu. 2023. "Mapping the Trends and Prospects of Battery Cathode Materials Based on Patent Landscape." *Frontiers in Energy* 17 (6): 822–832.

Yang, Fanfan, Renguang Zuo, and Oliver P. Kreuzer. 2024. "Artificial Intelligence for Mineral Exploration: A Review and Perspectives on Future Directions from Data Science." *Earth-Science Reviews* 258:104941.

Yik, Jackie T, Carl Hvarfner, Jens Sjölund, Erik J Berg, and Leiting Zhang. 2025. "Accelerating Aqueous Electrolyte Design with Automated Full-cell Battery Experimentation and Bayesian Optimization." *Cell reports. Physical science* 6 (5): 102548. Accessed June 3, 2025.

Zentner, Ellen. 2025. *Megatrends: How AI and Tech Are Redefining Global Defense,* May 1. Accessed June 4, 2025. https://www.morganstanley.com/articles/investing-in-defense-stocks.

Zhang, Weiguo, Jiangyun Zhang, Yanxin Hu, Li Zhang, Wenjun Zhang, Youpeng Chen, Guoqing Zhang, Liqin Jiang, Zhite Dai, and Yuliang Wen. 2024. "Investigations on the Essential Causes of the Degrading Properties of Ternary Lithium-ion Batteries with Different Nickel Content during Thermal Runaway Stage." *International Journal of Electrochemical Science* 19 (3): 100491.

Zhang, Yuanbo, Foquan Gu, Zijian Su, Shuo Liu, Corby Anderson, and Tao Jiang. 2020. "Hydrometallurgical Recovery of Rare Earth Elements from Ndfeb Permanent Magnet Scrap: A Review." *Metals* 10 (6): 841.

Zhao, Yanyan, Oliver Pohl, Anand I Bhatt, Gavin E Collis, Peter J Mahon, Thomas Rüther, and Anthony F Hollenkamp. 2021. "A Review on Battery Market Trends, Second-life Reuse, and Recycling." *Sustainable chemistry* 2 (1): 167–205.

Zheng, Shiqin, Shiwei Yang, Jiangyi Chen, Dong Wu, Bowen Qi, Chenyang Zhang, Wen Deng, et al. 2024. "New Progresses in Efficient, Selective, and Environmentally Friendly Recovery of Valuable Metal from E-waste and Industrial Catalysts." *Advanced Sustainable Systems* 8 (6): 2300512.

Zhu, Juner, Ian Mathews, Dongsheng Ren, Wei Li, Daniel Cogswell, Bobin Xing, Tobias Sedlatschek, et al. 2021. "End-of-life or Second-life Options for Retired Electric Vehicle Batteries." *Cell reports. Physical science* 2 (8): 100537.