MINERS

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DISCUSSION REPORT_

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MINERS: Key Summary of Initial Results

Working Paper (for discussion only) _ Pls do NOT cite.

Overall Modelling Framework

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The main objective of the project is to develop a framework to assess resilience in critical minerals supply chain and developing associated modelling tools, to propose policy pathways towards enhanced resilience through fostering UK-Canada collaboration. Our approach is built around **three main methodological** pillars (Figure 1).

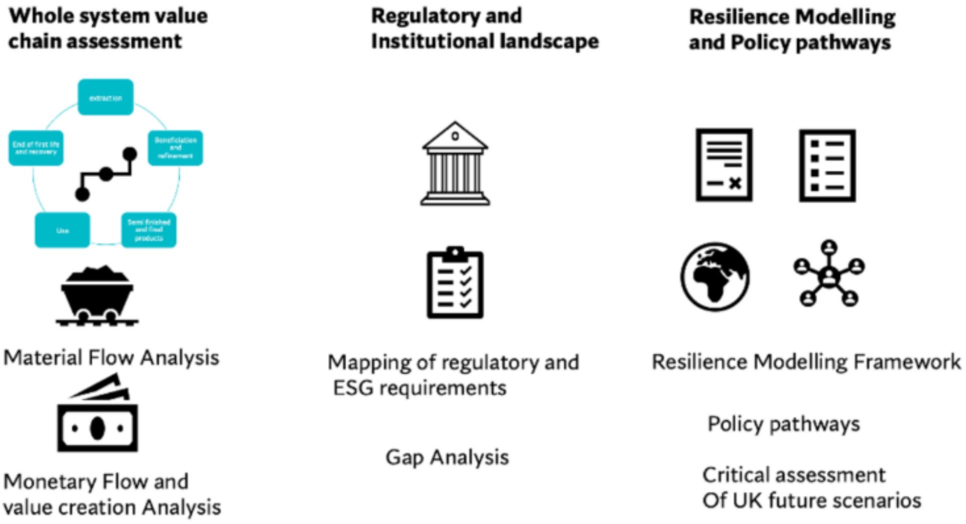


Figure 1: MINERS methodological approach

Assessing Resilience

Concept of resilience:

The ability of human societies and ecosystems to adapt, absorb, and recover after shocks. In Sprecher et al. (2015), resilience is defined as the capacity to supply sufficient materials or maintain material flows to meet societal demand, including providing suitable alternatives during disruptions. Liu, Lui, and Zhang (2023) add another perspective by emphasizing the interdependencies between upstream suppliers and downstream stages in the value chain, focusing on downstream strategies to recover when upstream supply is impacted.

In MINERS we adopt a working concept nested in complexity theory, where we dynamically assess resilience as the ability to evolve and transform in the face of changes, rather than the more static view of bouncing back to equilibrium. In line with the approach of '**Planetary Boundaries**', this dynamic understanding resilience connects with the idea of defining a **'safe operating space**' for Critical Minerals and identify the key boundaries beyond which ability to predict changes deteriorates.

Assessing resilience along the value chain

The proposed framework (Table 1) contemplates the linkages across the following levels:

1. The source of Shock
    1. Geological concentration/ reserve level
    2. Geopolitical stability
    3. Sudden changes in demand/ supply
    4. Social licence to operate
    5. Economic shocks
    6. Natural disasters, env hazards
    7. Logistics and distribution
2. The level of exposure
    1. Concentration of supply
    2. Dependency on specific CMs
    3. Adaptability of extraction, refining and manufacturing
3. The degree of vulnerability
    1. Limited access to alternatives or secondary materials
    2. Flexibility in manufacturing,
    3. % of value added depended on a specific CM/ CMs

Table 1: The proposed framework for assessing resilience

Main types of shocks	**Mitigation Strategies**
Geological concentration/ reserve level	Promotion of secondary markets for secondary materials Remanufacturing and take back systems Innovation and material substitution Mining technologies Alternative supply sources
Geopolitical stability	Promotion of secondary markets for secondary materials Remanufacturing and take back systems International cooperation/ alliances Alternative supply sources
Sudden changes in demand/ supply	Flexible extraction/ production/manufacturing
Social licence to operate	ESG requirements Net benefit
Economic shocks	Stockpiling Supply agreements Secondary materials can help to smooth price shocks of primary production ESG as value creation
Natural disasters, env hazards	Secondary materials Alternative supply sources
Logistics and distribution	Industrial clusters Infrastructure sharing and transport hubs
Policy induced supply/ demand changes	Secondary markets act as buffers Policies highlight important of maintaining some domestic capacity

While no mining-specific resilience standard exists, the literature provides a transferable set of metrics from supply-chain resilience and material criticality research. Based on literature review, Table 2 summarises some main proposed metrics to measure resilience in the supply chain. Most analysis only consider specific metrics. Metrics rarely considered possible downstream mitigation measures.

Table 2: A summary of main proposed metrics to assess resilience

Resilience capacity	Metric	Definition	Example of indicators	Key literature source(s)
Anticipation (risk exposure)	Supply concentration / diversification	Dependence on few suppliers or countries	HHI, % top-3 suppliers	Helbig et al. (2016); OECD (2021)
	Multi-sourcing index	Availability of alternative suppliers	Number/share of qualified suppliers	Ivanov & Dolgui (2020); OECD (2021)
Absorption (robustness)	Inventory buffer / stockpile coverage	Ability to maintain supply during disruption	Days/months of demand covered	Pettit, Fiksel & Croxton (2010); Ivanov (2021)
	Redundant capacity	Spare production or logistics capacity	% spare capacity; backup routes	Sheffi & Rice (2005); Pettit et al. (2010)
Adaptation (flexibility)	Substitutability	Ability to switch materials/inputs	% demand met by substitutes/recycling	Graedel et al. (2015); Helbig et al. (2016)
	Network connectivity / path redundancy	Ability to reroute flows	No. of viable paths; network centrality	Kim, Chen & Linderman (2015); recent mineral network modelling studies
	SCOR agility/responsiveness metrics	Speed of operational adjustment	Lead time, flexibility, responsiveness KPIs	APICS (2017 SCOR framework); Ivanov & Dolgui (2020)
Recovery (bounce-back)	Time to Recovery (TTR)	Time to return to baseline output	Days/weeks/months	Sheffi & Rice (2005); Simchi-Levi, Schmidt & Wei (2014)
	Time to Survive (TTS)	How long system can operate without supply	Duration until failure	Simchi-Levi et al. (2014)
	Economic loss / disruption cost	Financial impact of downtime	Lost revenue, NPV loss	Ivanov & Dolgui (2020)
System-level resilience	Percolation threshold / systemic fragility	Share of node loss before collapse	% network failure threshold	Buldyrev et al. (2010); network-science applications to resource trade
	Composite resilience index	Multi-dimensional resilience score	Weighted index of robustness + flexibility + recovery	Pettit et al. (2010); OECD (2021)

Questions

1. What are the key elements defining the resilience of the CM supply chain? Does the framework above cover most relevant ones? What other factors need to be considered?
2. What key strategies can be used to improve resilience? Are there any important gaps in the table above.
3. Are there specific metrics/ parameters you use to measure resilience?
4. Has there been effective national/ international initiative that have contributed towards improved resilience? e.g Minerals Security Partnership

Whole system mapping of complex value chains

Methodology

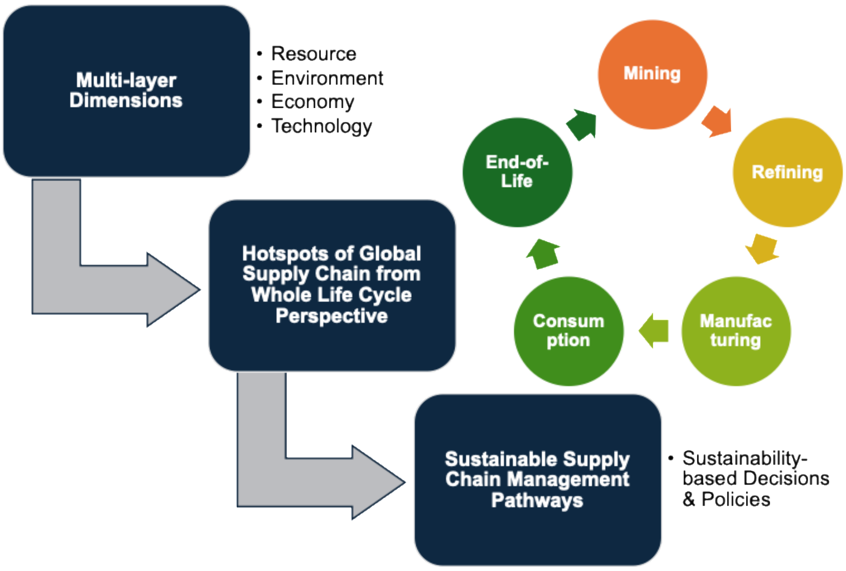


Figure 2: Integrated assessment framework for assessing nickel (Ni) sustainability

The key hotspots identified are critical elements in creating an integrated system sustainability assessment (Figure 2). Specifically, this project considers four dimensions, including resource, environment, economy, and technology. This research adopts a material flow analysis (MFA) model to trace physical material flows and stocks and develops a value chain analysis (VCA) model to assess the associated monetary value flows. A life cycle assessment (LCA) model is then employed to assess associated environmental impacts along the whole value chain. To ensure consistency across different models, a shared system boundary is defined and separated into five stages, including mining, refining, manufacturing, consumption, and end-of-life (EOL).

Global mine-level critical minerals (CMs) mapping

- **Global Lithium Resources Mapping**

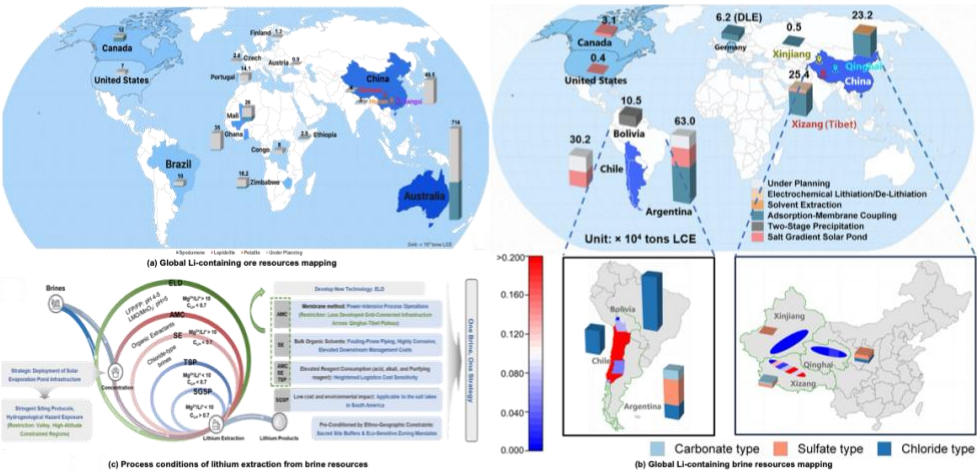
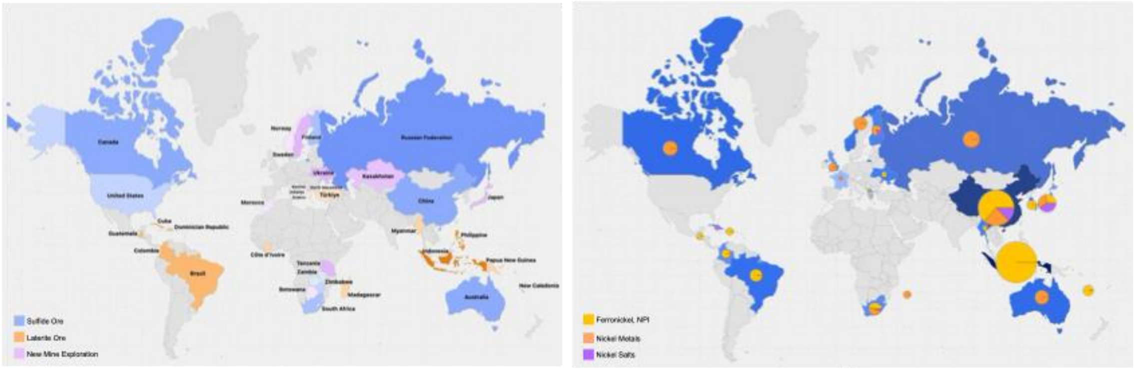


Figure 3: Global lithium (Li) resource distribution mapping: ore (a) and brine (b) types and process conditions of lithium extraction from brine resources (c), 2021 (Source: Liu et al., In submission)

Figure 3 (a) presents that global hard-rock lithium resources are highly concentrated in a limited number of countries. Australia dominates the world's ore-based lithium deposits, with overall production of 55.3 kt in 2021. China shows a potential development capacity of lepidolite mines in Jiangxi province, while regions in Africa, such as Ghana, Mali, and Zimbabwe, are emerging as significant sources of Li ores. By comparison, as demonstrated in Figure 3 (b), lithium brine deposits are mainly distributed across the world's three major plateaus, including the Andean Plateau in South America, the Qinghai-Tibet Plateau in China, and the Western Plateau in North America (Pan et al., 2025). They are also commonly classified into sulfate-, chloride-, and carbonate-type brines. Among them, South America and China collectively account for approximately 65% and 30% of global lithium brine resources, respectively.

- **Global Nickel Resources Mapping**



(a) (b)

Figure 4: Global nickel (Ni) resource distribution mapping: mining stage (a) and refining stage (b), 2021 (Source: USGS, ICMM)

Figure 4 (a) presents the global deposits of primary nickel (Ni) resources with essentially two main types: lateride and sulphide. Our data indicate that around 75% of the worldwide Ni deposits are laterite, where Indonesia and adjacent country islands as well as tropical regions of Central and South America (such as Brazil and Cuba) are the main regions. Indonesia has the largest Ni production of 1036 kt in 2021, followed by Philippines (387 kt) and New Caledonia (186 kt). The remaining 35% of Ni deposits are sulphide, which are mainly concentrated in Russia, Australia, Canada, and China, with production of 205, 151, 134, and 109 kt Ni, respectively, in 2021.

The intermediate nickel products exhibit significant differences depending on ore types (Figure 4 (b)). Laterite-rich regions dominate nickel pig iron (NPI) or ferronickel (FeNi) output, sulfide-based regions dominate refined nickel metals, while a limited number of countries contribute to nickel-sulfate or other salts production due to the growing demand of lithium-ion batteries (LIBs). Ferronickel accounts for the largest share of nickel intermediate products (1672 kt in 2021), followed by nickel metal (804 kt in 2021). Among countries, Indonesia is the largest producer with 796 kt Ni of NPI/FeNi in 2021. China ranked second at 675 kt Ni in 2021, with a diversified production structure.

Results of physical material flows

- **Global Lithium Material Flows**

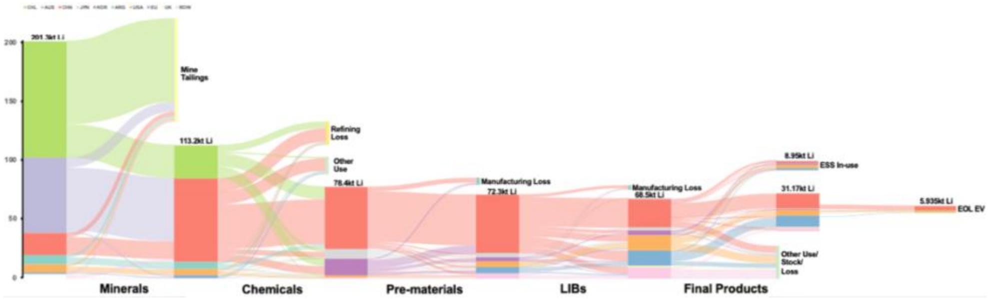


Figure 5: Sankey diagram of global Li physical material flows, 2021 (Source: Liu et al., In submission)

Figure 5 illustrates the global Li physical material flows in 2021. In the Li mining stage, Australia and Chile are the major suppliers, accounting for 49% and 25% of global lithium production in 2021, respectively. China dominates in the chemical refining stage, with 59.5 kt of Li chemicals in 2021. About 80% of the chemicals are then used domestically as battery pre-materials. In the battery cell production stage, China is still the world's largest producer. In 2021, LIBs production in China reached 47.5 kt, contributing to nearly 70% of the global total production. The EU and the U.S. followed China in battery production, partly as a response to the promotion of domestic battery production through targeted policies to increase supply chain resilience. In the product manufacturing and consumption stage, EVs have become the largest Li application segment in 2021 (31.2 kt), where China, the EU, and the U.S. are the major producers and consumers. The model estimates that 5.9 kt Li contained in EVs batteries entered EOL in 2021 globally. However, only 1.4 kt, around a quarter of the total waste batteries, were collected and recycled through the formal recycling system globally, although recycling mainly happened in China, recycling capacity is increasing in different parts of the world. In further iterations of the MFA we will aim to differentiate between recycling to blackmass and recovery of secondary metals through pyro and hydrometallurgical processes.

- **Global Nickel Material Flows**

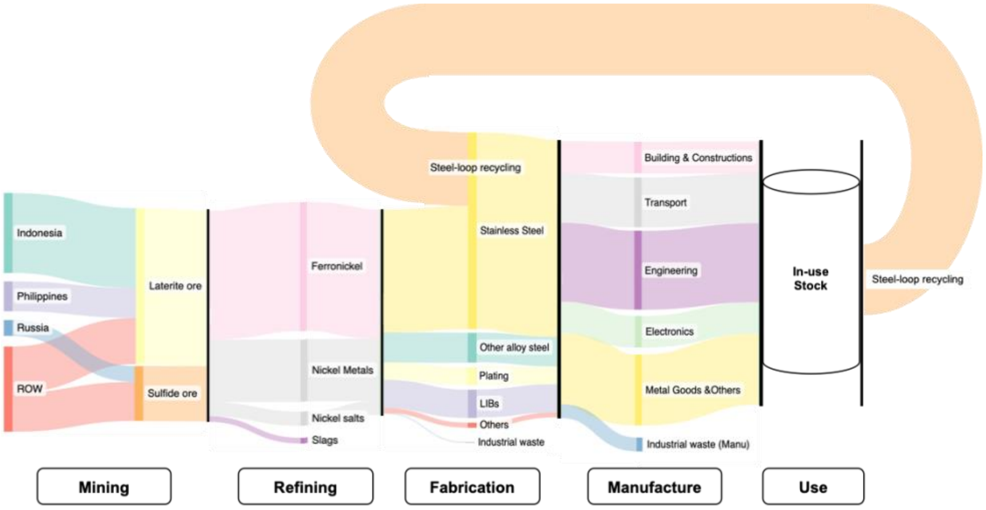


Figure 6: Sankey diagram of global Ni physical material flows, 2021
(Source: Nickel Institute, INSG, ISSF, WSA)

Figure 6 illustrates the global Ni physical material flows in 2021. During this period, nickel used in the fabrication of first-use products reached 3596 kt globally, with 26% of raw materials coming from secondary sources (scrap input). The stainless-steel sector accounted for the largest proportion of nickel used at this stage (71%), followed by other alloys (11%) and LIBs (10%). Regarding the manufacture stage, engineering, metal goods, and transport were the largest three end-use application fields of nickel, with the shares of 30%, 23%, and 19%, respectively. At the end-of-life (EOL) stage, our results estimate that global nickel recycled scraps could reach 1085 kt based on Su et al. (2025), accounting for 65% of total waste generation.

Data gaps and levels of uncertainty

- **Mining and refining stage**

We have been working on collecting primary bottom-up data on lithium and, more recently, nickel, with the aim of covering all currently operating mines worldwide. However, data completeness remains uneven due to the limited availability and accessibility of mine-specific information across different companies and regions (Figure 7).

Detailed information on mining and refining technologies at the mine level is often lacking. While process-based life cycle inventories (LCIs) for major nickel processing routes (e.g. RKEF, HPAL, and pyrometallurgical pathways for nickel ores to nickel sulfate) have been compiled (Ray et al., 2025), it is challenging to consistently assign these technologies to individual mines. In addition, process-level models for tailings management are relatively scarce, further contributing to uncertainty in environmental impact estimates.

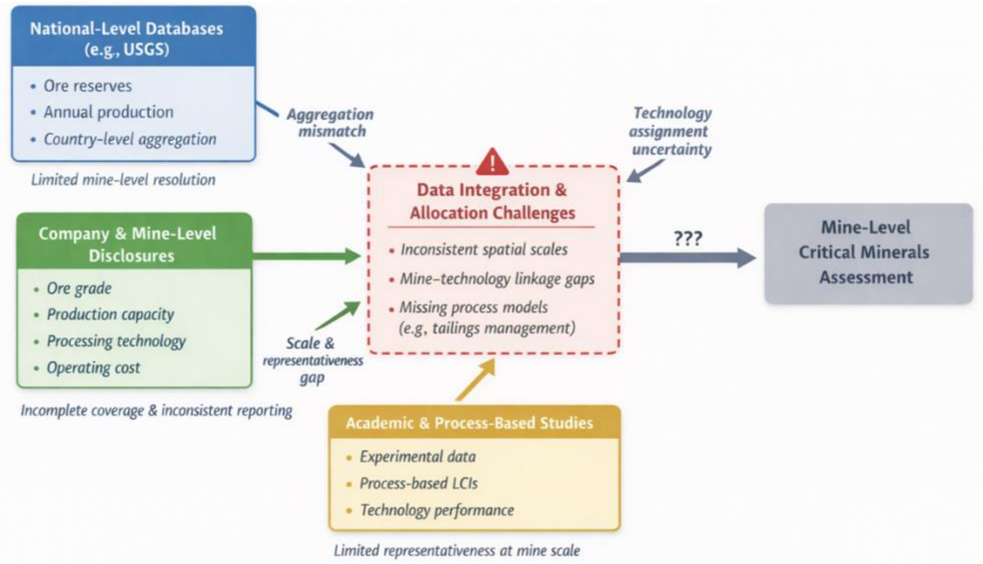


Figure 7: An overview of challenges in integrating mine-level data for sustainable mining management assessment

- **Products manufacturing and consumption stage**

In contrast to lithium, for which approximately 80% of supply is used in lithium-ion batteries, nickel is characterized by a highly diversified set of end-use products and sectors of application. At present, the analysis is based on global aggregated end-use distribution estimates are available from the Nickel Institute, but there is no traceability of how these global estimations have been generated. This poses a significant uncertainty level on allocating nickel flows from intermediate products to first-use products, as well as from first-use products to end-use products.

- **Waste treatment stage**

Current understanding of nickel recycling is dominated by the steel-loop pathway, in which nickel is recovered through stainless steel recycling. Based on the World Steel Association (WSA), recycling rate of stainless steel at the end-of-life (EOL) stage can reach approximately 70%, and recycled nickel, through this route, could account for up to 37% of the nickel content in stainless steel production.

With the rapid growth of nickel demand for batteries, recycling of battery metals has emerged as a fast-growing commercial opportunity. Although laboratory- and pilot-scale studies indicate that nickel recovery efficiencies in battery recycling processes can reach up to 95%, there is a lack of transparent, operational data at the commercial scale, leading to substantial uncertainty in real-world recovery performance and economic feasibility of recovery operations.

For other Ni-containing products, such as alloys, information on EOL recycling processes, Ni recovery efficiencies, and the traceability of recycled nickel remains very limited.

Questions

- **Issues related to the global mine-level dataset**
  1. Instead of secondary datasets (e.g. USGS, INSG, WSA), are there any other known sources of industrial-level or site-specific data on nickel mining and refining activities (e.g. company disclosures, industry databases, or proprietary datasets)?
  2. Are there any ongoing initiatives or open-access database guidelines and protocols to improve data consistency, reliability, reproducibility? Are there any other recommendations in improving the below existing global dataset we are generating as part of MINERS?

Table 3: Example of global mine-level ore dataset

Confiden	Mine Nam	Group Na	Latitude	Longitude	Asset Typ	Country o	Primary C	Secondar	Other Commodities	Operating Company	Mine Type	Ni Grade (%)	Production 2022	Production Capacity	Reserves (kt Ni)	Technology	Cost
Very Low	Pertambangan Nickel, Pom		-3.948	122.599	Mine	Indonesia	nickel			Vale Indonesia Tbk (PTVI), HUAYOU (		1.68	63.9	120		MHP	
High	Sorowako	Soroako Pt In	-2.569	121.378	Mine;Smelte	Indonesia	ferronickel	nickel	cobalt	Vale Indonesia Tbk (PTVI), HUAYOU Cobalt			46.9	60		MHP	
Moderate	PT Central Omega Resources		-1.881	121.326	Mine	Indonesia	nickel						12				
High	PT Halmaher	Weda Bay	-1.536	127.422	Mine	Indonesia	nickel	cobalt		Tsingshan Group, Eramet, Aneka Tar		1.23-1.48	36.6	120	2700	HPAL	
		North Konawe、 North Maluku、 Kolaka,			Mine	Indonesia	nickel			ANTAM		1.29-2.01	24.3	30	8632	RKEF	14.4k $/t
High	PT Huayue Ni	PT Huayue Ni	-2.840	122.166	Mine	Indonesia	nickel	copper	diamond;gold;iron or	HUAYOU Cobalt, Woyuan, Qingchuang International				420		MHP	
		QMB			Mine	Indonesia	nickel			GEM, CATL, EcoPro, HANWA			12.0	65			
	Obi Island	HPL, ONC			Mine;Smelte	Indonesia	nickel	cobalt		Ningbo Lygend Mining				240		HPAL	
		HJF, KPS			Mine;Smelte	Indonesia	nickel	iron ore				1.0-1.3		280		RKEF	
	Obi Island	WP&RKA			Mine	Indonesia	nickel	iron ore		Jinchuan, WP, RKA				30		RKEF	
	Morosi	PT Virtue Dragon Nickel Industry (VDNI) ,			Mine	Indonesia	nickel			Jiangsu Delong Nickel Industry Com		1.6-1.8		820		RKEF	

  3. What are currently considered the main industrial routes for nickel mining and refining? Are there any important routes or emerging technologies missing in the figure below?

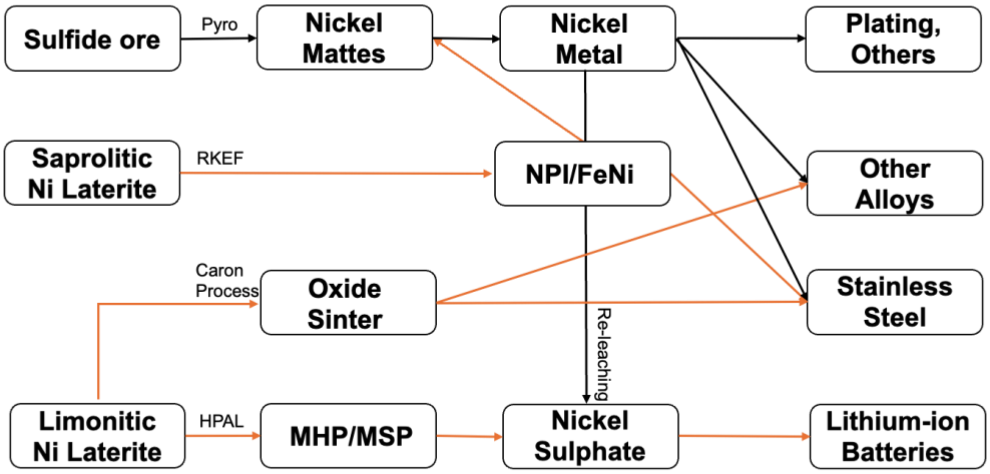


Figure 8: Main routes of nickel mining and refining processing

  4. Has tailings recovery been incorporated into mining activities? If so, what are the main technological routes?

- **Issues related to the global CMs material flows**
  1. Are there data sources or methodological approaches that allow a more detailed allocation of nickel flows along the value chain (e.g. from intermediates to first-use products, and from first-use products to end-use products)?
  2. While nickel recycling embedded in stainless steel scrap is relatively well documented, are there any industrial routes for recycling nickel from other alloys?
  3. How well established are the main routes of EOL battery recycling (e.g. pyrometallurgical, hydrometallurgical)? Are there any specific challenges in the

recycling processes, such as achieving level of purity to be used in batteries for Li? Is nickel typically recovered as a separate metal in battery recycling, or primarily recycled as part of secondary NCM cathode materials?

4. How does this affect the traceability and effective availability of recycled nickel for different downstream uses?
5. Is the price of recovered/ secondary nickel the same as primary materials? Are there commercialised as in primary markets?
6. Are there any other recommendations in improving the below global nickel flows?

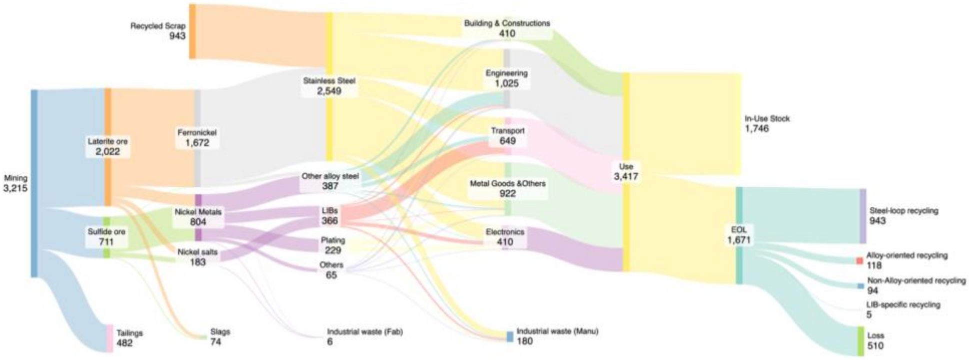


Figure 9: Revised Sankey diagram of global Ni physical material flows by self-estimation, 2021

Legislative and institutional landscape assessment

Main authors: Aden, G. and Domenech, T.

Mapping critical minerals (CMs) policies globally

Global policy activity on critical minerals has accelerated in recent years.

As part of the MINERS project a structured dataset has been developed building on the existing International Energy Agency's Policies and Measures (PaMs) database to map the global critical minerals policy landscape. The current dataset presently covers over 600 policy measures both at national and international across a wide range of jurisdictions. MINERS has developed a classifying framework that captures main policy intervention types, detailed sub-types, jurisdictional scope, implementation status, and thematic orientation. Each entry includes a short description, time coverage, and source references, enabling both qualitative review and quantitative analysis. A quick overview of the main type of policies and countries with initiatives in Critical Minerals is represented in **Error! Reference source not found.** (a&b).

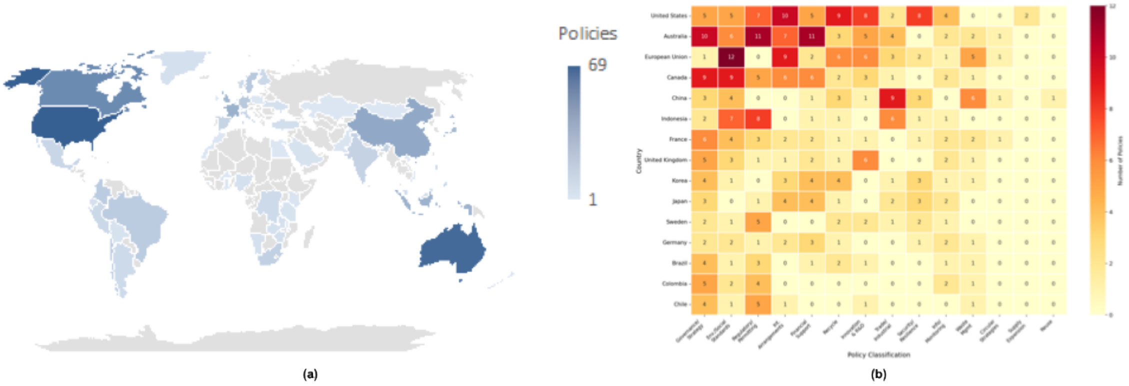


Figure 10: Summary of critical minerals (CMs) policies by country (a) and type (b)

Some preliminary findings identified that around 75% of the measures in the dataset were adopted from 2018 onwards, and approximately two-thirds (67%) since 2020. Most policies are already operational, with a roughly 88% classified as implemented. At the same time, the policy field is highly concentrated in a few countries and regions (**Error! Reference source not found.** (a)). The United States accounts for 69 identified policies, followed by Australia (64), the European Union (51), Canada (46) and China (32). In total, ten jurisdictions account for 56% of the policies in the dataset. This core group also accounts for a substantial share of global mining innovation and midstream capacity in critical minerals (R&D, patents, processing and battery value chains), implying that their policy choices will play a central role in shaping global supply-chain resilience and de facto standards for other countries.

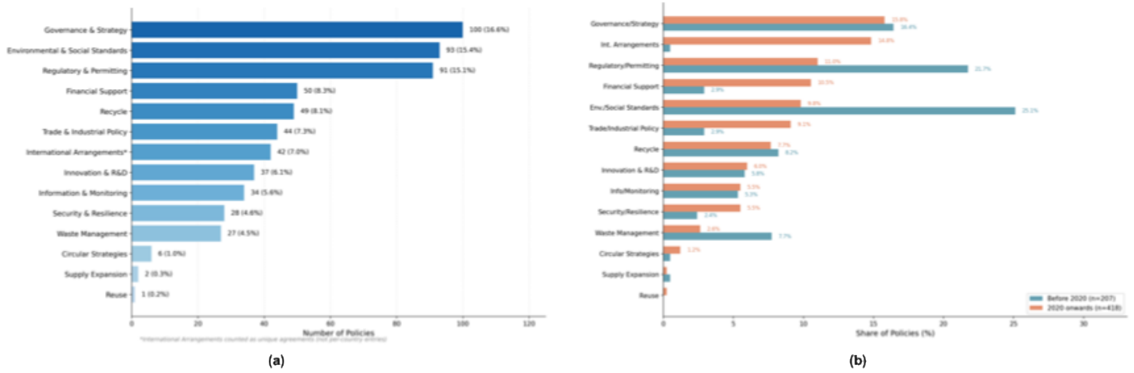


Figure 11: Global distribution of critical minerals (CMs) policies by classification

The distribution of policies in the dataset highlights a strong emphasis on upstream governance and enabling conditions (Figure 11). Governance and strategy measures represent the largest share of policies (around 17%), closely followed by environmental and social standards (15%) and regulatory and permitting reforms (15%). Together, these categories account for nearly half of all identified measures and primarily target early stages of the value chain, including exploration, project approval, and the establishment of strategic frameworks for critical minerals development. Financial support instruments and recycling-related policies form a secondary tier, each accounting for just over 8% of the dataset, reflecting growing—

but still limited—attention to investment incentives and material recovery. Viewed through a resilience lens, the current policy mix remains predominantly focused on reducing exposure to supply risks by facilitating new supply and improving governance at the mining stage. By contrast, comparatively fewer measures explicitly address downstream or system-level vulnerabilities.

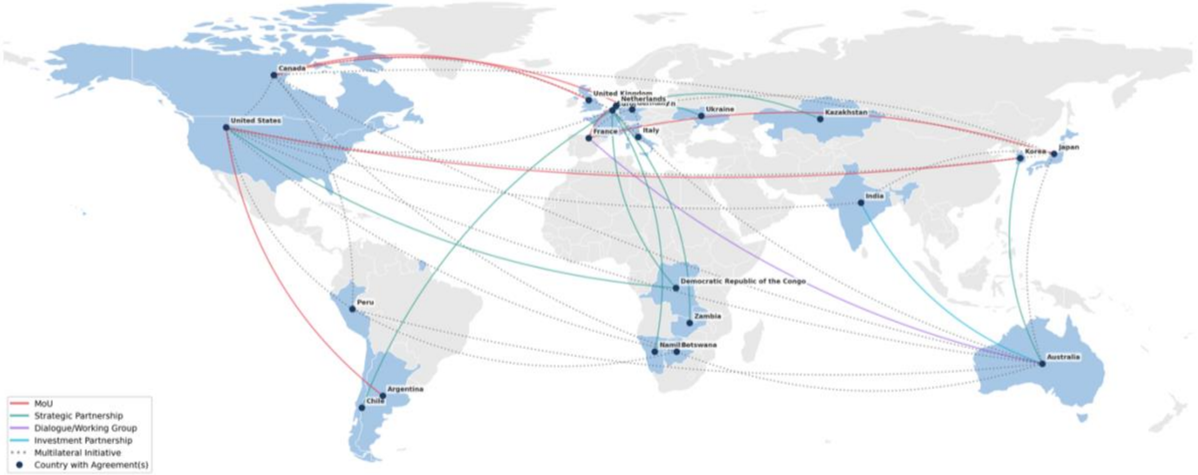


Figure 12: Mapping of public bilateral and plurilateral cooperation

International cooperation on critical minerals has expanded rapidly in recent years (Figure 12). The dataset identifies 41 international initiatives classified as international arrangements, of which 98% were launched in 2020 or later, highlighting the recent acceleration of cross-border policy coordination. These initiatives span a wide range of institutional forms, from formal multilateral partnerships – such as the Minerals Security Partnership – to bilateral memoranda of understanding (MoUs), joint declarations, and non-binding public statements signalling intent to cooperate. While more formal arrangements typically involve structured work programmes, shared objectives, and recurring ministerial or technical dialogues, looser instruments often focus on information sharing, strategic alignment, or the exploration of future collaboration without legal commitments. Participation is concentrated among a small group of economies: the United States is involved in 14 initiatives, followed by the European Union (13), Canada and Australia (8 each), and Japan (7).

Taken together, this pattern suggests that international cooperation is increasingly being operationalised through flexible partnership-based arrangements to manage geopolitical exposure, trade risks, and supply-chain vulnerabilities.

Questions

1. What are the most important under-addressed sources of vulnerability in critical mineral value chains?
2. What kind of policies are you most interested in seeing developed or expanded upon in the future?
3. How should policymakers think about **trade-offs between these instruments**, and are there combinations that you see as particularly effective or risky?