



Assessing critical mineral occurrence in battery technologies

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ABSTRACT

The prevailing geopolitical context has amplified the centrality of core material inputs in the interaction between technological innovation, economic security, and the climate emergency. Battery technologies represent one of the frontiers in this evolving landscape. In this paper, we examine the link between innovation in these technologies and their material inputs, assessed in terms of mineral occurrence in a sample of 33,036 full-text battery patents published from 2000 to 2021. Our findings, which cover 19 battery technologies, show that, on average, battery technologies increasingly rely on critical minerals. The analysis further reveals a rich tapestry of critical minerals beyond the conventional set of key battery minerals, namely lithium. Evidence shows that chromium, gallium, germanium, molybdenum, niobium, phosphate, silicon, tantalum, tellurium, titanium, and zirconium are all growing in relative importance. Analysis of battery technology specialisation profiles and patterns further highlight inventor countries' critical mineral needs. While the United States has grown more specialised in sodium-ion batteries, China shows a relative advantage in magnesium-ion, sodium-ion and lithium-ion batteries. Significantly, these patterns similarly reflect diverging paradigmatic shifts in battery innovation along a global “North-South” divide. We conclude with a discussion of potential pathways for battery development and propose avenues for further enquiry at the interface of mineral criticality and geoeconomics.

1. Introduction

Propelled by the rapid deployment of clean energy technologies, global demand for minerals is set to quadruple by 2040 (International Energy Agency [IEA], 2021). Further estimates point out that certain minerals will need more than 450 % growth in production by 2050 (Hund et al., 2023). In recent years, from 2017 to 2022, there has already been a doubling in the market size of these minerals (IEA, 2023a). Consistent with this outlook is the push by major countries to pursue “self-reliance”, “economic and national security”, or “open strategic autonomy” as a policy strategy amid shifting geopolitical dynamics (see Edler et al., 2020, 2023 for a discussion on the concept of “technological sovereignty” and its variants). These trends are poised to create substantial pressure for so-called critical minerals, i.e. metals and minerals that are both strategically important and at risk of supply

disruption¹ (European Commission [EC], 2023a).

However, the global sourcing chain for critical minerals is fraught with bottlenecks. The IEA (2021) finds that the current supply of and investment plans for many critical minerals will fail to meet the expected surge in demand. For one, a high concentration of reserves, production, and processing capabilities are located in a few geographic clusters and thus subject the supply chain to potential risks, distress, and disruptions. A few examples suffice to position the dilemma. With nearly 50 % of known cobalt reserves, the Democratic Republic of Congo (hereafter “DRC”) is the world's largest source of the mineral, accounting for approximately 70 % of global cobalt output. Australia, Chile, and the People's Republic of China (hereafter “China”) make up over 80 % of the global share of lithium production. China alone is home to 60 % of the global production of rare earth elements (REEs²) and is responsible for processing close to 90 % of REEs and over 50 % of cobalt and lithium

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¹ We adopt the European Commission's (EC) definition of critical raw materials.

² Rare earth elements (REEs) refer to a group of 17 elements composed of scandium, yttrium, and the 15 lanthanides. Contrary to their name, some REEs are relatively abundant, however are difficult to find in pure form since they are contained in the same ore, making their extraction expensive. They further fall into two categories, namely heavy REEs (HREEs) and light REEs (LREEs) (International Union of Pure and Applied Chemistry, 2005; USGS, n.d.).

(IEA, 2021). A confluence of other factors, including low substitution, declining ore quality, and long lead times (over 10 years on average), further aggravate the risk of potential strains on supply chains (IEA, 2021; Khan et al., 2016). Additionally, while limited solutions, including recycling and the recovery of minerals from mine tailings, are being considered (see Araya et al., 2021), these remain uncertain insofar as their economic viability and market incentives are concerned (International Renewable Energy Agency [IRENA], 2023).

Scientific literature on critical minerals is as broad as it is diverse (Abraham, 2015; Fraser et al., 2021; Grandell et al., 2016; Gunn, 2014; Hache et al., 2019; Månberger and Johansson, 2019; Olivetti et al., 2017; Sovacool, 2019). Yet recent studies have pointed to a lack of cross-disciplinary collaboration. Corbet et al. (2019), for instance, find that despite growing research interest in the financial economics of precious metals (i.e. gold, silver, platinum and palladium), scientific output in the field is largely siloed. Marty and Ruel (2025) show that from a sustainability, resilience and geopolitical perspectives, existing research streams on the challenges of rare metals (defined to include REEs, critical materials, and conflict minerals) supply chains are often addressed in isolation, with limited integration across these dimensions. These findings prove especially relevant as national strategies increasingly stress the role of interdisciplinary research in enhancing circularity along the critical minerals value chain (see European Parliamentary Research Service [EPRS], 2024; EC, 2023b; McDowall et al., 2017).

Relatedly, the impact of innovation on mineral criticality has not been sufficiently addressed in the literature (Diemer et al., 2022; Ku et al., 2018; Li et al., 2024). Vakulchuk et al. (2020), for example, find that minimal attention is given to the potential of innovations in technology to alter, substitute, or reduce future demand for these minerals. Similar concerns are echoed in a recent literature review which highlights the limitations of mineral demand estimates to account for innovation and mineral efficiency (Calderon et al., 2024). In the same vein, studies from leading sources on mineral supply chain data reinforce that future research move beyond linear projections to assess how technological innovation, material substitution and efficiency could moderate or change the critical mineral demand landscape (IEA, 2021; IRENA, 2023, 2024; United Nations Conference on Trade and Development [UNCTAD], 2025). Not only can “[n]ew product introductions...create inflection points (both upward and downward) as new technologies...require new materials or reduce or eliminate others” (Ku et al., 2024, p. 1213), but in the specific case of battery technologies, the subject of this study, “[i]nnovation has already decreased the demand for critical [minerals] significantly” (IRENA, 2024, p. 12).

To address these gaps, we seek to focus on a core technology for ecological transition and digital transformation while capturing otherwise overlooked interactions between critical minerals and battery innovation, such as security concerns (Shiquan and Deyi, 2023) and resource pressures (Vera et al., 2023). Accordingly, for the purposes of this paper, “clean energy technologies” refers to a broad range of technical solutions and systems that contribute to reducing greenhouse gas (GHG) emissions and advancing the global energy transition toward net zero. These technologies are designed to minimize environmental impacts, improve energy efficiency, and support the adoption of renewable and sustainable energy sources. According to the IEA (2024b), major clean energy technologies include solar photovoltaics (PV), wind turbines, electric vehicles (EVs), electrolyzers, heat pumps and batteries. Collectively, as of 2023, these represented a global market value of over USD 700 billion and are projected to exceed USD 2 trillion in market value by 2035 (IEA, 2024b, p.120).

Batteries constitute one of the chief drivers of global demand for critical minerals (IEA, 2021). Advances in battery technology (e.g. via the development of new battery chemistries) alongside significant reductions in battery costs (up to 90 % decline in average cost since 2010) (IEA, 2024a, p.17) have contributed to the widespread adoption of electric mobility and fostered greater energy storage capacity, placing batteries at the forefront of decarbonisation efforts (IEA, 2024a; 2024c;

UNCTAD, 2025). Batteries power a diverse and growing range of applications, among them portable consumer devices, EVs and behind-the-meter power systems (IEA, 2024a; Hund et al., 2023). In 2023, the total battery capacity deployed in the energy sector was four times the volume relative to 2020. In the same year, battery storage became the “fastest growing” among clean energy technologies (IEA, 2024a, p. 11).

While much of the focus has been on battery development, beyond the more conventional “battery minerals” (i.e., lithium, nickel, cobalt, manganese and graphite), the relative importance of other critical minerals analysed in this study remains underexplored (Carr-Wilson et al., 2024). A more comprehensive examination of the critical mineral composition of battery technologies is, therefore, of heightened scientific and strategic interest. This study springs from the premise that battery innovation is not neutral owing to the type and volume of mineral requirements on which a post-fossil-fuel future is predicated. Thus, considering the dynamic and context-sensitive nature of criticality, our analysis examines a wider set of 36 critical minerals. We employ this framework to guide an empirical exploration into the dynamics of mineral criticality with respect to technological innovation.

Specifically, the link between battery technologies and the critical minerals needed to sustain them is addressed from an innovation studies angle – patents are commonly used indicators of technological capability and change, providing quantifiable insights into inventive activity and the focus of research and development (R&D) efforts. The use of patent-based analysis in innovation studies highlights its significance in innovation measurement frameworks (Archibugi and Planta, 1996; Basberg, 1987; Castellaci et al., 2005). Notably, few studies (e.g. European Patent Office [EPO] and IEA, 2020; Metzger et al., 2023; Silva et al., 2023), offer systematic mapping of patenting trends in battery technologies, supporting evidence-based technology monitoring and innovation assessment in this domain. In this paper, we advance this line of work by focusing on the mineral content of these inventions. By the same token, we note that the use of patents as a proxy for innovation has well-documented limitations. Not all inventions are patented and not all patents map to commercial outcomes including in fast-moving high-tech fields (Jaffe and Trajtenberg, 2002; Mendonça, 2006; Mendonça et al., 2021). Similar considerations extend to the propensity to patent which varies across industry, regions, and over time (Lerner and Seru, 2022; Scherer, 1983; Van Zeebroeck et al., 2009), which is why the innovation indicators agenda remains vibrant and evolving (see Castaldi and Mendonça, 2022; Mendonça et al., 2004).

Our analysis covers 33,036 unique EPO battery patents published between 2000 and 2021 and aggregated in terms of international patent families (IPFs). These are first classified according to the International Patent Classification (IPC) system, a hierarchical scheme that enables detailed identification of technological content within patents (World Intellectual Property Organization [WIPO], 2014). We then set out to map the mineral composition of the identified battery patents using text-mining techniques to parse and extract all possible occurrences of the selected critical minerals. To operationalise the critical mineral inputs we offer a novel consolidation of lists proposed in IEA, World Bank and EU previous efforts. The relative frequencies of the materials employed in a given technological advance are taken for highlighting the significance of each mineral in a patent. This combined exploration of the classic patent indicator with the new capabilities for automatic big data in-text document perusal remains an underutilised research approach (Biggi et al., 2022), especially in a sustainability-related and sovereignty-sensitive policy context (Mendonça et al., 2021).

From this setup we aim to answer the following questions: (i) Are battery technologies becoming more dependent on critical minerals? (ii) Which critical minerals are gaining relative importance over time? (iii) What are the evolving characteristics of battery innovation associated with critical minerals? (iv) What do the findings suggest about the direction of future technological development and geoeconomic dynamics?

The results highlight a marked rise in mineral occurrence in battery-related patents and shed light on an emerging set of critical minerals – namely, chromium, gallium, germanium, molybdenum, niobium, phosphate, silicon, tantalum, tellurium, titanium and zirconium. While we are beginning to see the increased relevance of some of these less conventional battery minerals play out commercially, such as in the case of phosphate and silicon, inventive breakthroughs with respect to the vast majority have yet to surface, potentially opening interesting pathways for the future of battery innovation. A closer look at countries' technological specialisation reveals striking contrasts in the technological profile and direction of national battery development. Taking China and the United States (hereafter "US") as benchmarks, we find that between 2015 and 2021, aside from organic radical batteries, where the US held an unmatched advantage in 2015, the US tended toward despecialisation across most battery domains. Sodium-ion batteries emerged as the only technology to register increased specialisation during this period. Conversely, China is characterised by a higher degree of diversification of its technology profile with a higher-than-average specialisation in magnesium-ion, sodium-ion and lithium-ion batteries. These reflect larger shifts along a North-South divide, exemplified by specialisation patterns of G7 and BRICS + countries. While both economic blocs display increased specialisation in technologies such as sodium-ion, magnesium-ion and solid-state batteries, diverging trajectories can be seen for redox flow, lithium-ion, rechargeable alkaline, organic radical and nickel-iron technologies. These results are revelatory at best insofar as national R&D strategies for critical mineral are concerned and have important considerations for policymakers in an era in which geoeconomics becomes a defining context.

This paper is structured as follows. Section 2 explores the role of critical minerals in the intersection between technological innovation, economic security and the climate emergency. It also grounds the ongoing debate on critical minerals supply chain resilience and security within the current state of geopolitics. Section 3 provides an outline of the data collection and methodology. We present our analysis and research findings in section 4. Section 5 concludes this study.

2. Mineral criticality

A variety of core material inputs, both manufactured (e.g. semiconductors, cadmium telluride thin film, etc.) and raw (e.g. germanium, platinum, crystalline silicon, etc.) underpin the deployment of clean energy technologies such as solar PV, wind turbines, and batteries (Fig. 1). In recent years, the increase in the demand for these materials has underscored their criticality in light of their central role in the transition to a low-carbon economy.

"Criticality" refers to the combined assessment of a mineral's economic or strategic importance and its supply risk, with particular attention to the features that make supply especially vulnerable to disruptions in the short term (EC, 2011; 2023a). These include, but are not limited to, inelasticity of supply (e.g., when supply cannot respond rapidly to increased demand due to extended supply chains or economic bottlenecks), geographic concentration of production (e.g., reliance on a limited number of sources for extraction, processing or refining), and dependence on co-/by-product status (e.g., many critical minerals are not mined directly but as by-products, making their availability dependent on the extraction rates of host metals) (EC, 2011; 2023a). Furthermore, criticality is intrinsically dynamic (Ramdoo et al., 2023) and context-specific (e.g., country-specific, see Erdmann and Graedel, 2011; Srivastava & Kumar, 2022). The "critical" status of a mineral can diminish over time, thereby reshaping the strategic opportunities for a given country.

Within the context of our analysis, the scope of critical minerals extends to their role in clean energy technologies, specifically batteries, on account of the mineral composition and volume requirements needed to enable their production. Ensuring a reliable supply of said minerals, on the other hand, would almost certainly have far-reaching

environmental, social and governance (ESG) impacts (Carr-Wilson et al., 2024). In this section, the geoeconomic dimension is put into sharp focus.

2.1. The triple paradigm shift - technological innovation, economic security and climate change

2018 to 2022 evidenced a marked departure in the trajectory of global economic integration to one characterised by a policy-driven geoeconomic fragmentation (Aiyar et al., 2023; Baba et al., 2023). In 2018, the US, under President Donald Trump, implemented a series of tariff increases targeting a wide array of imports, most notably from China, signaling a sharp deviation from decades of otherwise stable trade policy (Fajgelbaum and Khandelwal, 2022). More recently, the COVID-19 pandemic sharply exposed the vulnerabilities inherent in globally integrated supply networks, while Russia's invasion of Ukraine in 2022 further underscored the strategic risks of import dependence. These developments likely precipitated a fractured geoeconomic landscape defined by intensified geopolitical competition, the emergence of strategically aligned trade blocs, supply chain reconfiguration, and renewed state intervention, to mention a few—manifested in policy responses that increasingly emphasize onshoring, reshoring, "friend-shoring," and the broader "de-risking" of strategic dependencies (see Cui et al., 2023; EC, 2020, 2020a; IEA, 2023c; Marty and Ruel, 2025; Müller, 2023; Vivoda and Matthews, 2024). As defended by the US Secretary of the Treasury, Janet L. Yellen (2020), "[friend-shoring] is the idea that countries that espouse a common set of values ... get the benefits of trade ... [through] multiple sources of supply and are not reliant excessively on sourcing critical goods from countries where [they] have geopolitical concerns". In practice, this translates to a deliberate re-routing of supply chains away from geopolitical rivals, primarily by Western countries (many of which are net importers of critical minerals) and toward countries with aligned political and strategic interests (Vivoda and Matthews, 2024). Arguably, nowhere is this more evident than across critical mineral supply chains (Månberger and Johansson, 2019; Vivoda et al., 2024).

The Minerals Security Partnership (MSP), a multilateral³ initiative led by the US, is among a number of already established alliances (e.g. the Sustainable Critical Minerals Alliance, the Energy Resource Governance Initiative (ERGI), the Quadrilateral Security Dialogue (QUAD), the Critical Minerals Mapping Initiative, the Five Eyes Critical Minerals Alliance (FVEY CMA), the Supply Chain Resilience Initiative (SCRI), the Indo-Pacific Economic Framework for Prosperity (IPEF) Agreement Relating to Supply Chain Resilience) mobilising to bolster and safeguard critical minerals supply (IRENA, 2023; Shiquan and Deyi, 2023; Srivastava & Kumar, 2024; US Department of United States Department of State, 2024; Vivoda and Matthews, 2024). The MSP is recognised as the first major policy initiative to institutionalise the concept of "friend-shoring" in response to mounting concerns over the concentration of critical mineral supply chains, particularly those dominated by China.

While some of these initiatives are in part motivated by the current geopolitical context, the extensive material requirements of the green transition herald greater cooperation. The political urgency vis-à-vis the

³ Members include Australia, Canada, Estonia, Finland, France, Germany, India, Italy, Japan, the Republic of Korea, Norway, Sweden, the UK, US and the EU.

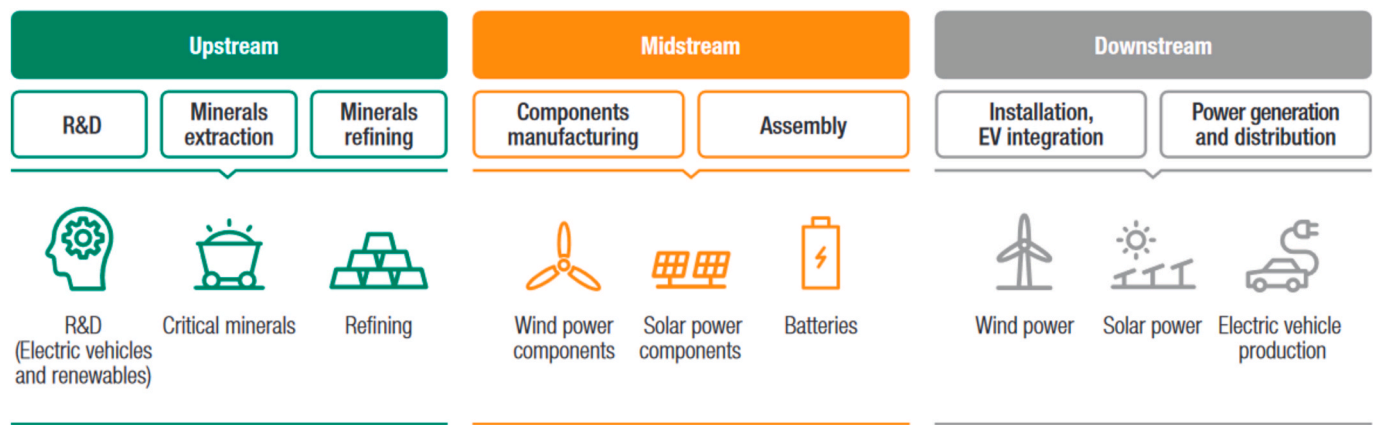


Fig. 1. Renewable energy value chain.

Source: United Nations Trade and Development (UNCTAD, 2023a).

strategic importance of critical minerals is also reflected in the scale and pace with which policy interventions and regulatory frameworks for addressing supply vulnerabilities are being rolled out. From periodic criticality assessments to attempts at weaning off reliance on critical mineral imports, globally, a race to secure access to critical minerals is underway.

Of the 34 critical minerals identified in the European Union's (EU) latest criticality assessment,⁴ 12 are fully import-dependent, that is, 100 % sourced (extracted or processed) outside the EU. Of note are antimony, beryllium, lithium, magnesium, niobium, platinum group metals (PGMs), phosphorus, REEs (heavy and light), scandium,⁵ titanium metal and vanadium. Within the EU, France and Spain account for the largest share of the global supply of hafnium (49 %) and strontium (31 %), respectively. According to the findings of the same criticality assessment, for some critical minerals, however, the EU relies exclusively on a single foreign source, as in the case of REEs whose supply, refining and processing capacities are controlled by China (EC, 2023a).

In May 2024, the Critical Raw Materials Act (hereafter the "EU CRM Act"),⁶ the most important regulation on critical minerals in the EU to date, entered into force. It was designed to shore up all stages of the "strategic" raw materials (SRM) value chain and to promote their circularity. The regulation sets targets for onshore production (at least 10 %), processing (at least 40 %) and recycling (at least 15 %) capacities to be achieved by 2030. It further strives to diversify the EU's import base so that no more than 65 % of its SRM imports are sourced from a single third country. At the national level, Member States will be tasked with developing critical minerals exploration programmes in addition to facilitating the necessary conditions for "Strategic Projects". Notable, therefore, is the formal designation of "Strategic Projects" as "raw material projects" that contribute to the EU's capacity to ensure the

resilience of SRM value chains. The "strategic" relevance of critical minerals is foremost determined on the basis of their use in the "green and digital transitions" (EC, 2023b).

To this end, support and funding for research and investment in critical minerals at the EU level are being channeled primarily toward exploration and mining, with a strong focus on ESG practices. These include a EUR 100 million equity-backed joint facility between the EU and the European Bank for Reconstruction and Development (EBRD) (EC, 2024), and a EUR 2 billion financing for critical raw material investment overseen by the European Investment Bank [EIB] (EIB, 2024). At the other end of the spectrum is an emphasis on recycling and material recovery operationalised through key policy levers such as the EU Battery Directive and initiatives such as the RHINOCEROS project (EC, 2022). Under the aforementioned battery regulation recycling efficiency targets are specifically mandated for lithium-ion (65 % by 2025) and lead-acid batteries (75 % by 2025), while material recovery rates for the same year for cobalt, nickel, lithium, copper and lead are set at 90 %, 90 %, 35 %, 90 % and 90 %, respectively. Key targets have also been set for 2030 and 2035 (EC, 2022).

Despite boasting a more robust mining industry, like the EU, the US is heavily dependent on imports of these materials, having designated 50 minerals as critical. Of these, at least 12 (namely, arsenic, cesium, fluorspar, gallium, natural graphite, indium, manganese, niobium, rubidium, scandium (an REE), strontium, tantalum and yttrium (an REE)) are 100 % import reliant and over a half exceed 50 % import reliance. China and Canada make up the primary import sources (US Geological Survey [USGS], 2024, 2022). The most recently published critical minerals assessment (i.e. the "Final 2023 DOE Critical Material List") designed to inform policy priorities around meeting the country's energy needs identified 18 minerals (US Department of Energy [DOE], 2025). Chief among said priorities concerns determining eligibility for tax breaks under the 2022 Inflation Reduction Act (IRA).

To that effect, IRA stands out for its provisions on battery raw materials. Specifically, preferential treatment and/or tax breaks only apply for "critical minerals" and battery components sourced or recycled domestically or in a country with which the US shares a free trade agreement (Congress, 2022). Exceptions to this extend to US allies such as Japan, with which the former enjoys a trade agreement on critical minerals (US Trade Representative [USTR], 2023). The greater emphasis by the US on domestic manufacturing, assembly and sourcing requirements builds on the country's larger aims to rebuild critical minerals supply chains in keeping with its "Made in America" goals (White House, 2022b).

The country has listed R&D in new extraction and processing methods, (direct) recycling techniques, and advanced resource recovery as a priority. These are in large part funded and overseen by the Department of Energy (DOE) in collaboration with national laboratories,

⁴ Critical minerals assessments at EU level are published every 3 years. To date, a total of five assessments have been released, with the first list published in 2011 and prepared as a priority action of the EU Raw Materials Initiative (RMI) launched in 2008. The latest critical minerals list, released in 2023, is based on the report titled *Study on the Critical Raw Materials for the EU 2023*. In this report, a distinction is made between critical raw materials and strategic raw materials (SRMs) in line with the proposal of the Critical Raw Materials Act (or EU CRM Act) Regulation.

⁵ Also an REE. However, it is treated separately in the EC report.

⁶ In complementarity with the EU CRM Act are a series of regulatory frameworks and initiatives for raw materials championed by the EC including the aforementioned RMI, the European Innovation Partnership (EIP) on raw materials established in 2012, the European Raw Materials Alliance (ERMA) launched in 2020 and managed by EIT (European Institute of Innovation and Technology) RawMaterials, in addition to a growing number of strategic partnerships on raw materials with third countries (or non-EU countries).

academia, industry stakeholders, among other entities. Some of the projects under this umbrella include the USD 75 million Minerals to Materials Supply Chain Facility (METALLIC), announced in 2024 and to be led by the National Energy Technology Laboratory (NETL) in partnership with nine national laboratories (NETL, 2024) and the DOE's first sponsored ReCell Center, a USD 15 million lithium-ion battery recycling center launched in 2019, housed at the Argonne National Laboratory (ANL) (ANL, 2019; ReCell, n.d.). DOE funding also supports geologic mapping for critical mineral exploration and research across the US. A notable example is the allocation in 2021 of USD 320 million to support the USGS Earth Mapping Resource Initiative (Earth MRI) within the USGS Mineral Resources Program (USGS, n.d.-a).

Meanwhile, China has a strong presence across critical minerals supply chains, including in the extraction and processing stages. Its stronghold extends further downstream, notably across the EV battery supply chain, where it boasts as much as 70 % of global production capacity for cathodes and 85 % for anodes with respect to cell components. It also captures a disproportionate share of global battery cell production, accounting for 75 % and is responsible for over half of global EV production (IEA, 2022a, p. 156). China's dominance is also beginning to show in the end-user segment. The price distribution of EVs, for example, reveals significant differences across major EV producers, with manufacturers in China leading the EV industry (IEA, 2023c). This spotlights a pillar of China's strategic advantage. One underpinned by its proximity to and ownership of critical mineral sourcing, both domestically and abroad (Müller, 2023). Nonetheless, such strategies are no longer exclusive to Chinese battery and EV manufacturers – indeed, it is now an emerging industry trend. More companies are entering into long-term off-take agreements with mineral suppliers and, in certain instances, acquiring ownership stakes in extraction and processing operations (Bridge and Faigen, 2022). CATL, a Chinese battery manufacturer, SK On, a Korean battery manufacturer, and US car manufacturers Tesla and General Motors, are among lead industry players that have pursued these types of investments (Foldy, 2022; General Motors, 2022; IEA, 2024a; Krauss and Ewing, 2023). These are viewed as essential to mitigating geopolitical, environmental, and economic risks associated with the global supply of battery minerals.

Moreover, Beijing's ongoing efforts to consolidate its REE industry suggest it seeks greater control over its supply chains while signalling that REEs remain a policy priority. Indeed, the development of high-end REE functional materials is among the key targets identified under its 14th Five-Year Plan⁷ (Xinhua News Agency, 2021). More broadly, China is actively pushing for greater self-reliance in line with its "Made in China 2025" plans (PRC State Council, 2022) and its broader "Dual Circulation" development model first outlined in the 14th Five-Year Plan. The former calls for the mobilisation of (state) resources to position China on the cutting edge of technological innovation, thereby lessening its dependence on third countries. The "Dual Circulation" model, on the other hand, promotes a predominantly domestic-centered growth strategy. Beyond its borders, China continues to pursue investments in mines and refineries, albeit with increasing challenges due to growing competition and owing to its substantial domestic needs. In 2020, its reliance on foreign sourcing of critical minerals exceeded 70 % for aluminium, copper, iron, lithium, nickel, and titanium, and for chromium, cobalt, and manganese reached 100 % (Zhou and Månberger, 2024; see also Gulley et al., 2019).

While the argument has been made regarding nuances in China's otherwise more inward-looking mineral strategies vis-à-vis its Western counterparts (Wübbcke, 2013; Zhou et al., 2025), by some accounts, China's focused R&D investments and recognition of its strategic

advantages in the global stage paint a more nuanced picture – one that reveals strong and targeted policy support for technological innovation and leadership along the global critical mineral value chain (Kalantzakos, 2020; Nakano, 2021). For instance, as Nakano (2021) brings to light, China's REEs strategic policy since the 7th Five-Year Plan (1986–1990) was indeed designed to prioritise the development of advanced REE applications domestically and for export, underpinned by a regulated foreign investment framework that restricted mining while encouraging downstream joint ventures and technology transfer. This contributed decisively to China's rise as the dominant global player in REEs and related industries. More importantly, in a testament to its winning strategy, a more recent example concerns China's graphite anode production capacity, which according to the IEA, represents more than seven times that of current global demand (International Energy Agency, 2024b). This level of concentration "has already driven prices down to levels that are too low for new entrants to the market to be competitive, given the large economies of scale enjoyed by existing Chinese producers" (IEA, 2024b, p.139).

A key research focus in the past 5 years has been innovation in mineral resource science (Zhai et al., 2021). Multi-year major national research programs with funding directed toward mineral deposit exploration, include the Development and Utilization of Strategic Mineral Resources (coordinated by China's Ministry of Science and Technology), the New round of breakthrough strategic actions in mineral exploration (launched by China's Ministry of Natural Resources) and the Extreme Enrichment and Ore-forming Dynamics of Strategic and Critical Metals (financed by the National Natural Science Foundation of China). The latter is an 8-year (2019–2027) program with a CNY 200 million (USD 28.6 million) of allocated funds according to which metals designated as "strategic and critical" are: REEs, PGMs, gallium, indium, thallium, germanium, selenium, tellurium, rhenium, chromium and cobalt (IEA, 2023d). Ore genesis and exploration in lead-zinc deposits has been a major research focus (Ali et al., 2023; Sun and Zhou, 2022; Zheng et al., 2023).

Conversely, the green transition is likely to raise the stakes for mineral-rich developing countries (see UNCTAD, 2023b; Goodenough et al., 2021). This aspect is already apparent, for instance, in the increasing investments in mining across South America, Southeast Asia and Africa. The EU's recently concluded cooperation agreements on critical minerals value chains with Argentina, Chile and Namibia, among others, are a case in point (EC, 2023d). In the same vein, resource nationalism is on the rise. From Malaysia to Zimbabwe, governments are poised to level the playing field. Indonesia, home to the world's largest known nickel reserves and a leading producer has established a legal framework for promoting the manufacturing and deployment of EVs domestically in tandem with its ban on nickel ore exports (Pirmana et al., 2023). The DRC and Zambia, both top suppliers of cobalt and copper, respectively, signed a historic memorandum of understanding (MOU) to jointly develop an EV battery supply chain. This initiative has been further strengthened by the signing of a trilateral MOU with the US on the margins of the US-Africa Leaders Summit in 2022 and under the overarching umbrella of the renewed US-Africa Partnership (US Department of State [DOS], 2024; United Nations Economic Commission for Africa, 2022; White House, 2022a).

Whether these events signal the undercurrents of a larger geopolitical paradigm shift is not in question. What is less clear is if resource-rich countries, many of which have traditionally operated on the periphery of global politics, can leverage their wealth in mineral resources to escape the resource curse that has come to plague their economies (Henri, 2019; Ploeg, 2011). Consider the DRC, home to the vast majority of the world's cobalt. Several studies point to a surge in the demand for cobalt in the coming decades (IEA, 2021; Deetman et al., 2018). The positive outlook in the demand for cobalt stands in stark contrast to a primary supply source mired in poverty and armed conflicts. Up to 30 % of the DRC's cobalt production comes from artisanal and small-scale mining (ASM) (Organisation for Economic Co-operation and

⁷ In long form, 14th Five-Year Plan (2021–2025) for National Economic and Social Development and Long-Range Objectives for 2035 (14th Five-Year Plan). Published in March 2021, the 14th Five-Year Plan spells out China's development goals.

Development, 2019, p.11). Cobalt ASM has been linked to some of the gravest prevalence of human rights abuse (most notably, child labour), health and environmental disparities (Kara, 2023; Sovacool, 2019). This phenomenon extends to other economic lifelines, including tin, tantalum, tungsten and gold ("3 TG") or the so-called "conflict minerals" for their use in funding armed conflicts (Church and Crawford, 2020; OECD, 2015a; Vogel, 2018). Despite efforts to enforce responsible sourcing through international guidelines⁸ designed to trace minerals to mine of origins, oversight is often lacking and expensive. This underscores the growing complexity of critical mineral global supply chains, confirming the need to reframe the global discourse on critical minerals to one that is inclusive and collaborative (see Coad et al., 2021, for a broader discussion concerning the "dark side of innovation").

2.2. The green transition amid the climate emergency

The 2015 Paris Agreement on climate change, adopted under the aegis of the United Nations (UN), consolidated the goal to limit the global average temperature increase below 1.5 °C (°C) above pre-industrial levels and the need to reach net zero greenhouse gas (GHG) emissions by 2050.⁹ Growing climate commitments have since materialised via the Conference of Parties of the United Nations Framework Convention on Climate Change, which seeks to align individual member countries' climate ambitions with the goals of the Paris Agreement. More countries, for example, are banning the sale of internal combustion engines (ICEs), among other fossil fuel infrastructure, with the EU, for its part, approving the phase-out of ICE by 2035 (European Parliament, 2022; IEA, 2022a,b,c). Concurrently, vast (and strategic) industries are being built on the premise that clean energy technologies will help address the climate emergency. The proliferation of EVs is a case in point. In 2022, global spending on EVs surpassed USD 425 billion, while EV sales soared by 55 % relative to 2021 (IEA, 2023c).

Notwithstanding their comparatively low carbon footprint - estimated at 6 % of GHG emissions generated by fossil fuel technologies, according to a study by the World Bank (Hund et al., 2023) - clean energy technologies consume a substantial amount of minerals. EVs, for example, use over six times more minerals than conventional fossil fuel-powered vehicles (IEA, 2021). Sustainably securing these will, therefore, be a compounded challenge seeing as the mining and processing of certain critical minerals come at high social and environmental costs. Sonter et al. (2020) find that 82 % of mining areas target materials critical for renewable energy production. The same study estimates that of the 50 million km² of land potentially affected by mining, 8 % overlaps with protected areas, 7 % with key biodiversity areas, and 16 % with remaining wilderness. Production of critical minerals such as REEs and copper has also been linked to pollutants and toxic waste, with environmental damage reported in China, the US, Brazil and the DRC (Kaniki and Tumba, 2019; Klinger, 2018; Reisman et al., 2012). Water contamination and depletion associated with the production of lithium have also become prevalent in major producing countries such as Chile, Argentina and Bolivia or more prominently in the Lithium Triangle, home to 70 % of the world's lithium deposits (Kaya, 2022; Vera et al., 2023).

The environmental concerns associated with the increased deployment of these technologies extend to the ocean floor. Although still in

the exploration phase,¹⁰ renewed momentum for commercial deep-seabed mining (DSM) operations is building. As of 2025, thirty-one 15-year exploration permits have been awarded by the International Seabed Authority [ISA] (ISA, n.d.), the regulatory body established under the 1982 UN Convention on the Law of the Sea (UNCLOS) to oversee mining in international waters (UN Oceans and Law of the Sea, 2025). Permits currently cover three types of deposits, namely, polymetallic nodules, polymetallic sulphides and cobalt-rich ferromanganese crusts (ISA, 2023). However, a limited understanding of the potential impacts of DSM on marine ecosystems and beyond has fuelled concerns (EC, 2023b; Hyman et al., 2022; Levin et al., 2020). According to a recent review of the literature in the field, "[there remain significant lacunae] of publicly available scientific knowledge ... [to facilitate] evidence-based decision-making" (Amon et al., 2022, para. 1). Likewise, the lack of a complete regulatory framework for DSM, particularly in view of the invocation of the "two-year rule" UNCLOS provision¹¹ (see UN Oceans and Law of the Sea, 2025), has added to growing calls for a moratorium effectively delaying negotiations until 2025 (ISA, 2023, 2024). Inevitably, resource-driven excursions into the deep-seabed reflect a growing reconfiguration of the global commons including the outer space, from the "common heritage of mankind" principle to a potential flashpoint of strategic competition (Klinger, 2018).

2.3. Supply chain geopolitics

In August 2023, export controls on gallium- and germanium-related items, raw materials critical to the manufacturing of semiconductors, among other core technologies, came into force. Citing national security concerns, under the new curbs announced by China's Ministry of Commerce (MOFCOM) (2023a), permits are needed to export these materials from the world's largest supplier - China supplies 94 % of the global share of processed gallium and 83 % of germanium (EC, 2023a). China's export control measures came after the US unveiled unprecedented export restrictions (as well as an Entity List) in October 2022, as part of its targeted attempts to stymie China's access to semiconductors manufacturing equipment, also on national security grounds (Bureau of Industry and Security [BIS], 2022).

As of September 2024, subsequent export restrictions by China on graphite, antimony and a ban on REE extraction and processing technologies followed (IEA, 2023b; MOFCOM, 2023b; 2024). Although common practice in the specific case of graphite, China's decision to limit exports of graphite came just days after a fresh wave of extended limits to the October 2022 targeted measures by the US (BIS, 2023) and amid an anti-subsidy investigation launched by the EU into China's EV exports (von der Leyen, 2023). Just as with gallium and germanium, China is the world's leading supplier of graphite, antimony and REEs (EC, 2023; USGS, 2024). Whether retaliatory or not (see IRENA, 2023 for an overview of China's 2010 REE trade dispute and Klinger, 2018 for an unpacking of the origins of the much cited and invoked Chinese REE embargo), Beijing's readiness to leverage its stronghold of critical value chains is, in no small measure, by design. In his speech at the seventh meeting of the Central Financial and Economic Affairs Commission (中央财经委员会) in April 2020, current leader Xi Jinping's appeal for "tighten[ing] international production chains' dependence on China ... as a countermeasure and deterrent ..." instrument (Xi, 2020) echoes through the chambers of a global stage that only now woke up to this race (see von der Leyen, 2023).

Much to the West's chagrin, China's economic ascent and technological advances have spurred a marked geopolitical reshuffling, undermining the so-called rules-based international order (Costa, 2023;

⁸ See the OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas (OECD, 2016).

⁹ To date, all but four nations are parties to the Paris Agreement, a legally binding international treaty on climate change. Every 5 years, parties to the agreement are required to communicate progressively ambitious national climate actions (or nationally determined contributions) to reduce their greenhouse gas (GHG) emissions.

¹⁰ Exploration entails assessing the location, size and quantity of the allotted ocean floor. No licenses for mining operations have been granted up to now.

¹¹ This particular provision was triggered in June 2021 by the Pacific Island nation of Nauru.

Kalantzakos, 2020; Nakano, 2021)¹² China, from the view of the US government, represents “the most serious long-term challenge to [this] ... order” (Blinken, 2022). Indeed, the “New Washington Consensus” is increasingly anchored in a realist logic with respect to its relations with China, an approach some scholars have long defended would prove sacrosanct to the US’s ability to delay China’s rise (see Mearsheimer, 1994, 1995, 2006). In June 2021, the [US] Innovation and Competition Act was passed. In it, China is deemed “the greatest geopolitical and geoeconomic challenge for [US] foreign policy” (Congress, 2021). More recently, in June 2024, a Critical Minerals Policy Working Group was established to oversee bipartisan legislation aimed at “addressing the [US]’ deep reliance on critical mineral imports, particularly from [... China ...]” (The Select Committee on the Strategic Competition between the [US] and [China], 2024).

Meanwhile, the EU sees its future through the prism of “economic security” and “(open) strategic autonomy”¹³ (von der Leyen, 2023). The former calls for a more cohesive and assertive Union in the face of unfair trade practices by third countries. A key step in this direction has been the adoption, in December 2023, of the Anti-Coercion Instrument (ACI). The ACI is part of a broader “European Economic Security Strategy” introduced in June 2023. It will serve as a tool of deterrence as well as a coordinated response mechanism to “risks” to the EU’s “economic security” in view of an increasingly hostile geopolitical climate (EC, 2023e; EC, 2023c). “Risks”, in this respect, are identified as, but not limited to, threats to the “resilience of supply chains” and related to the “weaponisation of economic dependencies” (EC, 2023f, p. 4). Tied to the EU’s capacity to defend itself is its pursuit for “(open) strategic autonomy”. The recognition of the EU’s shortfalls, as outlined in the “Versailles Declaration of 10 and 11 March 2022”, entails, among others, “reducing ... strategic dependencies” in “the most sensitive areas” such as “critical raw materials” (European Council, 2022, p.7).

The emerging geopolitical dynamics, taken together, lay bare a complex web of power play that stands in contradistinction with multilateral trade rules. What started as an aberration has quickly solidified into the state of play. Spiralling tensions between China and the US further spotlight the influence of geopolitics on already complex and highly fragmented global value chains. The implications seem profound in a context of climate emergency and technology disruption (Costa et al., 2022). It is within this context - of a charged geopolitical climate and a global rush to secure access to critical minerals that we zoom in on one of the mainstays of the green transition - battery technologies.

3. Methodology

In this section, we outline the methodology used to assess mineral occurrence in battery-related technologies by harnessing the information contained in patents.

3.1. Identification of relevant critical minerals

We draw on relevant reports by the IEA to define the set of critical minerals used in the analysis (see IEA, 2024a,b,c; 2023a,b,c,d,e,f). We supplement these with studies by the World Bank (see Hund et al., 2023; La Porta et al., 2017) as well as the list of critical minerals identified in

the EU CRM Act (see EC, 2023a; 2023b). A few considerations are therefore worth noting. While aluminium, antimony, iron, phosphate, and steel do not integrate the main scope of the IEA’s aggregate demand projections with respect to clean energy technologies (and batteries) in particular, both aluminium and steel are still heavily used in battery modules and packs. They are considered equally relevant by the World Bank, plus aluminium integrates the EU’s critical minerals list. Likewise, iron and phosphate were added because of their role in lithium iron phosphate (LFP) and lithium manganese iron phosphate (LMFP) cathode chemistries, both of which are gaining renewed popularity and are expected to consolidate the leading position by share by 2035 (IEA, 2024a, b,c). Finally, antimony is used in lead-acid batteries per the EC’s classification (see EC, 2023a, p.47). What results is a complete set of critical minerals (including all PGMs and REEs) as shown in Table 1.

3.2. Battery technologies

Rechargeable (or secondary) batteries, the subject of this study, can be broadly defined as electrochemical energy storage devices that convert chemical energy into electrical energy, making it possible to capture and release energy on demand (Wang et al., 2012). As such, batteries enable greater integration of renewable energy sources (e.g. solar and wind), which are otherwise variable and intermittent, into the electric grid. Critical minerals represent a central fixture of battery cells and are important determinants of advances in this domain. Specifically,

Table A.1
Set of critical minerals.

	Minerals	IEA	World Bank	EU CRM Act
1	Aluminium (Al)/bauxite	✓	✓	✓
2	Antimony (Sb)			✓
3	Arsenic (As)	✓		✓
4	Boron (B)	✓	✓	✓
5	Cadmium (Cd)	✓	✓	
6	Chromium (Cr)	✓	✓	
7	Cobalt (Co)	✓	✓	✓
8	Copper (Cu)	✓	✓	✓
9	Gallium (Ga)	✓	✓	✓
10	Germanium (Ge)	✓	✓	✓
11	Graphite/natural graphite	✓	✓	✓
12	Hafnium (Hf)	✓	✓	✓
13	Indium (In)	✓	✓	
14	Iron (Fe)		✓	
15	Lead (Pb)	✓	✓	
16	Lithium (Li)	✓	✓	✓
17	Magnesium (Mg)	✓		✓
18	Manganese (Mn)	✓	✓	✓
19	Molybdenum (Mo)	✓	✓	
20	Nickel (Ni)	✓	✓	✓
21	Niobium (Nb)	✓		✓
22	PGMs*	✓	✓	✓
23	Phosphate	✓	✓	✓
24	REEs**	✓	✓	✓
25	Selenium (Se)	✓	✓	
26	Silicon (Si)/Si metal	✓	✓	✓
27	Silver (Ag)	✓	✓	
28	Steel	✓	✓	
29	Tantalum (Ta)	✓		
30	Tellurium (Te)	✓	✓	
31	Tin (Sn)	✓	✓	
32	Titanium (Ti)/Ti metal	✓	✓	✓
33	Tungsten (W)	✓		✓
34	Vanadium (V)	✓	✓	✓
35	Zinc (Zn)	✓	✓	
36	Zirconium (Zr)	✓	✓	

Note: PGMs* comprise iridium (Ir), osmium (Os), palladium (Pd), rhodium (Rh), ruthenium.

(Ru) and platinum (Pt). REEs** comprise cerium (Ce), dysprosium (Dy), erbium (Er), europium (Eu), gadolinium (Gd), holmium (Ho), lanthanum (La), lutetium (Lu), neodymium (Nd), praseodymium (Pr), promethium (Pm), samarium (Sm), scandium (Sc), terbium (Tb), thulium (Tm), ytterbium (Yb) and yttrium (Y).

¹² In his May 2022 speech regarding the Biden’s “administration’s approach to the People’s Republic of China”, US Secretary of State, Antony Blinken, defended the rules-based international order as “the system of laws, agreements, principles, and institutions that the world came together to build after two world wars to manage relations between states, to prevent conflict, to uphold the rights of all people”. For the complete speech see (Blinken, 2022).

¹³ The notion of “strategic autonomy” has evolved in EU discourse from a uniquely defence and security strategy to one that, more recently, lends itself to the EU’s broader external policies as regards to protecting its values and interests. See Council of the European Union and ART (2021).

beyond their multifaceted end-uses, batteries vary in properties, a significant part of which is determined by their cathode (positive electrode) and anode (negative electrode) materials (IEA, 2021). Within lithium-ion batteries, for example, common cathode chemistries include lithium cobalt oxide (LCO), lithium nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminium oxide (NCA) and lithium manganese oxide (LMO). These differ in crucial parameters such as density, specific energy, cycle life, maturity, toxicity levels, cost and safety factors, to mention a few (IEA, 2021, p. 90).

3.3. Battery patent analysis

Patents have long been used as proxy measures for empirical research on the economics of innovation (e.g. Archibugi, 1992; Griliches, 1990; Mendonça et al., 2021). They are pivotal indicators of research, innovation and technological advancement, serving both to protect intellectual property and to disclose technical knowledge, thereby providing a material basis for gauging representative content (EPO, 2024a, 2024b).

Advances in battery technology have seen a growing use of patent indicators to assess the status and direction of innovation in this field. A number of recent studies (see EPO and IEA, 2020; Metzger et al., 2023; Silva et al., 2023) reveal, on the basis of patent counts, strong growth in inventive activity related to batteries, lending support to the booming innovation dynamics taking place across major battery technology variants. This parallels more recent trends in European patents documented by the EPO of a sustained rise in the number of filings, with the “electrical machinery, apparatus and energy” field (which includes battery technologies) registering the fastest growth both in 2023 (+12.2 %) and 2024 (+8.9 %) (2023; 2024c).

Our study builds on this body of work by conducting a text-based analysis to uncover the composition as well as the trajectory of the critical minerals behind this evolution. The focus on the mineral (or chemical) content in patent analysis is not new. Biggi et al. (2022), for example, measured toxicity in chemical and pharmaceutical inventions based on the compounds disclosed therein. Diemer et al. (2022) relatedly explored the link between critical and conflict materials and their geographies within the context of information, communication, and technological inventions. Adopting a similar methodological approach, De Cunzio et al. (2023) investigate the relationship between critical raw materials (CRMs) and green technologies, defined in terms of CRMs intensity. Finally, based on keyword occurrence analysis applied to patent text data related to frontier technologies, Li et al. (2024) find that 10.87 % of 5,146,615 patents analysed rely on rare metals use.

As widely employed as they are, the use of patents as innovation indicators is subject to a fair share of limitations. For one, patents do not cover all inventions (Guellec & Van Pottelsberghe de la Potterie, 2004). Cohen et al. (2000), for instance, found that among a range of mechanisms firms use to safeguard their inventions, patents are the least sought after. Instead, trade secrecy, lead time and other strategies tend to be more preferable alternatives. Even within patented inventions, some studies have found that a substantial number are unused (see Palomeras, 2003; Gilbert and Newbery, 1982). Moreover, the methodological pitfalls of patent statistics are likewise extensively discussed in the literature (Pavitt, 1985; Hinze and Schmoch, 2004).

3.4. Data acquisition procedure

The dataset built for this study combines bibliographic (e.g. publication date, number of inventors) and descriptive or full-text (e.g. titles, claims, descriptions) patent data extracted from the EPO. The bibliographic data were retrieved from the EPO Patent Statistical Database (PATSTAT) online platform using a curated SQL query script. The full-text data cover European Patent (EP) publications available for download in bulk. The two datasets were merged to account for the full-text features and their corresponding bibliographic information. We first

conduct a systematic categorisation of battery patents by technology fields using their IPC codes and then cross-referenced with patent metadata by combining the IPC code mapping with keyword searches in the patent document to refine distinctions between battery types. For example, battery-related patents are predominantly found under IPC class H01M, which covers electrochemical cells and systems. This includes relevant subclasses such as H01M 2 (“Constructional details, or processes of manufacture, of the non-active parts”) and ‘H01M 4 (“electrodes”). A complementary search query for lead-acid batteries, for instance, includes but is not limited to key terms such as “VRLA”(or valve-regulated lead acid) and “SLA” (sealed lead acid).

IPFs are used as indicators, meaning that each IPF corresponds to a single invention, and it is used to consolidate invention applications in several jurisdictions (Dechezleprêtre et al., 2017; EPO, 2024a). Thus, the dataset is free from double-counting and included comprised of 33,036 individual inventions. It is worth noting that there is an 18 months delay from the date patents are filed to when they are published (or made available to the public). This is reflected in the time lag observed between the PATSAT Edition (i.e. 2023) and the temporal scope of the analysis (EPO, n.d.). The steps from the data extraction process to text preprocessing are detailed in Fig. 2.

For the purposes of this study, a patent document is defined as a combination of full-text features. Due to the significant number of missing abstracts in our data however (double that of the claims and the descriptions), these were excluded from the final dataset. The elimination of the abstracts has no bearing on the integrity of the data, as no patents were lost as a result. While this does not impact the computations with respect to patent counts, it does translate to a relatively smaller corpus on which to conduct the text-mining analysis. The code work for this study was written in Python and executed in Jupyter Notebooks.

The procedures further included tagging of the extracted patents by battery technologies by means of regular expressions and cross-referencing with their respective IPC codes. Fractional counting was used to account for overlaps across the battery technologies. A total of 19 categories were identified. These will be made evident through the results. This step in our analysis was modelled after Metzger et al.’s (2023) work.

3.5. Accounting for the mineral content in patents

The definition of mineral occurrence is crucial for the set-up of the present analysis. A key-term frequency-based approach was used, specifically, the relative frequency of the mineral term occurrence for each IPF scaled by 1000 (Eq. 3.4.1). Due to substantial variations in the relative frequencies, these were also normalised in the range [0, 1] (Eq. 3.4.2). We calculated the relative frequency using the formula:

$$RF_i = f_i / \sum_{i=1}^n f_i * 1000 \quad (3.4.1)$$

Min-max normalisation was calculated as follows:

$$x' = x - \min(x) / \max(x) - \min(x) \quad (3.4.2)$$

Where x' is the normalised value, x is the original value, and min and max correspond to the minimum and maximum values, respectively.

In addition to the main analytical framework detailed in steps (i)–(ii), two more estimations were employed. Namely, the Herfindahl–Hirschman Index (HHI) and the revealed technological advantage (RTA) index. The HHI is intended to measure mineral concentration within each battery technology. It was calculated by taking the sum of the squares of the absolute frequencies of the mineral composition i in a given battery technology j (see Herfindahl, 1950; Hirschman, 1945). It takes the corresponding formula:

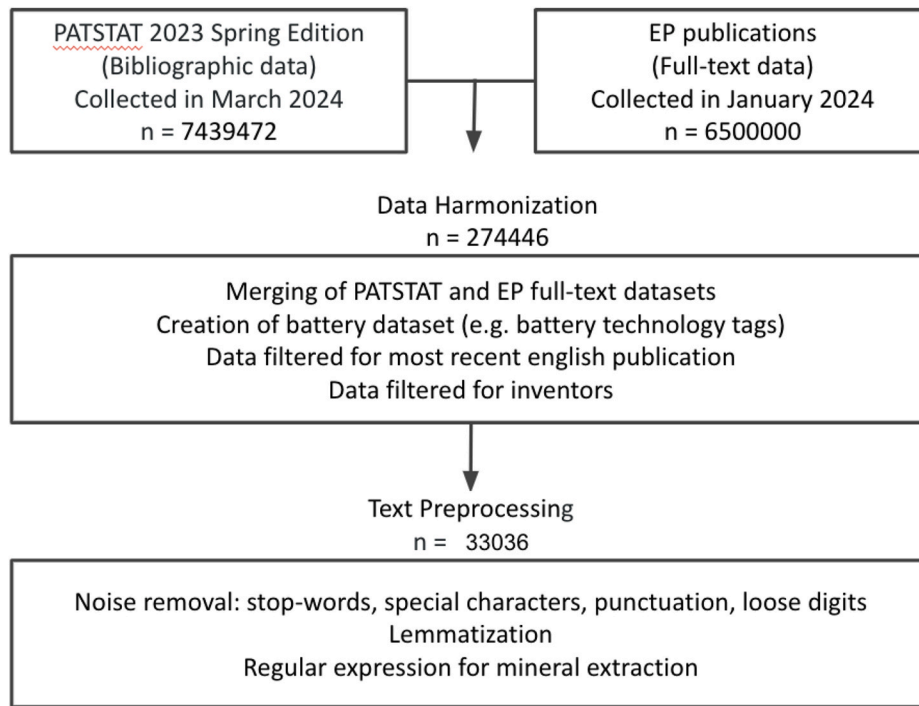


Fig. 2. Data extraction and preprocessing.

$$HHI_{ij} = \sum_{i=1}^n f_{i^2} \quad (3.4.3)$$

Finally, we define the relative specialisation by measuring the share of country j 's IPFs in technology i relative to its share of IPFs in all technologies. P stands for IPFs.

$$RTA_{ij} = \left(P_{ji} / \sum_j P_i \right) / \left(\sum_i P_j / \sum_i \sum_j P_{ij} \right) \quad (3.4.4)$$

The RTA is further standardised in the range $[-1, 1]$, following the

formula $(RTA - 1)/(RTA + 1)$ to facilitate graphical interpretation of the results. Standardised $RTA = -1$ corresponds to lack of activity, $RTA = 1$ if an inventor country is active in no other than the given technology; $RTA < 0$ suggests a lower-than-average, $RTA > 0$ a higher-than-average activity; $RTA = 0$ reflects a balanced, average status. Standardised RTA values reflect an internal balance among the technologies in the given country, and as such positive values must always be balanced by negatives ones (see OECD, 2015b; EC, 1997, p. M-23).

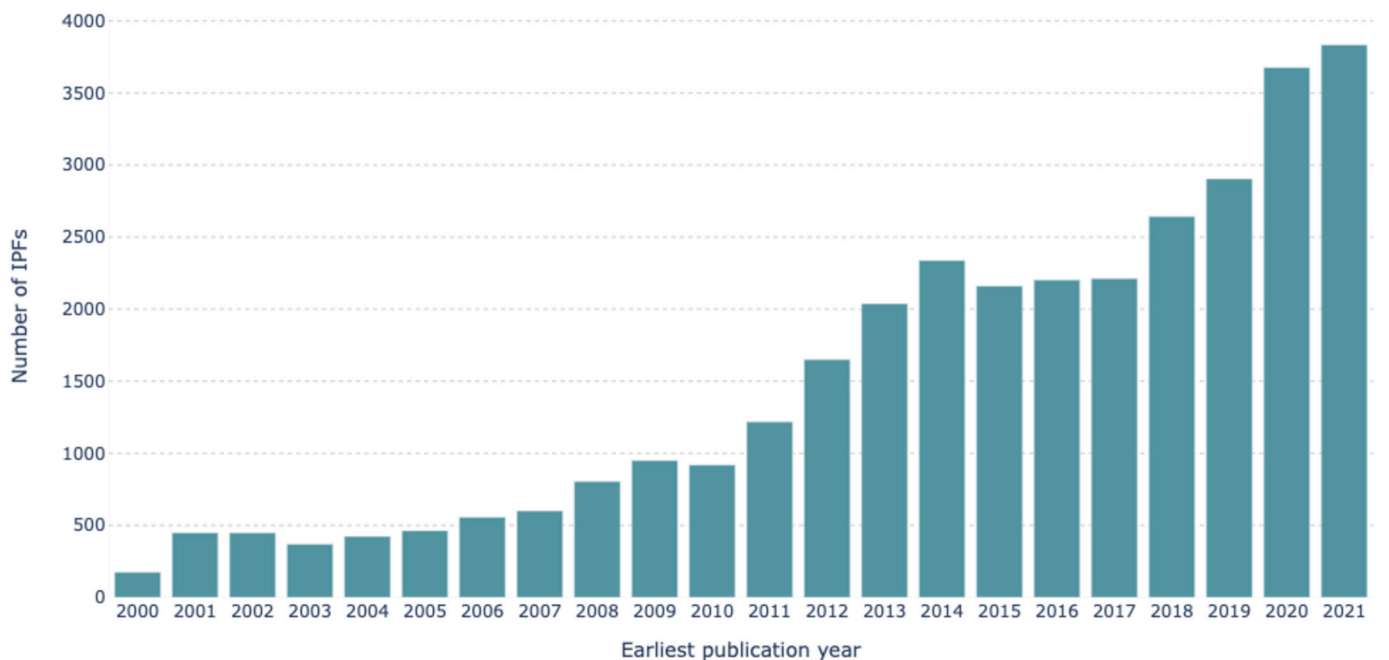


Fig. 3. Development of battery patenting activity, 2000–2021.

4. Results

In this section, we present and discuss the findings of our analysis. We start by providing an overview of the patenting landscape in aggregate terms.

4.1. Overview of battery patenting activity

Total patenting activity, comprising 33,036 patents related to batteries, increased considerably between 2000 and 2021, registering a 21-fold increase over the same period, as shown in Fig. 3. This upward trend first comes into view from 2003 to 2014, with the following 3 years seeing a stabilisation in the number of IPFs, only to pick up again afterwards when approaching the year 2020. The observed trend pattern closely mirrors global trends in patents related to electricity storage revealed in the EPO and IEA joint report (see EPO & IEA, 2020, p. 5, Figure E1). These are further supported by the rapid growth in general electricity grid-related patenting documented in a second and more recent EPO and IEA joint study (EPO & IEA, 2024).

The rise in patenting activity has also seen the surge of a diverse pool of battery types, as illustrated in Fig. 4. Lithium-ion batteries continue to dominate the technology space, generating over half of the IPFs in the 2000–2021 period. This parallels actual developments in the battery market where lithium-ion batteries, as of 2022, account for nearly half of the market share (UNCTAD, 2025).

As regards the origin of inventions (Fig. 5), Japan, the Republic of Korea, the US and China, respectively, represent the top 4 foremost contributors. Japan alone outpaces everyone else while European countries, led by Germany and the UK, also feature prominently, albeit lagging far behind.

The observed patterns can be ascribed, at least in part, to national policy-driven incentives and intellectual property strategies. These have demonstrably shaped the trajectory of battery innovation at the country level, as evidenced, for example, in China. Notably, a long-term agreement, established between China and the consortium that owns LFP patent rights, exempted Chinese manufacturers of LFP batteries from paying global licensing fees provided that production and use remained within China. This arrangement, which expired in 2022, has been instrumental in accelerating China's cost advantage and consolidating its leadership in LFP technology (IEA, 2022b; IRENA, 2023). As of 2022, LFP batteries represent more than 40 % of the Chinese EV market, as opposed to a considerably lower 6 % in Europe and 3 % in the United States and Canada (IRENA, 2023, p. 30). More generally, cross-country comparisons reveal significant variability in international patenting, influenced by market size, industry, firm resources, and national policies (Granstrand, 1999; Paci et al., 1997; Schiffl and Kittl, 1978). Only a subset of inventions, typically those with high commercial value or

strategic importance, are pursued abroad through international filings or patent families (Dechezleprêtre et al., 2017). Moreover, inventors and firms tend to patent domestically far more than internationally (Mendonça et al., 2021). Such geographic bias is compounded by national patent office practices, which often develop policies of innovation promotion (Hašičić et al., 2015).

Not surprisingly, the five leading inventor countries by total number of contributions (cf. Fig. 5) correspond to the top five inventor countries across all the patented technologies (see Fig. 6). However, distinct regional variations can be observed. While Japan holds the largest share of patents across the majority of battery technologies (specifically, lithium-ion, nickel-iron, nickel-metal hydride, nickel-zinc, lead-acid, nickel-hydrogen, rechargeable alkaline, redox flow, sodium-ion, sodium-sulfur and solid-state batteries), the Republic of Korea, which stands as the second highest overall contributor of IPFs, has the highest concentration of IPFs in lithium-air, nickel-cadmium and other lithium batteries. The US, while active in many of the studied battery technologies, is the second highest contributor of IPFs in solid-state (followed by the Republic of Korea, China, and Germany), redox flow (followed by the Republic of Korea, China and Germany), rechargeable alkaline (followed by the Republic of Korea, China and Austria), organic radical (followed by Italy, the republic of Korea and the United Kingdom), lithium-sulfur (followed by Japan, Germany and China), lead-acid (followed by the Republic of Korea, China and Italy) and calcium-ion batteries (followed by Spain, France and Germany). China for its part, is the second highest contributor of sodium-ion (albeit far behind from Japan, followed by the US, the Republic of Korea and the United Kingdom) and magnesium-ion (followed by the US, the United Kingdom and the Republic of Korea). Lastly, only three countries hold patents in aluminium-ion batteries, and these are Canada, Switzerland and Germany, respectively. Together with aluminium-ion and calcium-ion, organic radical, magnesium-ion and sodium-sulfur make up the 5 smallest number of IPFs.

Geographic nuances are also captured in the ranking of battery technologies across top inventor countries where a slight reshuffle is observed when compared to Fig. 4. Lead-acid batteries are ranked 5 rather than 2 (cf. Fig. 4).

4.2. Mineral occurrence – the big picture

How mineral-intensive are battery technologies? Increasingly, trends in mineral occurrence clearly reflect the growing importance of critical minerals in battery technologies. We observe a steady rise in the aggregate number of mineral mentions throughout the studied period. The pace of this growth is captured in the 3-year moving average in Fig. 7. This positive trajectory coincides with the growth in battery patenting activity (cf. Fig. 3).

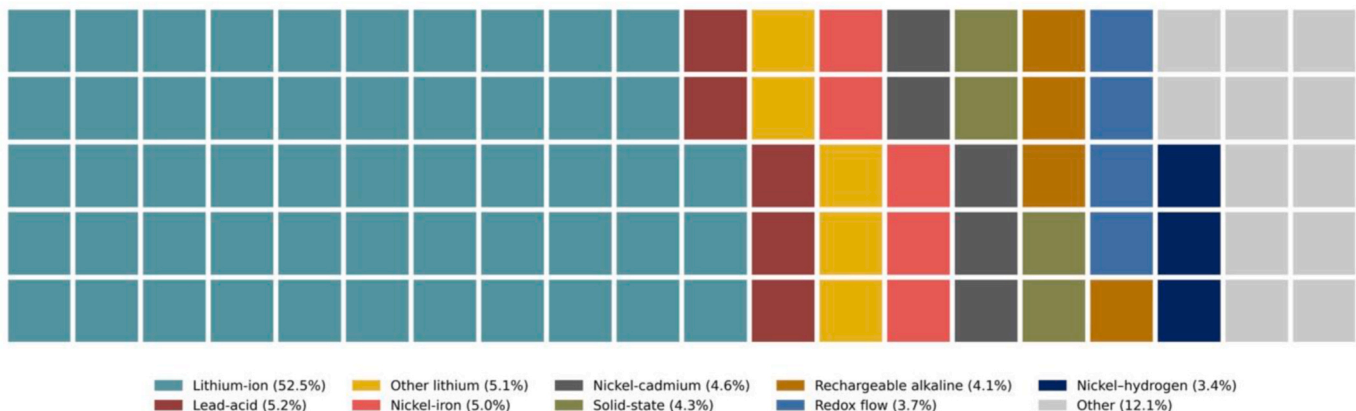


Fig. 4. Share of IPFs by battery technology, 2000–2021.

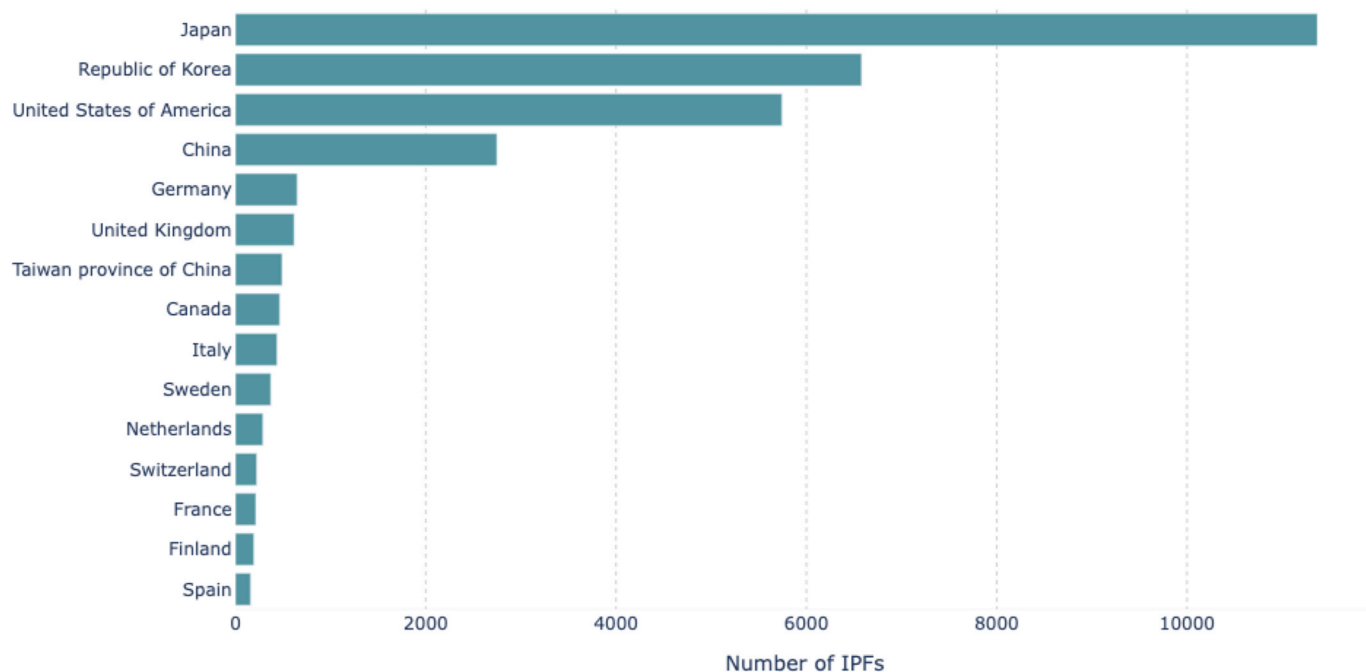


Fig. 5. Distribution of IPFs by top 15 inventor countries, 2000–2021.

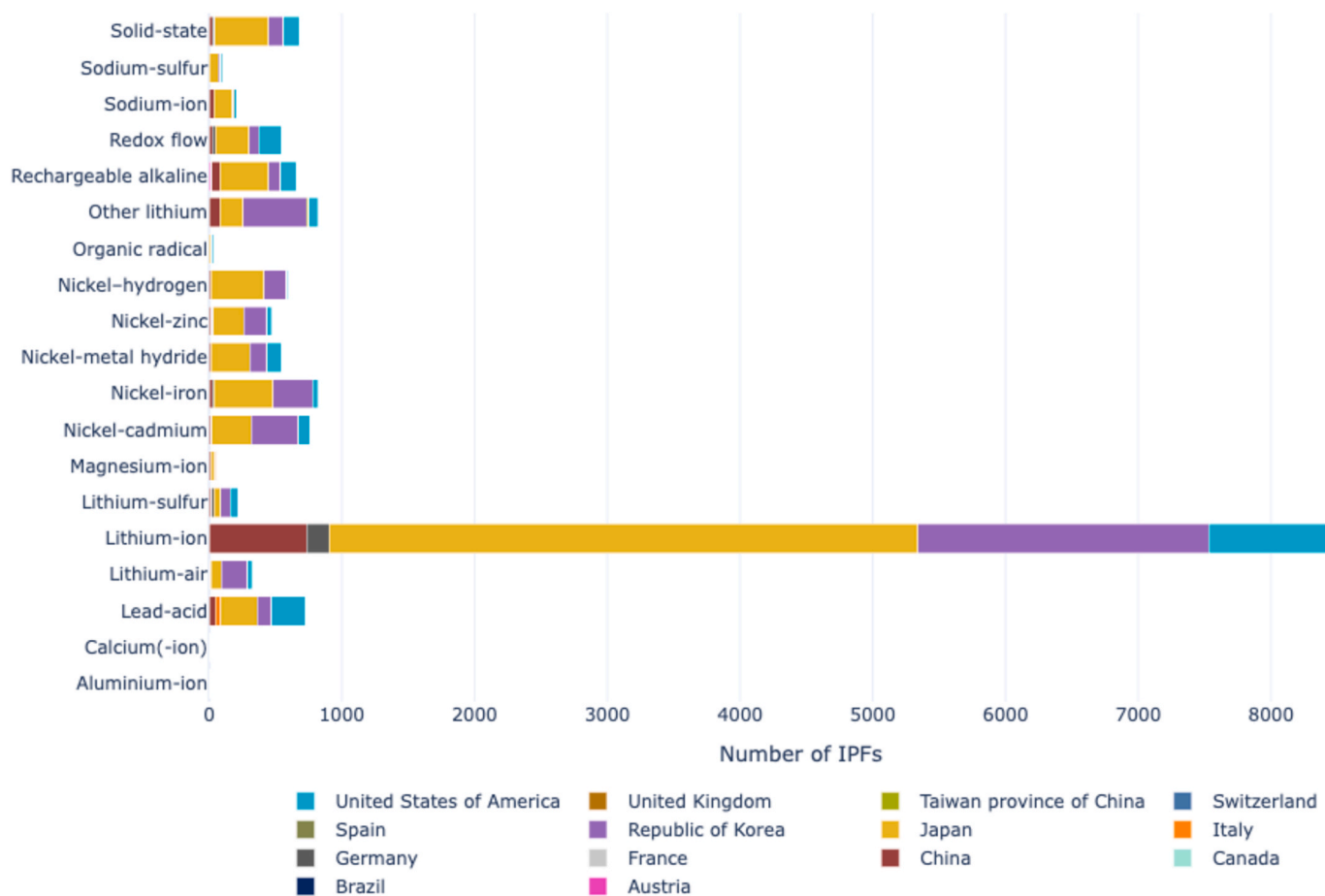


Fig. 6. Battery technologies by countries 2000–2021.

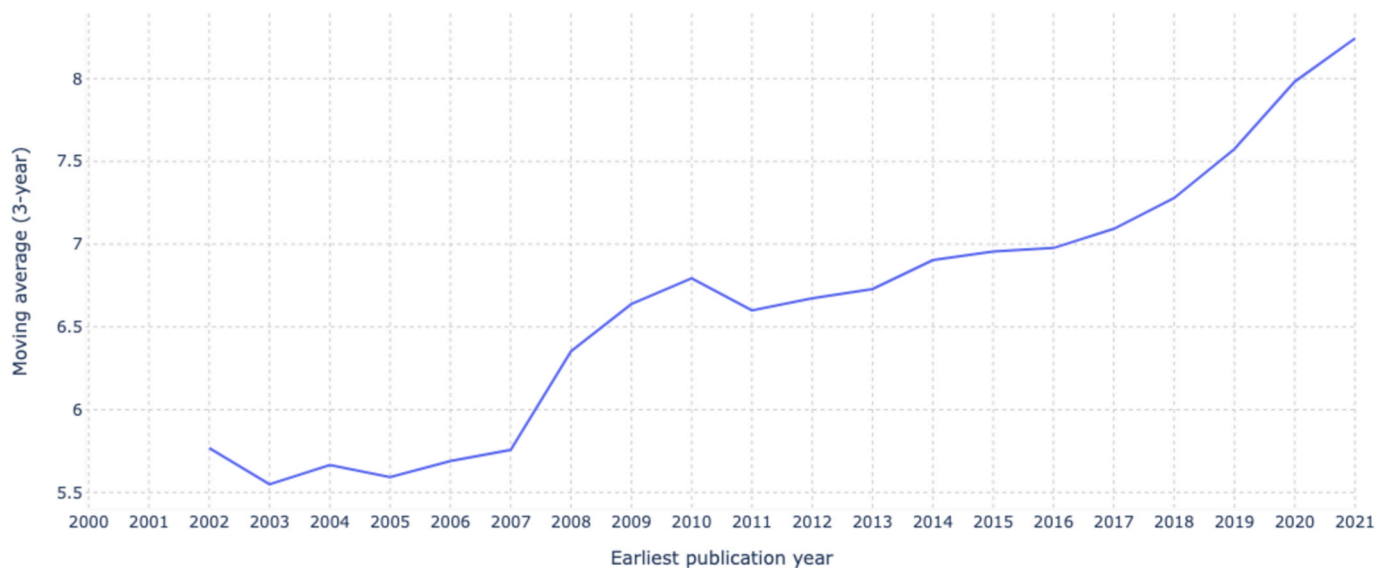


Fig. 7. Three-year moving average of mineral occurrences, 2000–2021.

Note: Fig. 7 is used for illustrative purposes only. It represents the 3-year moving average of the annual averages of mineral mentions. Here, the absolute frequency of each mineral term in a given IPF is counted only once.

At a more granular level, we find that all critical minerals selected for our study are present in the data. This outcome suggests the expansive and very dynamic nature of the battery innovation scene. In particular, as Fig. 8 reveals, mineral occurrence is highest for lithium, nickel and lead. A number of other minerals, including manganese, cobalt copper, aluminium, graphite, and silicon, trail not far behind. This figure may be understood as offering an indirect perspective on resource pressures, since it provides an indication on the rate and direction of mineral-intensive innovation. In addition, when examining individual trends (see Fig. 9), we see significant annual variability across the majority of the minerals, with some exhibiting one-off upticks during the studied period. This aspect is evident for antimony, arsenic, boron, and selenium prior to 2007 and for REEs in 2013.

However, for other minerals, more notable patterns emerge. Specifically, gallium, germanium, phosphate, silicon and titanium all show clear positive trends. Among these silicon has the highest occurrence followed by titanium and phosphate, respectively. Similarly, niobium, zirconium, tantalum, tellurium and chromium are also growing, though at a more subdued pace. Lithium displays stable growth after 2005 and aluminium and molybdenum after 2009, following their lowest points. While graphite sees a striking increase from 2020. On the opposite end are minerals such as nickel and tin, which exhibit downward trends, although nickel does register some relatively subtle yet stable rise post 2015. In the same vein, cobalt, cadmium, manganese and silver started off strong but have levelled off in recent years. Like nickel, cobalt sees some slight yet continued increase after 2015.

For some of the minerals, the observed trends in mineral occurrence are consistent with recent commercial breakthroughs and may also signal important new directions in battery innovation. The rise in mineral occurrence for silicon and germanium accordingly can be explained by broader and more promising research and development of higher-capacity anode materials for lithium-ion batteries (Liu et al., 2020). Already evident, for example, is the uptake of silicon-based anodes (IEA, 2023c, 2024b). Here we highlight two market trends. One concerns the combined use of silicon and graphite in the anode of lithium-ion batteries (Dimov et al., 2004; Yan et al., 2023), and the other, silicon anodes as an alternative to or replacement for graphite anodes (Wu et al., 2019). Similarly, concomitant with the downward trends in mineral occurrence observed for nickel (especially) and cobalt (to a lesser degree) is the rise of LFPs. Due to their reliance on iron and phosphorus, this relatively lower-cost cathode variant has contributed to the shift away from

chemistries with higher nickel and cobalt content, such as NMC and NCA, a shift set in motion on the one hand by increases in the price of nickel and cobalt, and on the other hand, by ethical concerns around the sourcing of cobalt (IEA, 2023c). Still, due to their superior energy density (Bridge and Faigen, 2022) and an even stronger industry impetus to reduce reliance on cobalt (IEA, 2021), nickel-rich batteries remain dominant with a tendency for increased nickel content (IEA, 2023c; IRENA, 2024).

Findings on mineral occurrences are further corroborated by patenting trends observed over the period of the analysis. Fig. 10 traces the evolution of mineral IPFs (i.e., IPFs that contain mineral occurrence) with respect to the total (represented by the Total IPFs line). In line with the overall upward trajectory in patenting activity, IPFs with occurrences of more conventional minerals, including aluminium, cobalt, copper, graphite, iron, lead, lithium, manganese and nickel, more closely mirror this overall trend and pattern. This facet tends to be more subtle for less conventional battery minerals.

A closer look into the ratio of mineral IPFs relative to total IPFs (see Fig. 11) points to upward trends across almost all minerals. Cadmium, lead, nickel, PGMs and REEs stand out as notable exceptions.

4.3. Mineral composition of battery technologies: profile and trends

Here, we cross-reference our set of critical minerals against the leading battery technologies identified in the study. Starting with Fig. 12, a rather rich and diverse landscape of minerals emerges. Lithium is by far the most salient mineral, and it is heavily present across all 19 battery technologies. Interestingly, this may reflect a growing focus on hybrid-ion technologies whereby several metallic charges (e.g. Na+/Li+) are used rather than a single one (Guo et al., 2022; Maletti et al., 2021). Lead, nickel, aluminium, cobalt, copper, and graphite are also heavily featured. Moreover, aluminium-ion batteries, despite representing the most negligible contributions in terms of the number of IPFs, are highly silicon-intensive. In contrast, redox flow batteries are chiefly vanadium-based. This is consistent with the state of the art. Vanadium is non-degradable and the current construction of flow batteries allows it to avoid permanent cross contamination of the electrolytes (MIT, 2023). Veering into less conventional minerals, zirconium is interestingly more prominent in lithium-air, organic radical and solid-state technologies. The latter domain also documents the highest gallium and germanium content of all the technologies. Finally, despite the smaller role PGMs

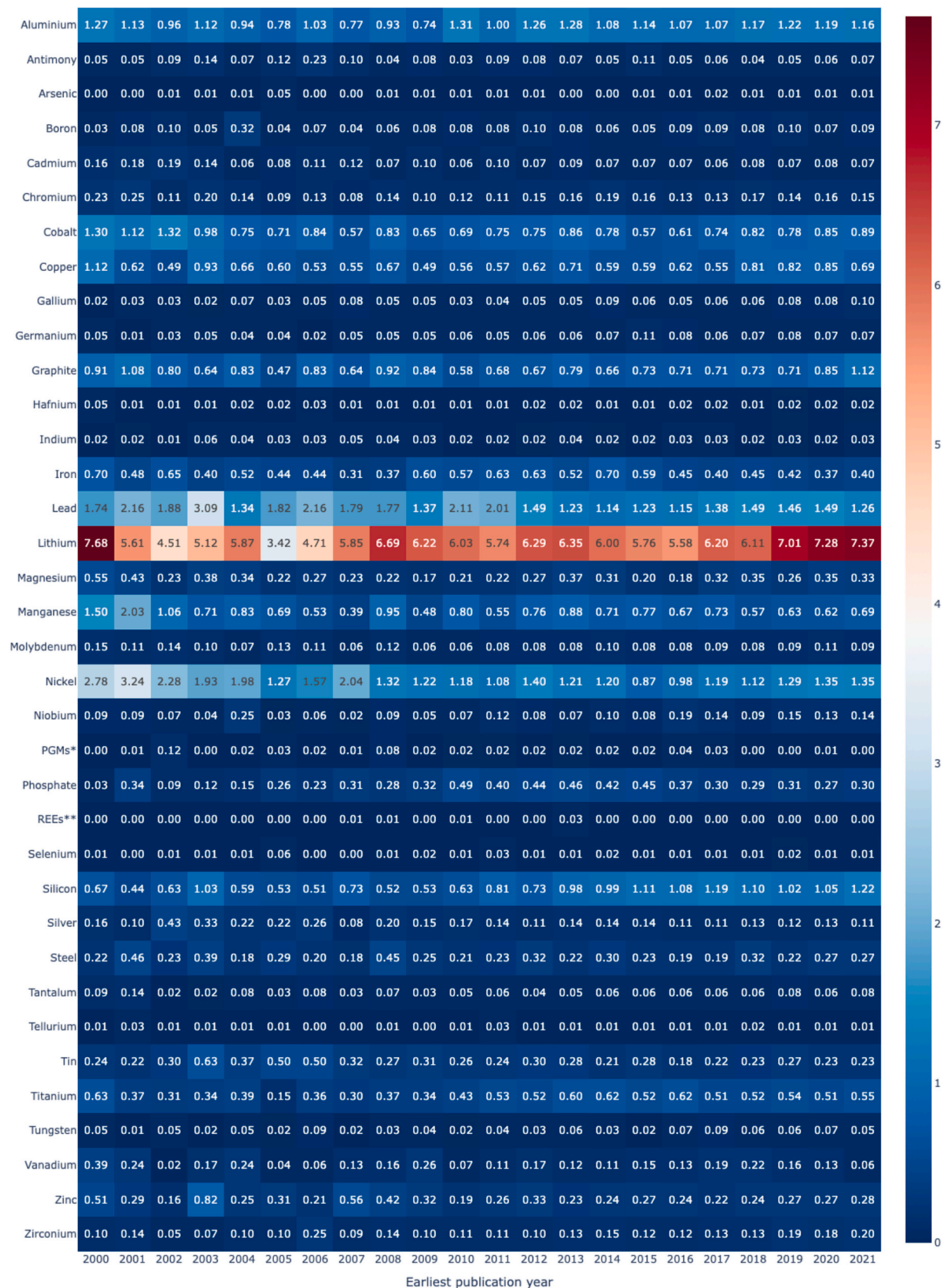


Fig. 8. Mineral occurrence, 2000–2021.

Note: in the above figure, dark red represents high occurrence, and dark blue represents low occurrence.



Fig. 9. Evolution of mineral occurrence, 2000–2021.

play relative to the aforementioned minerals, they are present in organic radical and redox-flow technologies.

To gain further insight into the mineral profile corresponding to each major battery technology, we compare mineral concentration using the Herfindahl–Hirschman concentration index (denoted as HHI). A higher HHI suggests that a narrower set of minerals dominates a given technology. To that effect, Fig. 13 provides an indication of the degree of mineral concentration. From 2015 to 2021, we document an increase in the level of mineral concentration in all but one technology namely, nickel-hydrogen. There are significant differences, however, as to the degree of concentration. Sodium-sulfur batteries, in particular, account for the greatest change in concentration.

4.4. Relative specialisation across battery technologies

Arguably, a country's revealed technological advantage (RTA) reflects and dictates its critical mineral needs. This aspect can be particularly true in view of their position primarily as a critical mineral exporter or importer. Here, we track the evolution of the inventor country's specialisation benchmarked against all 19 battery technologies. Accordingly, in Fig. 14 to Fig. 16, we highlight that of China and the US as well as two of the main North-South blocs, namely G7 and BRICS+, which both countries integrate. These are illustrated for the years 2015 and 2021.

China shows overall increased specialisation in tandem with a more active patenting profile across a broader set of technologies. Specifically, it went from lacking specialisation across at least five battery technologies to achieving higher-than-average specialisation in magnesium-ion and sodium-ion batteries in the span of 6 years. It also reports higher relative specialisation in other lithium and lithium-ion batteries. The US, for its part, unveils a more retracted profile, having de-specialised from

at least three technologies including sodium-sulfur, lithium-sulfur and rechargeable alkaline, and amassed lower-than-average specialisation across the great majority of the selected technologies. It nevertheless reports increased specialisation in sodium-ion technologies.

With regards to the economic blocs, over the same 6-year period, increases in solid-state (highest increase), sodium-ion, rechargeable alkaline, nickel-cadmium, magnesium-ion and nickel-hydrogen are observed for G7 countries (see Fig. 15). With the exception of aluminium-ion, which remained idle, all the other technologies saw decreased specialisation. By contrast, except for nickel-iron and sodium-sulfur (in 2015), there is almost no difference in the specialisation profiles of the BRICS + countries versus that of China, attesting to China's oversized weight in relation to the bloc.

In fact, this picture becomes even clearer in the specialisation profile for the BRICS + when China is excluded (see Fig. 16). The G7 countries, on the other hand, present a more balanced picture even without the US, which suggests fairly more robust patenting across most if not all member countries.

Taken together, these findings (see Fig. 15) reflect larger paradigmatic shifts along a North-South divide whereby on one hand, we observe patterns of convergence towards technologies such as lead-acid (–), sodium-ion (+), solid-state (+), sodium-sulfur (–), nickel-zinc (–), nickel-metal hydride (–), nickel-cadmium (+), magnesium-ion (+), other lithium (–), nickel-hydrogen (+) and lithium-air (–), and on the other hand, diverging trajectories can be seen for redox flow, nickel-iron, lithium-sulfur, lithium-ion, rechargeable alkaline and organic technologies.

5. Discussion and conclusions

Battery technologies are garnering an ever-prominent role as the



Fig. 10. Trends in battery innovation (total vs mineral IPFs), 2000–2021.

Note: mineral IPFs are determined based on the count of IPFs with at least one mineral occurrence.

world transitions away from fossil fuels (Bauer et al., 2022; Kittner et al., 2017). Indeed, the remarkable growth of battery-related patenting activity also provides evidence of this effect. Through this study, we set out to map the critical minerals associated with these technologies, a research domain that has remained largely underexplored. Empirically, integrating patent-based evidence into innovation studies supports more granular, real-world monitoring of the evolving inventive technical domain informed by policy priorities and R&D directions. Hence, the inclusion of a wide range of critical minerals in our analysis helps to situate innovation in battery technologies within the current policy-driven supply security framework, especially “[i]n an era when critical minerals have become the cornerstone of technological advancement and economic security” (Vivoda et al., 2024, para. 1).

Our findings thus augment the literature on technological change/innovation in two ways: first, the development of alternative and viable battery technologies to a heavy and growing reliance on lithium-ion batteries. There is an array of new battery technologies which rely on much more abundant and widely distributed material inputs. Sodium-ion, magnesium-ion, lithium-sulfur (uses sulfur as the cathode material) and solid-state batteries (enables the use of alternative metals such as sodium or magnesium) are among the most prominent found in our analysis. China, for instance, is shown to have higher-than-average specialisation in the first three technologies, and G7 countries, collectively, registered increased specialisation in sodium-ion, magnesium-ion and solid-state batteries. By the same token, our findings reveal a number of novel metal-ion batteries, beyond lithium-ion (specifically, sodium-ion, magnesium-ion, aluminium-ion and calcium-ion). Of these, sodium-ion batteries are already in production and are projected to achieve close to 10 GW-hours of installed capacity in 2025 (UNCTAD, 2025, p. 9).

Second, material substitution contingent on the potential for

advances in battery chemistry. Our results also show that while major battery minerals, including lithium, nickel and cobalt, remain dominant (in relative terms), a new set of minerals (i.e. chromium, gallium, germanium, molybdenum, niobium, phosphate, silicon, tantalum, tellurium, titanium, and zirconium), is growing in importance, attesting to a much more dynamic inventive space. Still, the extent of the use of critical minerals like gallium or niobium in batteries is not yet clear. And, for less-known (battery) critical minerals such as titanium and zirconium, market data scarcity adds a layer of uncertainty (IRENA & Norwegian Institute of International Affairs, 2024). Concurrently, some minerals exhibit marked decreasing trends, such as in the case of nickel and tin, and to a lesser extent, cobalt, cadmium, manganese and silver. These findings may suggest a shift in the makeup of core battery minerals, some of which are starting to emerge commercially.

The present study advances understanding of the intersection between battery innovation specifically and mineral criticality. While advancements in battery technologies hold tremendous promise for the future of energy storage, they also recentre the discussion on the possible impact of new technologies (driven by battery chemistries) to substantially alter critical mineral demand (see Hache et al., 2019; O’Sullivan et al., 2017; Overland, 2019; Renner and Wellmer, 2020). From a technological sovereignty standpoint, our findings put into perspective the extent to which geopolitical considerations around the reorientation of strategic supply chains may take precedence. This aspect is supported, on the one hand, by the dynamic nature of the mineral composition of battery technologies and, on the other, by the specialisation patterns observed across inventor countries. Consequently, understanding the extent to which innovation is shaping criticality is a strategic imperative and underscores the need for a balanced consideration to both the risks and opportunities brought about by such dynamics. In line with these findings, the EU, US, and China have each



Fig. 11. Trends in battery innovation (IPFs ratio), 2000–2021.

intensified support for R&D and innovation along the entire critical mineral supply chain with notable focus on both primary and secondary sourcing.

On one hand, there is the immediate need to secure supply of critical minerals (through investments in mining, processing and refining) and on the other, countries are actively exploring solutions that optimize material substitutability, efficiency and recyclability, in line with circular economy principles. The latter presents a window of opportunity to substitute critical minerals with more abundant or sustainable options, which in turn has the potential to reduce environmental impacts, enhance national resource security, and build more robust and resilient supply chains. However, emerging battery chemistries introduce uncertainties related to their precise resource requirements and commercial readiness. The large-scale commercialisation of post-lithium batteries is projected to be gradual and security risks may persist or re-emerge as the technology landscape evolves (Yokoi et al., 2024). This warrants adaptive and forward-looking policy frameworks that integrate continuous assessment of technological progress and resource availability. Governments and industries are thus encouraged to align innovation agendas and investment strategies to capitalise on substitution possibilities. Supporting R&D, facilitating market deployment of alternative chemistries, and incentivising the modernisation of manufacturing and recycling infrastructures are critical steps.

Although our results capture, in important ways, a range of apparent developments consistent with research and commercial advances in recent years, the analytical approach considered presents some limitations. First, the observed patenting trends may not always lead to commercially viable products or translate into commercial use. As discussed earlier, firms may file patents primarily for strategic reasons (e.g., blocking competitors or strategic non-use) rather than to support planned commercialisation (Cohen et al., 2000). Consequently, findings

based on patent analysis capture innovation intent rather than direct evidence of commercial exploitation. As such, patent data should be interpreted with caution and supplemented with complementary measures of innovation such as R&D spending or non-technological intangibles (Hall et al., 2000; Mendonça et al., 2004). Second, analysing large volumes of text revealed a level of lexical ambiguity, especially pronounced for mineral (or chemical) symbols that resemble English language prepositions (i.e., homonyms), such as in the case of arsenic (As) and indium (In) as well as in single-character symbols such as boron (B) and vanadium (V) which hold varied interpretations in the context of a patent document. To remedy this, only extensive names were used for minerals meeting these criteria and in so doing, results are likely understated. A case can, therefore, be made to integrate more complex solutions to better handle false positives, such as part-of-speech (or POS) tagging algorithms (not used here) (for an overview, see Jurafsky and Martin, 2024) or compatible chemical recognition applications. Third, due to memory constraints, our analysis focuses on patents granted by the EPO. While our use of IPFs as innovation indicators guarantees unique patented inventions filed in multiple jurisdictions, expanding the geographic scope would provide an important measure of inventive output on a global scale.

Future research might also consider examining how the composition of critical minerals is distributed across the main actors in the private, public and not-for-profit sectors and whether there are particularities reflected in their mineral strategies along ESG criteria. Framing this analysis from a circular economy perspective offers a promising framework for understanding systemic eco-innovation, effectively aligning innovation studies with sustainability transitions (De Jesus et al., 2018, 2019; De Jesus and Mendonça, 2018; Lehmann et al., 2022). Moreover, considering the rising relevance of some of the examined critical minerals further analysis into potential risks to reliability of

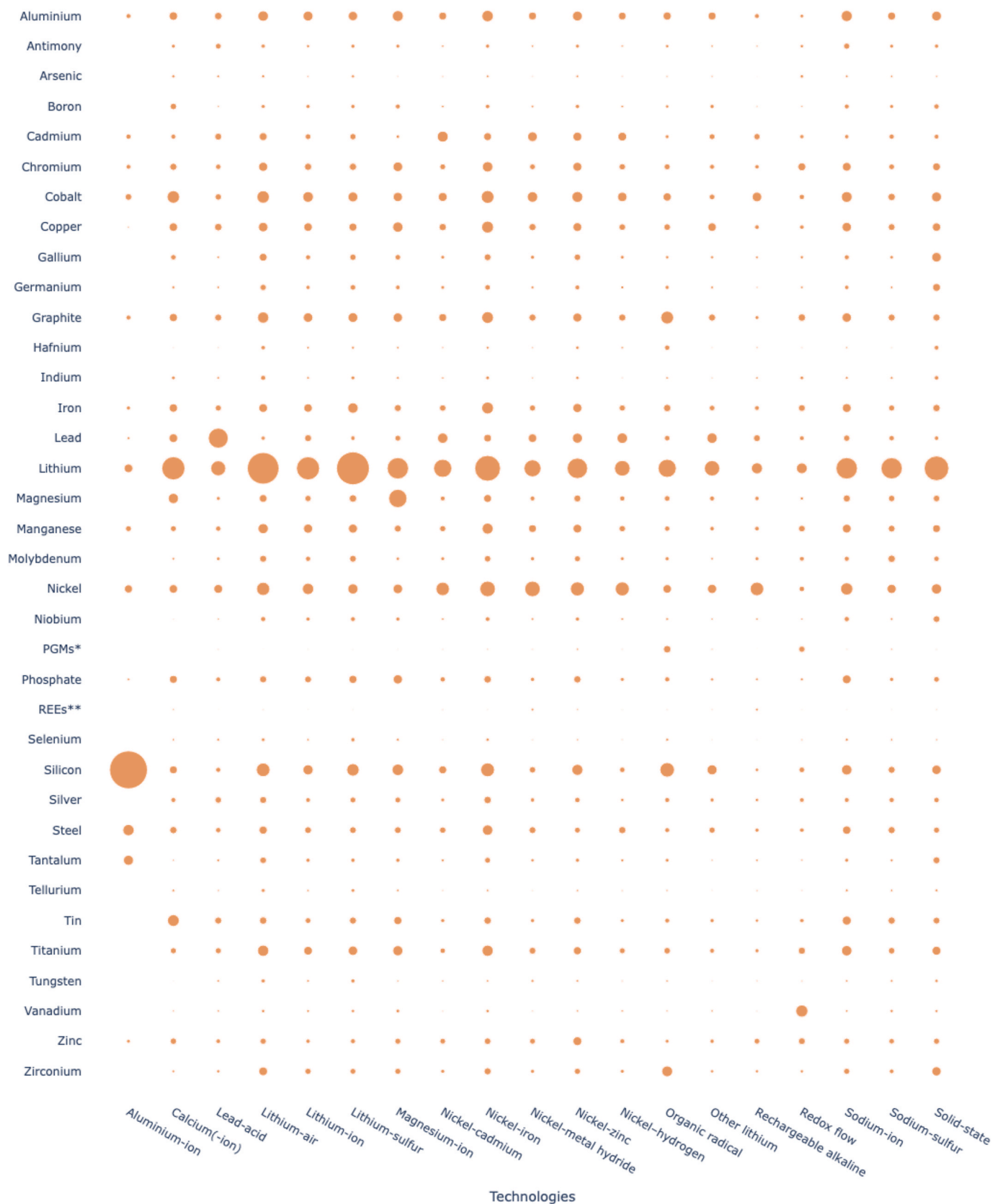


Fig. 12. Mineral occurrence across battery technologies, 2000–2021.

Note: the size of the bubbles provides an indication of the relative frequency of each mineral.

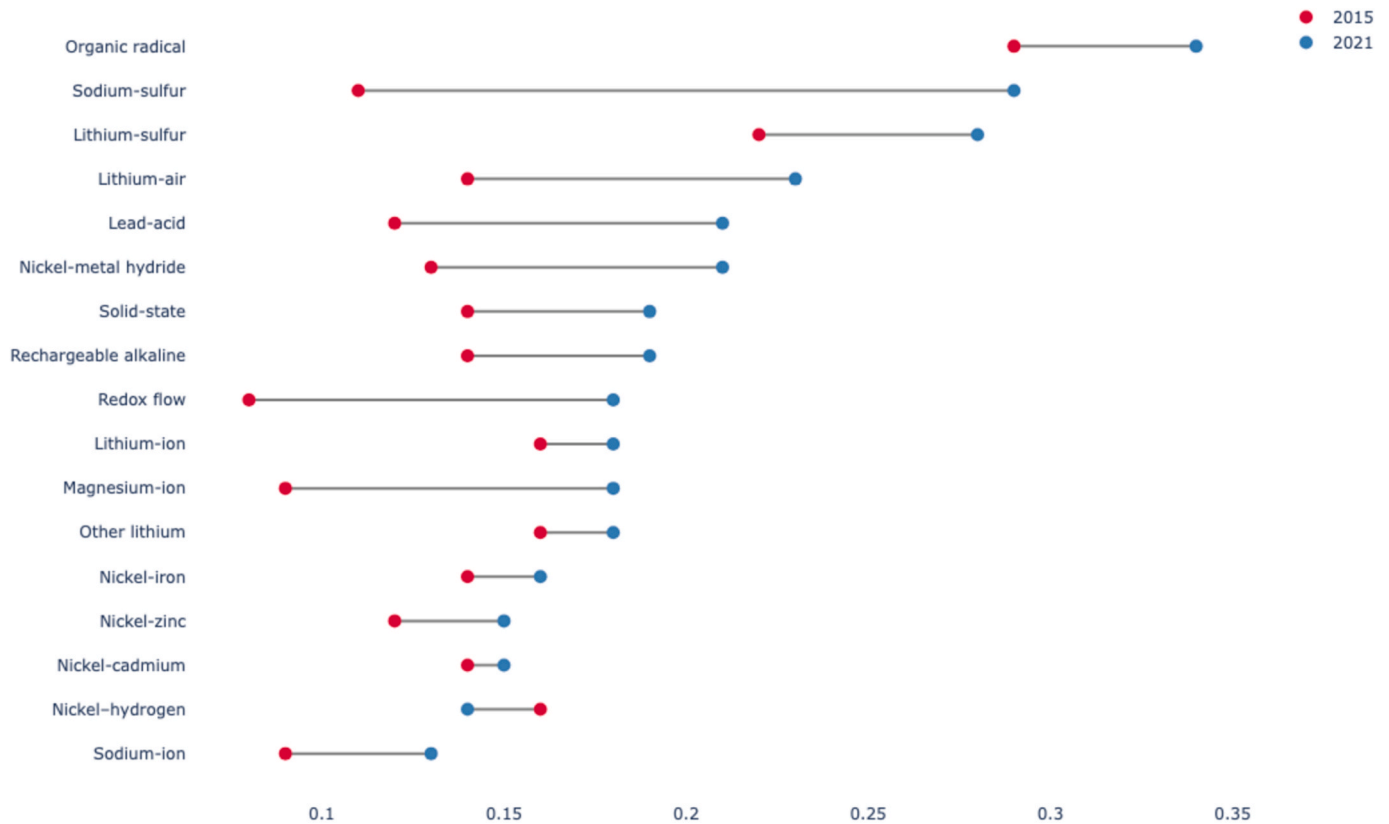


Fig. 13. Herfindahl-Hirschman concentration patterns, 2015–2021.

Note: aluminium-ion and calcium(-ion) batteries are not included in the analysis due to a lack of data for the selected years.

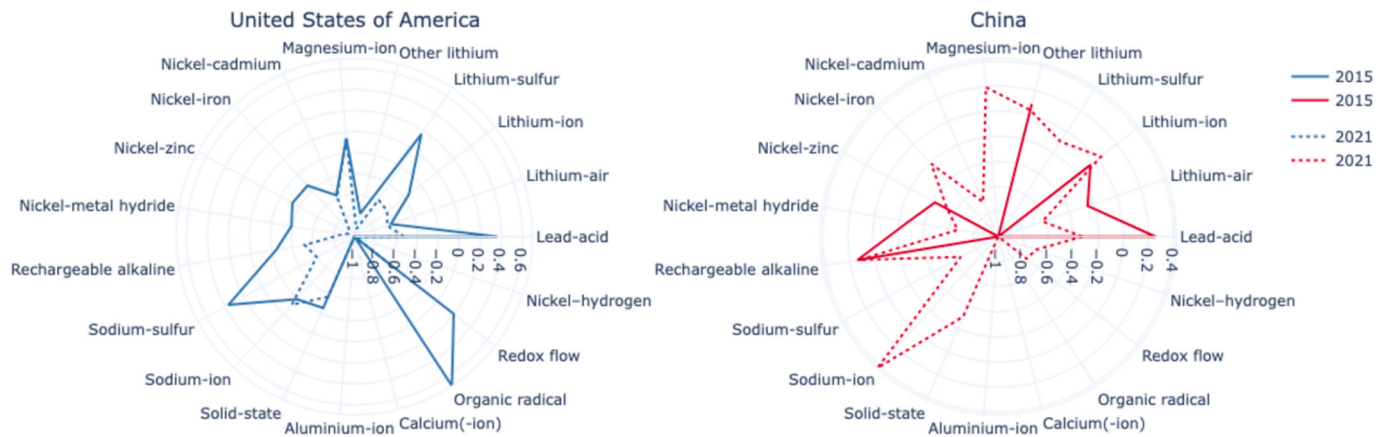


Fig. 14. RTA patterns (US vs China), 2015–2021.

supply would be a natural extension to this study. Indeed, more than half of the supply of each of these minerals comes from the top 3 producing countries. In some cases (e.g. for gallium and niobium), a single source accounts for up to 90 % of world production (USGS, 2024).

There is also an opportunity to extend and explore the present analysis in the context of emerging debates in contemporary security studies, particularly in energy security. Today's energy security agenda demands not only technical and strategic solutions but also integrated, multi-level responses that address socioeconomic disparities and systemic risks. Yet, "[i]n attempting to ensure the stability of supplies, core powers are increasingly militarizing their approach to energy security" (Collins, 2025, p.351). This is even more relevant in the present context in which new frontiers like the global commons are being redefined as

an "arena for geopolitical proxy wars" (Klinger, 2021, p. 200). This strategic shift marks a profound transformation: international cooperation risks being supplanted by resource-driven rivalry as critical minerals become focal points for geopolitical influence, technological supremacy, and national security. There is a consensus that critical minerals supply chains must be made more resilient, in large part because our shared goals towards decarbonisation depend on it. Our study, however, brings into focus the question of how and to what extent countries' mineral security strategies will enable this future, especially against the backdrop of an increasingly multipolar world.

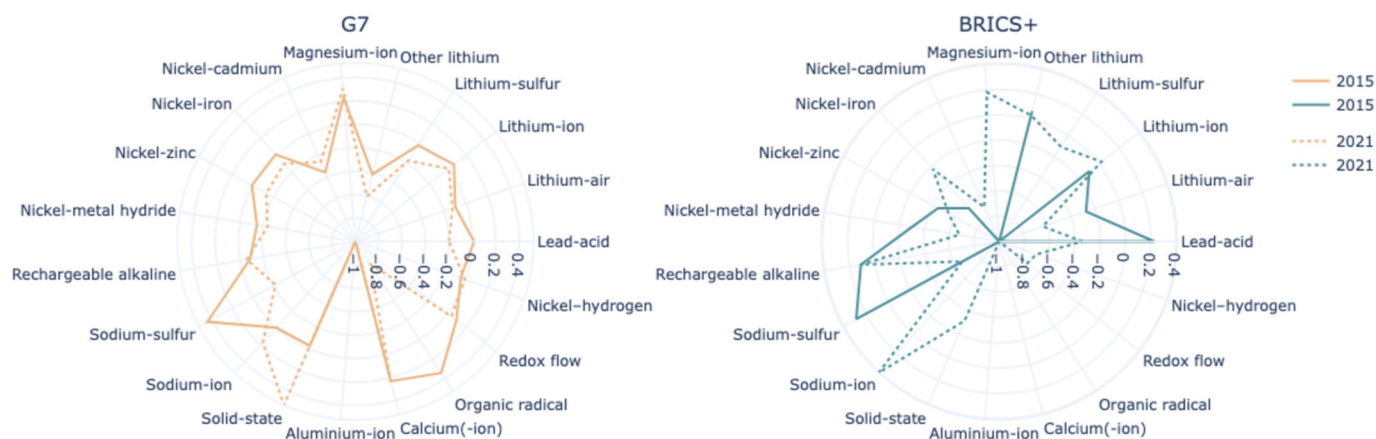


Fig. 15. RTA patterns (G7 vs BRICS+), 2015–2021.

Note: G7 members include Canada, France, Germany, Italy, Japan, the UK and the US. BRICS + members include Brazil, Russia, India, China, South Africa, Iran (Islamic Republic of), and the United Arab Emirates. Egypt and Ethiopia are missing from the BRICS + list due to the absence of patenting activity as per our data set.

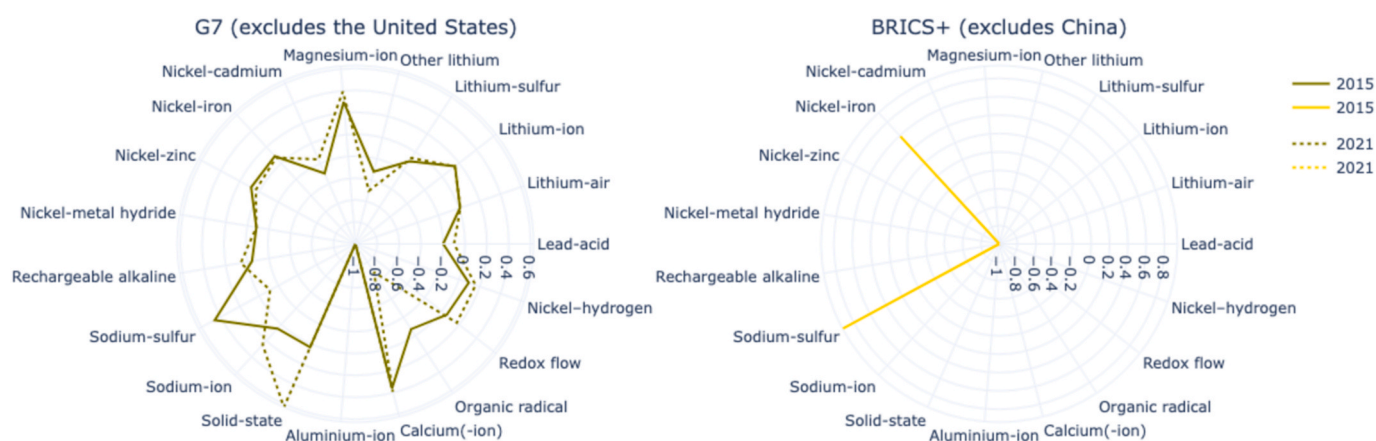


Fig. 16. RTA patterns (G7 without the US vs BRICS + without China), 2015–2021.

CRedit authorship contribution statement

Elsa Camuamba: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation. **Bruno Damásio:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Sandro Mendonça:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Conceptualization.

Research data

All data processing scripts and analysis code are available at <https://github.com/elsanatalia/critical-minerals>.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that support the findings of this study were obtained from the European Patent Office under specific access conditions. Due to legal restrictions, the raw data cannot be shared publicly.

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