CellPress

Joule

Perspective

Clean energy demand must secure sustainable nickel supply

R. Basuhi,[1,9] Karan Bhuwalka,[2,9] Elizabeth A. Moore,[3] Isabel Diersen,[1] Rameen H. Malik,[4] Eric Young,[5] Romain G. Billy,[6] Robert Stoner,[7] Gerbrand Ceder,[8] Daniel B. Müller,[6] Richard Roth,[3] and Elsa A. Olivetti[1,3,*]

SUMMARY

Unprecedented demand for critical energy transition metals will expand global mineral supply and reshape commodity landscapes. We discuss the opportunity for demand signals to discern the nature of supply development and create incentives for sustainable production in the long term. We focus on global nickel supply and outline the nickel industry's challenges in aligning economic incentives and socio-ecological impacts as it responds to growing demand. We explore the evolving role of Indonesia in the nickel and battery supply chain and envision how discerning demand structures can influence regional production priorities. We argue that discerning demand signals must be translated into responsible practices with effective standards to support low-impact nickel processing. To this end, coordinated minerals policy, harmonized governance mechanisms, and inclusive decision-making processes will be essential.

INTRODUCTION

The clean energy transition to decouple the global economy from fossil fuels is underway. As renewable energy deployment increases around the world, battery electric vehicles (BEVs) will be critical in decarbonizing road transportation.[1] Electric vehicle (EV) growth trends reinforce this expectation: the International Energy Agency (IEA) reports that annual electric car sales in 2023 were more than 6 times higher than in 2018, accounting for 18% of all new cars sold in the year.[1] Studies project accelerating growth and diffusion of BEVs in advanced and emerging markets alike—a positive trend within the energy transition. However, BEVs use 5–6 times more critical materials than internal combustion engine vehicles (ICEVs), requiring multi-fold increases in extraction, processing, and refining capacities of battery minerals in a short time frame.[2] Facing this urgency, experts warn that temporal tensions can exacerbate the externalized costs of prevailing extractive practices and create unsustainable patterns in the clean energy transition.[3]

In this perspective, we discuss nickel supply where abundant low-cost production coincides with unsustainable practices and reinforces low prices. Low prices discourage investing in clean energy integration or low-impact technologies in mining and processing operations. A combination of capital-intensive nickel projects and future demand uncertainty creates a bleak economic outlook for sustainable nickel mining and processing. Drawing from nickel, we discuss three factors critical to sustainable production for the battery supply chain: (1) demand that discerns

CONTEXT & SCALE

Continued rapid deployment of electric vehicles (EVs) provide a fundamental component of pathways to decarbonize transportation. Sustainable and resilient future supply of battery constituents derived from mined minerals will be essential to this transition for all major economies. Nickel, a critical metal used in dominant nickel-based cathode chemistries is under scrutiny for its emissions intensity and supply concentration. Emerging production pathways in Indonesia produce battery-grade nickel with as much as 10× higher emissions than sources from Canada, and Indonesian nickel producers supplied 50% of global nickel consumption (including stainless steel applications) in 2023. In this perspective, we outline technical, economic, environmental, and geological considerations underpinning three major battery-grade nickel process flows and discuss the role of demand in aligning interests and incentives that advance sustainable processing pathways.

Joule 8, 2960–2973, November 20, 2024

the socio-ecological impacts of supply; (2) metrics, standards, and systems of certification that can propagate demand-side signals up the supply chain; and (3) responsible investment strategies that catalyze change in nickel-producing regions. We conclude by offering an outlook on the current role of, and future developments in, nickel-based battery chemistries.

BACKGROUND

Nickel is a key component of many commercial EV battery cathode chemistries. Nickel-rich cathodes comprised 55% of light-duty EV batteries in 2023 and dominate use cases where high energy density for longer driving ranges is preferred.[1] A major share of global nickel production (66% in 2022[4]) serves stainless steel applications today (see Box 1), but demand for battery-grade nickel is expected to grow 400%–600% by 2030 as battery manufacturing and BEV sales accelerate in climate-driven scenarios.[5] Although demand is sensitive to assumptions about future battery chemistry mix, the IEA projects that nickel production for battery use in 2040 to meet mid-century net-zero targets[5] will exceed total nickel produced in 2022 (Figure 1A). Over the next decade, much of this new supply is expected to be derived from nickel resources in Indonesia (Figure 1B).

Indonesia, rich in lateritic nickel resources, is a key region in the global nickel supply chain, producing 1.8 Mt of nickel in 2023[18] (a 10-fold increase since 2016; Figure 1A). The archipelago holds the largest nickel reserves in the world, estimated at 55 Mt in 2023.[18] Mining is also a critical part of the Indonesian economy, contributing to 12.2% of the national GDP[19] and 12.7% of its tax revenue.[20] For much of the country's mining history, Indonesia has exported raw ore, the lowest-value product in the minerals value chain.[21] Over the last decade, however, the Indonesian government directed efforts to build downstream processing capacity to capture greater economic value within its borders and participate in the low-carbon transition.[22] The Indonesian Battery Corporation (IBC), formed by major energy and mining enterprises in 2021, aims to develop domestic battery supply chains and manufacturing capabilities and become a global EV producer.[23] With concerted domestic policies and targeted foreign investment from China into the country's mining sector, Indonesian producers now supply nearly half of globally mined nickel (see Figures 1A and 1B) and its share in downstream commodities like mixed precipitates and matte continues to grow.[24] Besides being a major investment partner, China is also a major importer of Indonesian nickel products. Nickel matte imports to China increased from just 10 kt in 2020 to over 300 kt in 2023, with 93% sourced from Indonesian laterites.[25] Other major laterite-rich regions include the Philippines, New Caledonia, and Western Australia.[7]

As nickel production expands rapidly, increased scrutiny exposes key environmental, social, and governance (ESG) concerns. In early 2024, Australian miners BHP and Fortescue called on the London Metals Exchange (LME) to differentiate between "clean" and "dirty" nickel in its contracts.[26] This call for commodity differentiation based on ESG criteria came after prevailing low class 1 nickel prices through late 2023 caused higher-cost mines in Western Australia (BHP Nickel West[27] and First Quantum Ravensthorpe[28]) and New Caledonia (Glencore Koniambo Nickel[29]) to curtail production or shut down. Costs and socio-ecological impacts of mining and processing vary by geographical location due to differences in orebody geology, primary energy supply, regional environmental protections, and protocols for obtaining social license to operate. In some producer geographies, regulations internalize some of the costs of mining and processing activities

[1]Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA

[2]Department of Energy Science and Engineering, Stanford University, Stanford, CA, USA

[3]Materials Systems Laboratory, Massachusetts Institute of Technology, Cambridge, MA, USA

[4]Institute for Data, Systems and Society, Massachusetts Institute of Technology, Cambridge, MA, USA

[5]SINTEF, Trondheim, Norway

[6]Industrial Ecology Programme, Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim, Norway

[7]MIT Energy Initiative, Massachusetts Institute of Technology, Cambridge, MA, USA

[8]Department of Materials Science and Engineering, University of California Berkeley, Berkeley, CA, USA

[9]These authors contributed equally

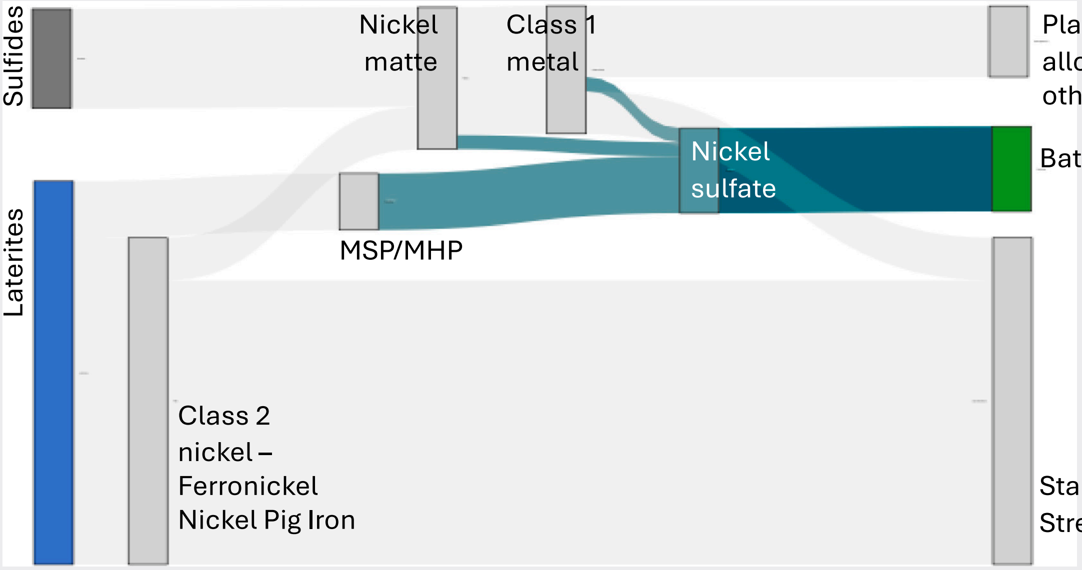
*Correspondence: elsao@mit.edu

https://doi.org/10.1016/j.joule.2024.10.008

Box 1. Production pathways for battery-grade nickel

Battery cathode active materials consume high-purity chemicals as precursors, with nickel-containing chemistries requiring high-purity nickel sulfate hexahydrate ($NiSO_4.6H_2O$). Within the nickel industry, highly pure feedstocks are termed class 1 nickel, defined as containing >99.8% nickel.[6] In the earth, nickel-rich orebodies contain <2% nickel,[7] and numerous mineral and metallurgical processes must be employed to extract nickel from heterogeneous geological materials, including iron oxides, magnesium hydrosilicates, and more. Smelting (pyrometallurgical) and leaching (hydrometallurgical) are two broad classes of processing technologies used to separate metals from host minerals and gangue before refining to the relevant purity. The below figure illustrates the global material flow of nickel.

Geologically, nickel is found in sulfide and laterite ores.[8] Sulfide smelting provides thermodynamically easier and less energy-intensive routes to “class 1” nickel via nickel matte (about 30%–60% nickel).[9] On the other hand, smelting of laterite ores is primarily used to produce “class 2” nickel (<99.8% nickel) in ferronickel and nickel pig iron feedstocks containing 10%–30% nickel and 50%–60% iron.[6] Until recently, class 2 nickel only supplied stainless steel production.[10] However, with greater abundance of economically accessible lateritic reserves[7] and growing battery demand for class 1 nickel, laterite-rich nations like Indonesia are adopting new processing technologies (sulfidation to matte) that flexibly convert class 2 nickel to class 1 battery-grade feedstocks.[11] Laterite leaching pathways such as high pressure acid leaching (HPAL) also produce mixed intermediaries (MSP/MHP or mixed sulfide precipitate/mixed hydroxide precipitate) that are refined to class 1 nickel but are operationally more complex than smelting.[7] Table 1 describes technoeconomic and environmental considerations of the three battery-grade nickel production pathways.



Material flow schematic showing ores, traded nickel commodities, and end-use applications

Representative flows are based on approximate production data in 2023. MSP/MHP, mixed sulfide precipitate/mixed hydroxide precipitate.

through stringent environmental review processes and permitting policies.[30] In others, however, weaker environmental governance attracts investments seeking low-cost opportunities in a risk-prone sector. For example, by one account, installing SO_x capture raises the costs of a smelter project from 30 million USD to 100 million USD.[31] When higher-impact sources are both lower in cost and easier to permit, rapid expansion of production can lower prices and undermine the viability of environmentally conscious production modes. In Indonesia, the fast-tracking of nickel production and processing as national strategic projects[32] has rapidly expanded the global nickel supply.[24] Twenty new processing plants are expected to come online in Indonesia by 2026, totaling 950 kt in additional nickel processing capacity.[33] At the same time, provisions in the Omnibus law that expedite production also weaken environmental and community protections,[34] leading to a glut of nickel supply that overlooks many socio-ecological costs of nickel mining and processing.[35]

Table 1. Technoeconomic, environmental, process, and production considerations for three pathways to nickel sulfate

–	Laterite leaching	Laterite smelting and sulfidation	Sulfide smelting
Intermediate to nickel sulfate production	mixed hydroxide or sulfide precipitates (MHP, MSP)	nickel matte	nickel matte
Geological considerations	can use low-grade limonite and saprolite ores[a] within laterites	high-grade saprolite ores needed, getting depleted[b]	very low economic reserves[c]
Current intermediates production (2023)	350–470 kt	280–300 kt	700–800 kt
Major producing country	Indonesia	Indonesia	Russia, Canada
Development time[d] (years)	4.3–21.1[e]	∼1–2 years (for NPI-matte conversion)[f]	no recent developments
Capital intensity (USD/tpa)	\$25,000–32,000 (in Indonesia); \$50,000–140,000 (outside)	\$18,000–20,000 (smelter); \$1,000–2,000 (converter)	\$30,000–50,000
Cash cost[g] (USD/t Ni)	\$9,400–21,000	\$17,000 (of which NPI-matte conversion costs \$3,000)	\$8,000–19,000
GHG emissions[h] (tCO$_2$e/t Ni)	18–33 tCO$_2$e/t Ni[i]	40–120 tCO$_2$e/t Ni[j]	14–17 tCO$_2$e/t Ni[k]
Other environmental considerations	challenging tailings management[l]	high SO$_x$ and particulate matter emissions[m]	SO$_x$ emissions[n]

[a] Laterite profiles show two classes of ores: surface limonites contain nickel within hydrated iron oxides and deeper saprolites contain nickel within (low iron) magnesium hydrosilicates.[8]

[b] High-grade ores with approx. 1.7% Ni content are needed to maintain smelting composition for ferronickel (FeNi) and nickel pig iron (NPI) production. Estimates of Indonesian reserves suggest that high-grade ores may be depleted in 6–9 years.[12]

[c] Undeveloped high-grade sulfide resources for future extraction are very low, with only 1 high-grade sulfide discovery in the last decade. On average, historically, sulfide mines have taken over 13 years from discovery to production, and, therefore, forecasts to 2035 expect new sulfide capacity to contribute minimally to battery nickel supply.

[d] Development time for battery-grade intermediates production (MHP/MSP or matte) capacity post discovery includes feasibility, start-up, and ramp-up stages. For smelting/sulfidation pathway, processes at existing smelters in Indonesia are expanded and thus do not involve mine construction and associated stages.

[e] Indonesian projects occupy the lower end of this range, with Obi and Huaye Nickel-Cobalt plants taking 4.3 and 4.4 years from feasibility to production, respectively. In comparison, the most recent projects to open outside of Indonesia—Goro in New Caledonia in 2021 and Ramu in Papua New Guinea—took 21.1 and 19.4 years, respectively, and involved a much longer ramp-up duration.[7] The Goro project took over 10 years to ramp-up after construction, and capital costs grew from an initial estimate of \$1.5 billion to \$5.9 billion for a 60,000-kt-per-annum plant.[13]

[f] As a new, emerging pathway, data on development time are approximated by estimating time from announcement by companies Tsingshan and PT Huake to production. According to news sources, both announced plans in 2021 and confirmed production in 2022 and 2023, respectively. In this pathway, existing smelters are retrofitted with ferronickel-matte conversion facilities and can be developed faster.

[g] Data from S&P Capital IQ Pro, estimated on a payable metal basis. In this estimation, intermediates production costs are scaled by a factor to approximate refining to class 1 metal for ease of comparison. We also use co-product allocation of costs, where cost is distributed across multiple mineral products on a revenue basis. Operating costs of some high pressure acid leach (HPAL) projects and sulfide projects are sensitive to co-product quantity and price, as they also produce cobalt and platinum group metals, respectively.

[h] Each intermediate commodity varies in nickel composition. Therefore, GHG emissions are calculated for extraction and processing stages on a per-ton-contained-nickel basis for comparability and additivity.

[i] Estimates vary based on project location and energy sources used as well as process details. We surmise range from IEA (18–32 tCO$_2$e/t Ni[2]), GREET 2022 (23 tCO$_2$e/t Ni[14]), and an LCA report by MinViro in collaboration with the German Association of Automotive Industry (33.3 tCO$_2$e/t Ni[15]).

[j] Estimates depend heavily on energy source used as well as nickel content in FeNi/NPI, which can vary from 10% to 30%. Current production is limited to Indonesia, where processes are largely coal powered. A large range is surmised—we find that GHG emissions estimates of FeNi/NPI production span 40–120 tCO$_2$e/t Ni,[16] but literature estimates for conversion from FeNi/NPI to matte or class 1 or sulfate are not available as it is a relatively new process. An LCA report by the German Association of Automotive Industry[15] estimates that the total emissions for nickel sulfate via sulfidation of FeNi/NPI is 98 tCO$_2$e/t Ni. Of this total, 40% is contributed by coal-powered electricity for the rotating kiln electric furnace (RKEF) and 45% from direct coal use as an energy carrier and reductant.

[k] Sulfide smelting is partially exothermic, so matte production using sulfide ores consumes less energy, leading to lower emissions. We sum up emissions intensity of class 1 metal production (7–10 tCO$_2$e/t Ni according to IEA[2]) and subsequent class 1 to NiSO$_4$ conversion (7 tCO$_2$e/t Ni according to GREET[14]).

[l] Riverine and marine tailings disposal in Papua New Guinea and Indonesia are reported to cause adverse ecosystem impacts, polluting waters and soils and affecting livelihoods depending on fisheries and agriculture, and draw widespread civil society scrutiny. In response to growing pressure, Indonesia halted new permits to deep-sea tailings disposal in 2021.[17]

[m] SO$_x$ and particulate matter emissions attributed to nickel supply are a function of ore type, mine-level processes, energy sources, and regional regulatory contexts. Laterite smelting and sulfidation processes produce SO$_x$ and PM emissions mainly due to captive coal use.

[n] Regions also differ in stringency of air pollution standards. GREET estimates for SO$_x$ emissions for class 1 nickel production vary by region—3 tSO$_x$/t Ni for class 1 production in Russia and 1 tSO$_x$/t Ni for the rest of the world.

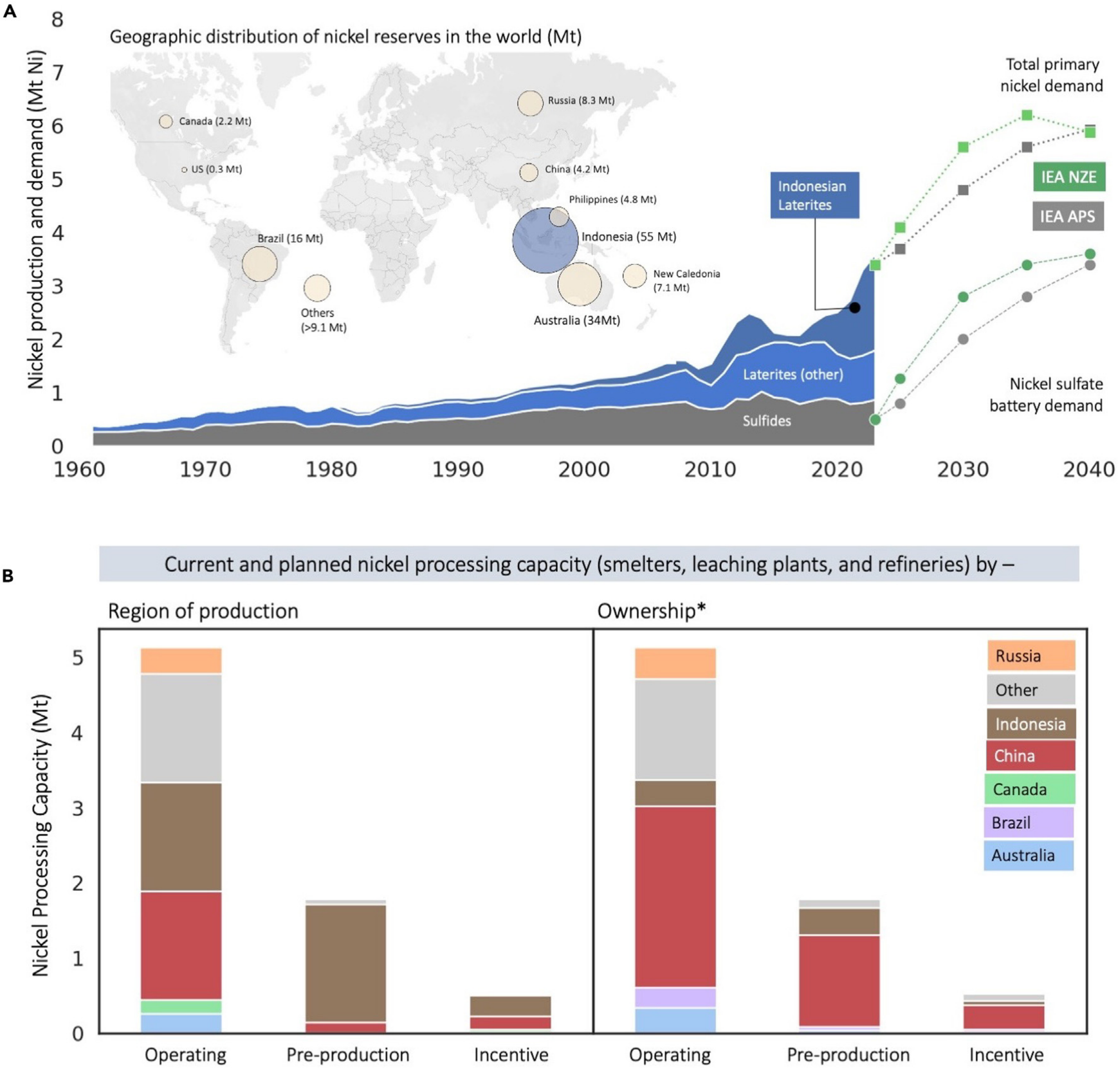


Figure 1. Changing landscape of global nickel production

(A) Historical production growth and future demand for total primary nickel and nickel sulfate for batteries. Future demand estimated for net-zero emissions (NZE) and announced pledges scenario (APS) from IEA's Global Critical Minerals Outlook (2024). Production data adapted from Mudd and Jowitt,[7] extended for 2022–2023 using US Geological Survey (USGS) estimates. Data for reserves from USGS Mineral Commodity Summaries (2024).

(B) Nickel-processing capacity in operating, pre-production, and incentive facilities divided by region of production and ownership. *Ownership is assigned to the country of the private or state-owned entity with the largest equity in the project. Data from S&P (2024) on processing facilities includes smelters, leaching plants, refineries, and sulfate plants. Pre-production is defined as projects where a go-ahead decision has been made and is being readied for production, including construction or commissioning stages. Incentive projects are defined here as those that are either undergoing a scoping study or a feasibility study or have a completed feasibility study but have not yet made a go-ahead decision. Processing facilities for which development stage is unreported (2%–4% of total reported production) were not included.

Lateritic pathways, both smelting and leaching, require more energy than sulfide smelting and, depending on the fuel used, emit more greenhouse gases (GHGs) (see Table 1 and Box 1). Smelting followed by sulfidation is more carbon intensive (60–120 tCO_2e) than high-pressure acid leaching (35 tCO_2e/t), and the energy powering these operations in Indonesia is largely coal based.[21] Consequently, the contribution of nickel processing to battery-life-cycle GHG emissions are significant. One recent study found that when the nickel in an NMC811 battery is sourced from laterite smelting, it increases the breakeven mileage of an EV by 70,000 km compared with a battery with nickel sourced from sulfides.[36] When all atmospheric emissions are accounted for, EVs with nickel-rich batteries (NMC811) can have higher life-cycle social costs than ICEVs, largely due to sulfur dioxide emissions from nickel processing.[37]

Nickel mining is also land intensive and has been linked to deforestation and displacement. A report by Climate Rights International voices land grabbing and water rights concerns by communities near the Weda Bay Industrial Park in Indonesia (set to produce 500 kt nickel by 2030).[35] A recent academic study[33] correlates Indonesian nickel ore production from 2001 to 2020 with land cover changes around nickel mines and finds that land use intensity may be up to 20× higher than previous estimates. Lateritic deposits are surficial, and the projected rapid production increase is set to more than double the nickel mining area[33] from 360 km^2 in 2020 to 800 km^2 by 2026. Although this estimate includes associated processing facilities and waste storage, it excludes the indirect effects of mining effluents and wastes on the surrounding environment. With less than 2% of the ore being nickel, much of the mined material must be managed as waste in the form of waste rock, tailings, slag, etc.[38] Tailings, specifically, raise concerns around laterite leaching pathways, as fine particles, acid, and metalliferous discharge can contaminate soils.[39] Indonesia's geography further intensifies these concerns: wet tropical climates and frequent seismic activity challenge land-based tailings containment, while deep-sea tailings placement risks marine impacts of unknown scale and scope.[21] Unchecked mining activities can irreparably impact biodiversity in tropical rainforest ecosystems[40] and devastatingly disrupt the lives and livelihoods of land-connected peoples.[41]

Nickel mining and processing, then, presents a complex, multi-actor conundrum. On one hand, energy transition trajectories rely on low-cost batteries and, therefore, incentivize scaling up low-cost nickel production. Responding to this demand, resource-rich nations draw upon their mining and processing sectors to capture naturally endowed resource wealth, forge industrial growth, and advance national development. On the other hand, without relevant institutional safeguards, existing incentive structures prioritize low-cost production by undermining community rights,[42] locking in emissions-intensive technologies,[16] and damaging delicate ecological balances.[43] On the demand side, battery chemistry choices depend on materials prices,[1] encouraging producers to maintain low prices. On the supply side, however, a combination of low prices and uncertain future demand increases the risk associated with investing in cleaner processing routes that require large capital investments. Consequently, low nickel prices beget unsustainable practices, incentivizing long-term patterns of externalizing the socio-ecological costs of production to vulnerable populations.

DISCERNING DEMAND MOTIVATES SUSTAINABLE SUPPLY

We define discerning demand as demand-driven signals that stipulate socio-ecological attributes for production and incentivize suppliers to prioritize such attributes. When local regulations are not aligned with international best practices, discerning demand can help level market considerations of commonly externalized factors. Such demand signals also exhibit tipping behavior: a critical mass of market participants can shift supply characteristics[44] toward sustainable outcomes.

Demand that is discerning of the socio-ecological impacts of supply may form due to policy push, market pull, or a mix of the two. For example, disclosure regulations for conflict minerals in the US led to responsible sourcing standards and certification schemes for tin, tantalum, tungsten, and gold (3TG) minerals production, modified supply-chain choices among major consuming industries (most notably, electronics), and created demand for conflict-free minerals.[45] In another example, market-based demand for a greener supply chain by leading electronics and automotive manufacturers has grown the segment of certified low-carbon aluminum production.[46] Among examples of collaborative actions and public-private partnerships, the federally coordinated First Movers Coalition in the US rallies demand for sustainable steel across industries.[47]

For nickel, the role of discerning demand from downstream actors such as automakers and EV battery manufacturers is 2-fold. First, for existing projects, discerning demand can support the economic viability of low-impact nickel production. For instance, in 2022, EV manufacturer Tesla and mining company Vale signed a long-term contract to supply low-carbon class 1 nickel in the US from its Canadian operations, with verified carbon footprints under 8 tCO_2e/t nickel.[48] Offtake agreements stipulating social and environmental attributes not only mitigate price risk but also provide clear market signals on the value of aligning production practices to end-users' sourcing policies. For such offtakes to be scalable, this value and the benefits of addressing externalities must exceed the cost of restricting demand to discerning supply channels. Second, for future projects, discerning demand can influence upstream decision-makers such that low-impact projects are designed and prioritized. To fulfill this second role, however, coordinated policies and partnerships are needed to align demand and production incentives. Critical minerals policies in consuming regions can support firm sourcing behavior based on sustainability attributes (like low emissions, community benefits, and tailings safety) and facilitate diffusion of international standards. In the EU, the Critical Raw Materials Act can establish rules for acceptable environmental footprints of relevant materials on the European market.[49] The EU Carbon Border Adjustment Mechanism already requires importers to collect data on the carbon intensity of ferronickel and nickel pig iron used in stainless steel applications,[50] and the EU battery regulation is expected to impose similar requirements for minerals in the battery supply chain.[51] In the US, the Inflation Reduction Act (2021) supports region-based differentiation of battery materials to estimate EV subsidies[52] but is currently agnostic to socio-ecological factors. Australia, a free-trade-agreement partner to the US, can co-develop transparent "green" supply parameters within the scope of EV subsidies. Concerted policymaking can amplify demand signals and, in turn, sustainable production practices can increase supply-chain resilience for energy and minerals security.[53]

DISCERNING DEMAND RELIES ON ROBUST METRICS

In response to the call to differentially price green nickel supply, the LME stated that the "(green) nickel market is too illiquid" and lacks standard definitions for what clean and green mean,[54] instead opting to monitor pricing in direct supplier agreements. In March 2024, Metalshub, a partner to the LME, announced that it would start reporting on the trade of low-carbon Class 1 nickel (defined as <20 tCO_2e/t Ni).[55] Benchmark Minerals Intelligence also launched green nickel prices, tracking transactions with mining companies aligned with Benchmark's sustainability standards based on 79 privately assessed ESG indicators.[56]

What does green mean? And who decides this meaning? Climate change urgency prioritizes low-carbon as a green attribute, but sustainability (or lack thereof) is multi-dimensional, multi-modal, and multi-causal.[57] Moreover, a singular focus on carbon emissions can obscure other social and environmental concerns that often co-occur and interact with one another.[3] Processes for selecting key sustainability attributes for green nickel must be place based and include regional and community expertise alongside representative voices of affected peoples. Even within Indonesian nickel production, concerns vary by island. Facilities in Sulawesi and Kalimantan endanger primate species due to deforestation, while projects built near the coast of small islands like Obi Island and East Halmahera impact fisheries and destroy coral reef ecosystems.[34] Place-based pollution externalities can threaten livelihoods and precipitate conflicts by eroding social trust.[58] Moreover, stated socio-economic benefits can be severely optimistic and lack the granularity to address "on the ground" tensions. For instance, the quality of jobs is seldom characterized. Stakeholder interviews suggest that many local jobs are unstable, unskilled, and short-term and last only through the construction phase of the project.[34] In recent press, journalists also note several worker rights violations in the nickel supply chain,[59] including fatalities due to unsafe working conditions.[60] However, most existing risk management systems only mandate documentation and disclosure, and methodologies for characterizing and capturing complex social and ecological impacts are still nascent.[61]

Beyond defining what green means, discerning demand must account for the distributional impacts of pursuing green options. Understanding who bears the costs and who reaps the benefits[62] over different time horizons[63] is essential to allocating resources across space and time equitably. Entrenched processes monetize quantifiable impacts[64] using conversion factors such as the value of reduced mortality risk (typically for health impacts of air pollution[65]) or social cost of carbon (for GHG emissions[37]). For a globalized supply chain, the former is difficult to value and compare across regions and the latter can obfuscate the locus of burden. Moreover, regional regulations typically amplify inequities in willingness and ability to pay to decrease population risk. As a result, no single set of metrics or flat cost/benefit accounting methodology can adequately estimate the equity implications[66] of supply development. Instead, demand-side support for projects must be based on externality assessments that acknowledge an imbalance of power among various rights holders and beneficiaries and contextualize the impacts of mining and processing activities over relevant spatiotemporal dimensions. In Indonesia, direct health impacts and economic damages linked to nickel processing are concentrated in impoverished areas in Central and Southeast Sulawesi and North Maluku,[65] whereas decisions to develop nickel supply often rests within the central government's mandate of national resource development.[34] Just transition concerns and the mining sector's reliance on coal-based power further complicate the calculus of costs and benefits accrued by various stakeholders.[67] For discerning demand to improve the socio-ecological impacts on nickel-producing regions, externality valuation must be embedded within cohesive standards frameworks that appropriately characterize the distribution of responsibilities and inequities.

Voluntary sustainability standards (VSSs), often conceived and maintained by multi-stakeholder initiatives (MSIs), propagate mechanisms for private governance of externalities in minerals value chains.[68] MSIs focus on sourcing (Responsible Minerals Initiative for conflict minerals), select stages of production (Initiative for Responsible Mining Assurance [IRMA] for mine sites), or a specific metal value chain (Responsible Steel Initiative and Aluminum Stewardship Initiative). Many frameworks draw from principles and good practice guidance documents[69] published by the International Council on Mining and Metals (ICMM). The Copper Mark Advisory Council provides responsible production standards and assurance frameworks for copper, nickel, molybdenum, and zinc value chains. Patterned after the Copper Mark, the Nickel Mark allows nickel producers to demonstrate compliance with 32 ESG criteria[70]; nickel extraction and processing sites are awarded the Nickel Mark certification if they maintain adequate risk management and disclosure systems. To support discerning demand by downstream actors, however, a more extensive framework of standards is needed—to trace material flow as well as to measure, report, and verify metrics. The Aluminum Stewardship Initiative uses two types of standards in tandem to construct such a framework: chain-of-custody standards establish the provenance of minerals sourcing and socio-environmental performance standards set disclosure rules, promote good governance and management practices, and stipulate thresholds for polluting activity (such as GHG emissions intensity <11 tCO_2e/t).[71] For nickel, in addition to traceability, measurement, and verification, sustainability standards in the battery value chain and stainless-steel value chains must be aligned so that impacts are not simply displaced from one end-use to another.[16]

Effective sustainability standards will be key to operationalize discerning demand, but ineffective voluntary standards can dilute market signals and undermine sustainability efforts. Reasons for ineffectiveness are many,[72] and we highlight two that apply to the nickel context. First, trust in standards can be undermined if not all relevant stakeholders participate. Of all the relevant standards applicable to the nickel supply chain, only the IRMA includes civil society organizations in its standards-setting processes. Critics also argue that because governance of certifications like the Copper or Nickel Mark is privately managed, and the interpretation of guidance on many environmental criteria relies on ICMM standards set by the mining industry itself, accountability and evidence for real improvement is rather opaque.[73] Second, data collection and availability often constrain efforts to assess sustainability across diverse sources. Many privately managed certification programs use manual reporting templates, which introduce significant costs for industrial practitioners. Lacking regulatory pressures, cost and time barriers to voluntary efforts limit the usability of audit results to discern between suppliers. Only 7 projects in the world have completed IRMA certification (with 11 in process) and only one nickel mine, Barro Alto, has received an IRMA audit score.[74] As discerning demand needs tipping, lack of adequate adoption leads to existing suppliers reshuffling without overall impact reduction. High collection costs also restrict data access to industrial partners of the initiative. As a result, unbiased analysis of the industry's progress on sustainability is limited[75] and the credibility of certification mechanisms can be wanting.[76]

RESPONSIBLE INVESTMENT FOSTERS SUSTAINABLE SUPPLY

Sustainable mineral extraction and processing requires significant capital investment, and derisking this investment will be critical to sustainable capacity building. Investors finance projects that promise profitability. However, demand uncertainty and price volatility create additional risks that tip mining decision making toward low-capital pathways with faster ramp-up times, even as it externalizes socio-ecological concerns. Permitting and financing processes in Indonesia further reinforce investment trends that reward short-term profit perspectives and counter clean energy narratives. For instance, the exemption of captive coal power from Indonesian regulation to accelerate renewable energy development and the classification of captive coal plants as transition assets is expected to prolong emissions-intensive nickel processing.[77] In short, capital allocated to nickel mining and processing projects systemically undermines sustainability because the alternative offers higher returns with lower risk. Lower-impact underground sulfide mining projects as well as HPAL projects outside Indonesia are more capital intensive (see Table 1), often located in regions with stringent environmental protections and longer permitting timelines. Operational changes, like low-carbon energy integration[78] or dry stacking of dewatered tailings,[79] are also expensive. Discerning demand can derisk investment in sustainable extraction and processing capacity—directly via offtake agreements as well as indirectly by instituting a robust system of standards that steers financing decisions toward low-impact pathways. In the longer run, discerning demand can also support the economic case for investing in battery recycling infrastructure and improve materials circularity considerations.[80]

Diversified investment sources and responsible investment levers that differentially support sustainable capacity building will be essential to expand a cleaner nickel supply. Investment from international lending institutions as well as public listing on international stock exchanges can improve transparency of environmental reporting and incentivize adoption of international standards.[34] Investor endorsement of sustainability standards can help finance certified projects, and targeted pressure can advance environmental goals by improving accountability.[81] For instance, after the Brumadinho tailings dam failure in 2019, the Investor Mining and Tailings Safety Initiative, a group of 112 institutional investors representing USD 14 trillion in assets under management, called for tailings facilities disclosure and a tailings dam database to assess stability and safety.[82]

Value-chain actors can also affect change more directly by co-investing and leveraging integrated supply chains. Western automakers and battery manufacturers can mobilize investment in nickel projects that meet their ESG standards and improve supply-chain resilience.[83] Public-private partnerships and vertical integration opportunities are central to Indonesia’s vision of sustainable development, and investment in supporting infrastructure for mining and renewable energy projects will be critical. Responsible investment can complement just-transition-led economic development in resource-rich nations and translate discerned demand into sustainable nickel capacity, provided public policy and institutions drive political will for coordinated, climate-aligned strategies.

OUTLOOK

Striving for minerals sustainability is challenging and the nickel landscape presents unique social, environmental, geopolitical, and temporal tensions. In this perspective, we explore the evolving nickel supply context and argue for the opportunity for demand signals to discern sources of supply. In this concluding outlook, we briefly outline demand response to supply concerns and present the evolving demand context for EV batteries.

Extreme price volatility in recent years[84] and journalistic reports[85,86] of dirty nickel production in Indonesia, coupled with rapid performance improvements in cheaper lithium iron phosphate (LFP) batteries, spur substitution trends away from energy-dense nickel-based chemistries. In 2023, nickel-free LFP comprised 30% of all EV battery cathodes globally (up from just 6% in 2020) and was the dominant chemistry in China, with >65% market share.[1] Although nickel-based chemistries still make up 90% of EV battery sales in the US and EU,[1] prominent Western automakers have also indicated plans to introduce lower-cost LFP-based models.[87]

Despite significant innovation at the battery-pack level to compensate for its lower energy density (at the materials level), LFP remains inferior to nickel-based chemistries in terms of driving range for a given battery weight and volume. Partially substituting Fe with Mn (in LMFP) increases energy density but incremental benefits are not likely to challenge energy-dense high nickel cathodes soon. As EV drivers report range anxiety,[88] compounded by concerns of charger availability and cold-weather performance, substitution toward less-expensive but lower-energy-content LFP may further challenge the broader market adoption of BEVs. Shift to lower-value LFP chemistries can also make battery recycling less economically competitive in the future.

Promising cathode substitutions, such as lithium-excess disordered rock salts,[89] can match the energy density of high-Ni batteries while using inexpensive Mn and benefiting from similar cell-to-pack improvements as LFP but are still in the early stages of technological maturity. Solid-state batteries, where liquid electrolytes are replaced by inorganic solids, promise another technology option to revolutionize energy storage[90] but are currently limited by higher (projected) initial costs and manufacturability challenges. Even though solid-state batteries are agnostic to cathode choice, their transition to lithium metal as a highly efficient anode material will increase the importance of cathode energy density in setting the cell-level energy content, thereby guaranteeing a future for high-Ni-based or similar high-energy-density materials.

Choice of battery chemistry options in the EV roadmap is shaped by performance considerations, consumer preferences, and supply-chain constraints.[91] Conversely, nickel supply evolves under incentive structures formed by how EV markets negotiate cost-performance-sustainability trade-offs in the battery supply chain. In February 2024, following several months of unfavorable price conditions, Indonesia's deputy coordinating minister of mining stated that low prices are key to protecting nickel demand and guarding against substitution to LFP.[92] Indonesian producers are projected to ramp up supply despite low margins to grow nickel capacity and build a domestic downstream battery value chain. But rapid supply expansion at low prices externalizes costs to communities, climate, and the environment, and a worrying pattern emerges. Substitution risk encourages nickel producers to adopt a short-term outlook, intensifying ESG risks. Increasing nickel supply-chain risks compromise future nickel-based chemistries, fulfilling the shorter-term outlook.

Successful EV uptake across all vehicle market segments must meet a range of consumer preferences and will need a wide range of battery chemistries and technologies. The energy transition cannot afford to lock out high-performance-technology options if countries must meet stated ICEV phase-out trajectories. At the same time, unchecked nickel mining and processing activities undermine the sustainability of electrification strategies. Current supply-chain-engagement modes are fragmented, passive, insufficient, and unable to address the prevailing tensions within decarbonization trajectories—opting only to assess risks and disengage from complex supply chains, limiting future technology options. To realize net-zero ambitions, clean energy demand must assume a more active role in aligning interests and incentives toward resilient, responsible, and low-carbon battery minerals supply. Discerning demand, supported by effective standards and coordinated investment strategies, will be essential in pursuing this active role.

ACKNOWLEDGMENTS

The authors acknowledge Dr. John Ryter and Mrigi Munjal for their input on minerals supply development and the associated environmental impacts of mining.

AUTHOR CONTRIBUTIONS

Conceptualization, K.B., B.R., and E.A.O.; investigation, K.B., B.R., R.H.M., E.A.M., I.D., E.Y., and R.G.B.; writing – original draft, B.R., K.B., and G.C.; writing – review and editing, B.R., K.B., and E.A.O.; visualization, B.R., K.B., E.A.M., I.D., and E.Y.; supervision, E.A.O., R.R., R.S., and D.B.M.; project administration, B.R. and E.A.O.; funding acquisition, E.A.O., R.R., and R.S.

DECLARATION OF INTERESTS

The authors declare no competing interests.

REFERENCES

1. IEA (2024). Global EV Outlook 2024. https://www.iea.org/reports/global-ev-outlook-2024.
2. IEA (2021). The Role of Critical Minerals in Clean Energy Transitions. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions.
3. Lèbre, É., Stringer, M., Svobodova, K., Owen, J.R., Kemp, D., Côte, C., Arratia-Solar, A., and Valenta, R.K. (2020). The social and environmental complexities of extracting energy transition metals. Nat. Commun. *11*, 4823. https://doi.org/10.1038/s41467-020-18661-9.
4. Nickel Institute (2022). The Life of Ni.
5. IEA (2024). Global Critical Minerals Outlook 2024 – Analysis. https://www.iea.org/reports/global-critical-minerals-outlook-2024.
6. Crundwell, F., Moats, M., and Ramachandran, V. (2011). Extractive Metallurgy of Nickel, Cobalt and Platinum Group Metals (Elsevier).
7. Mudd, G.M., and Jowitt, S.M. (2022). The new century for nickel resources, reserves, and mining: reassessing the sustainability of the devil's metal. Econ. Geol. *117*, 1961–1983. https://doi.org/10.5382/econgeo.4950.
8. Marsh, E.E., Anderson, E.D., and Gray, F. (2013). Nickel-Cobalt Laterites: a Deposit Model (U.S. Geological Survey). https://doi.org/10.3133/sir20105070H.
9. Mudd, G.M. (2010). Global trends and environmental issues in nickel mining: sulfides versus laterites. Ore Geol. Rev. *38*, 9–26. https://doi.org/10.1016/j.oregeorev.2010.05.003.
10. Eckelman, M.J., Reck, B.K., and Graedel, T.E. (2012). Exploring the global journey of nickel with Markov chain models. J. Ind. Ecol. *16*, 334–342. https://doi.org/10.1111/j.1530-9290.2011.00425.x.
11. Foss, M.M., and Koelsch, J. (2022). Need Nickel? How Electrifying Transport and Chinese Investment Are Playing Out in the Indonesian Archipelago (Baker Institute for Public Policy, Rice University).
12. Devitt, P., and Nangoy, F. (2023). Indonesia's High-Grade Nickel Ore Reserves May Be Depleted in 6 Years (Reuters).
13. Wood Mackenzie. (2023). The rise and rise of Indonesian HPAL – can it continue? https://www.woodmac.com/news/opinion/rise-of-indonesian-hpal/.
14. Iyer, R.K., Dai, Q., and Kelly, J.C. (2023). Nickel life cycle analysis updates and additions in the GREET model (Rev. 1) (Argonne National Laboratory).
15. Tijsseling, L.T., and Whattoff, P.W. (2023). Product Carbon Footprint of Nickel Sulfate Hexahydrate Production (German Association of the Automotive Industry).
16. Young, E. (2021). Battery Nickel Bottlenecks. https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2976498.
17. Nangoy, F., and Ungku, F. (2021). Facing Green Pressure, Indonesia Halts Deep-Sea Mining Disposal (Reuters).
18. USGS (2024). USGS Mineral Commodity Summaries 2024. https://www.usgs.gov/publications/mineral-commodity-summaries-2024.
19. Taufikurahman, M.R., Firdaus, A.H., Ahmad, T., Febriani, D.A., and Satria, A. (2023). The Impact of Mining Sector Investment on National and Regional Economic Performance (INDEF). https://indef.or.id/wp-content/uploads/2023/12/072023_pb_mining_eng.pdf.
20. Ministry of Finance, Republic of Indonesia (2023). Recent Macroeconomic and Fiscal Update.
21. World Trade Organization (2022). Indonesia – Measures Relating to Raw Materials. https://www.wto.org/english/tratop_e/dispu_e/592r_e.pdf.
22. Pandyaswargo, A.H., Wibowo, A.D., Maghfiroh, M.F.N., Rezqita, A., and Onoda, H. (2021). The emerging electric vehicle and battery industry in Indonesia: actions around the nickel ore export ban and a SWOT analysis. Batteries *7*, 80. https://doi.org/10.3390/batteries7040080.
23. Indonesia Battery Corporation https://www.indonesiabatterycorp.com/en/future-project.
24. Tritto, A. (2023). How Indonesia Used Chinese Industrial Investments to Turn Nickel into the New Gold (Carnegie Endowment for International Peace).
25. Andy Home (2024). China's Refined Nickel Trade Signals New Production Trend (Malaya).
26. Financial Times (2024). Global miners call on LME to introduce green premium for nickel. https://www.ft.com/content/892bb299-29bd-4e73-b929-9c835690f9f8.
27. BHP (2024). Western Australia Nickel to temporarily suspend operations. https://www.bhp.com/news/media-centre/releases/2024/07/western-australia-nickel-to-temporarily-suspend-operations.
28. Rajagopal, D. (2024). First Quantum to Cut Australian Nickel Mine Output, Slash Workforce (Reuters).
29. Glencore (2024). Koniambo nickel to transition to care and maintenance. https://www.glencore.com/media-and-insights/news/koniambo-nickel-to-transition-to-care-and-maintenance.
30. Johnson, E.L., Ericsson, M., and Löf, A. (2023). The mining permitting process in selected developed economies. Land Use Policy *131*, 106762. https://doi.org/10.1016/j.landusepol.2023.106762.
31. Nornickel (2021). Quintessentially Nickel. https://nornickel.com/upload/iblock/5dc/2021_11_29_Quintessentially_Ni.pdf.
32. Sulaiman, S. (2024). Indonesia Adds Nickel Parks Worth Nearly $40 Billion to Strategic Plan (Reuters).
33. Heijlen, W., and Duhayon, C. (2024). An empirical estimate of the land footprint of nickel from laterite mining in Indonesia. Extr. Ind. Soc. *17*, 101421. https://doi.org/10.1016/j.exis.2024.101421.
34. Malik, R. (2024). Stakeholder views on the uptake of sustainable and responsible nickel mining and processing supply chains for electric vehicles in Indonesia. https://dspace.mit.edu/bitstream/handle/1721.1/156950/malik-rameenh-sm-tpp-2024-thesis.pdf?sequence=1&isAllowed=y.
35. Climate Rights International (2024). Nickel Unearthed: the Human and Climate Costs of Indonesia's Nickel Industry.
36. Peiseler, L., Schenker, V., Schatzmann, K., Pfister, S., Wood, V., and Schmidt, T. (2024). Carbon footprint distributions of lithium-ion batteries and their materials. https://doi.org/10.21203/rs.3.rs-4385579/v1.
37. Bruchon, M., Chen, Z.L., and Michalek, J. (2024). Cleaning up while changing gears: the role of battery design, fossil fuel power plants, and vehicle policy for reducing emissions in the transition to electric vehicles. Environ. Sci. Technol. *58*, 3787–3799. https://doi.org/10.1021/acs.est.3c07098.
38. Nassar, N.T., Lederer, G.W., Brainard, J.L., Padilla, A.J., and Lessard, J.D. (2022). Rock-to-metal ratio: A foundational metric for understanding mine wastes. Environ. Sci. Technol. *56*, 6710–6721. https://doi.org/10.1021/acs.est.1c07875.
39. Adiansyah, J.S., Rosano, M., Vink, S., and Keir, G. (2015). A framework for a sustainable approach to mine tailings management: disposal strategies. J. Clean. Prod. *108*, 1050–1062. https://doi.org/10.1016/j.jclepro.2015.07.139.
40. Aska, B., Franks, D.M., Stringer, M., and Sonter, L.J. (2023). Biodiversity conservation threatened by global mining wastes. Nat. Sustain. *7*, 23–30. https://doi.org/10.1038/s41893-023-01251-0.
41. Owen, J.R., Kemp, D., Lechner, A.M., Harris, J., Zhang, R., and Lèbre, É. (2023). Energy transition minerals and their intersection with land-connected peoples. Nat. Sustain. *6*, 203–211. https://doi.org/10.1038/s41893-022-00994-6.
42. Owen, J.R., Kemp, D., Harris, J., Lechner, A.M., and Lèbre, É. (2022). Fast track to failure? Energy transition minerals and the future of consultation and consent. Energy Res. Soc. Sci. *89*, 102665. https://doi.org/10.1016/j.erss.2022.102665.
43. Luckeneder, S., Giljum, S., Schaffartzik, A., Maus, V., and Tost, M. (2021). Surge in global

metal mining threatens vulnerable ecosystems. Glob. Environ. Change *69*, 102303. https://doi.org/10.1016/j.gloenvcha.2021.102303.

44. Lenton, T. (2023). Global Tipping Points Report (Global Systems Institute, University of Exeter).
45. Young, S.B. (2018). Responsible sourcing of metals: certification approaches for conflict minerals and conflict-free metals. Int. J. Life Cycle Assess. *23*, 1429–1447. https://doi.org/10.1007/s11367-015-0932-5.
46. Liu, S., and Nguyen, M. (2023). China Boosts Green Aluminium Certification as Demand Grows (Reuters). https://www.reuters.com/sustainability/china-boosts-green-aluminium-certification-demand-grows-2023-11-07/.
47. Gamage, C., Ramirez, K., Terry, J., Wilmoth, R., and Wright, L. (2023). US businesses need low-emissions steel, and it's time for US steelmakers to get it to them. RMI. https://rmi.org/us-businesses-need-low-emissions-steel-and-its-time-for-us-steelmakers-to-get-it-to-them/.
48. Vale. (2022). Vale confirms supply deal with Tesla for low-carbon nickel. https://vale.com/fi/w/vale-confirms-supply-deal-with-tesla-for-low-carbon-nickel.
49. European Commission Critical Raw Materials Act. https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/critical-raw-materials-act_en.
50. Nickel Institute (2023). Ferronickel and NPI importers to the EU: get ready for the EU Carbon Border Adjustment Mechanism and its data collection and submission requirements. https://nickelinstitute.org/en/blog/2023%E5%B9%B4/september/ferronickel-and-npi-importers-to-the-eu-get-ready-for-the-eu-carbon-border-adjustment-mechanism-and-its-data-collection-and-submission-requirements/.
51. Nickel Institute (2023). The EU Battery regulation: what does it mean for nickel producers? https://nickelinstitute.org/en/blog/2023%E5%B9%B4/august/the-eu-battery-regulation-what-does-it-mean-for-nickel-producers/.
52. Trost, J.N., and Dunn, J.B. (2023). Assessing the feasibility of the Inflation Reduction Act's EV critical mineral targets. Nat. Sustain. *6*, 639–643. https://doi.org/10.1038/s41893-023-01079-8.
53. Ali, S.H., Giurco, D., Arndt, N., Nickless, E., Brown, G., Demetriades, A., Durrheim, R., Enriquez, M.A., Kinnaird, J., Littleboy, A., et al. (2017). Mineral supply for sustainable development requires resource governance. Nature *543*, 367–372. https://doi.org/10.1038/nature21359.
54. Varriale, L. (2024). "Green" nickel market too illiquid to trade on contract, lacks definition: LME. https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/metals/030524-green-nickel-market-too-illiquid-to-trade-on-contract-lacks-definition-lme.
55. Metalshub. (2024). Metalshub will start reporting volumes of Class 1 Nickel traded. https://www.metals-hub.com/blog/metalshub-will-start-reporting-volumes-of-low-carbon-class-1-nickel-traded/.
56. Onstad, E. (2024). Benchmark to Launch Green Nickel Prices on Thursday (Reuters).
57. Bridge, G. (2004). Contested terrain: mining and the environment. Annu. Rev. Environ. Resour. *29*, 205–259. https://doi.org/10.1146/annurev.energy.28.011503.163434.
58. Franks, D.M., Davis, R., Bebbington, A.J., Ali, S.H., Kemp, D., and Scurrah, M. (2014). Conflict translates environmental and social risk into business costs. Proc. Natl. Acad. Sci. USA *111*, 7576–7581. https://doi.org/10.1073/pnas.1405135111.
59. Liljas, P.E. (2024). Cheap coal, cheap workers, Chinese money: Indonesia's nickel success comes at a price. The Guardian. https://www.theguardian.com/world/2024/apr/11/cheap-coal-cheap-workers-chinese-money-indonesias-nickel-success-comes-at-a-price.
60. Cheung, R. (2023). Workers Keep Dying at This Chinese Nickel Mining Company in Indonesia. VICE. https://www.vice.com/en/article/china-nickel-smelting-factory-indonesia-gunbuster-belt-and-road/.
61. Langdon, R., Berry, F., Northey, S., Giurco, D., Li, W., Farjana, S., and Cox, D. (2022). Certification and sustainability assessment for battery materials: review of requirements and data commonalities (Future Battery Industries Cooperative Research Centre).
62. Owen, J.R., Kemp, D., and Marais, L. (2021). The cost of mining benefits: localising the resource curse hypothesis. Resour. Policy *74*, 102289. https://doi.org/10.1016/j.resourpol.2021.102289.
63. Roche, C., Sinclair, L., Spencer, R., Luke, H., Brueckner, M., Knowles, S., and Paull, M. (2021). A mining legacies lens: from externalities to wellbeing in extractive industries. Extr. Ind. Soc. *8*, 100961. https://doi.org/10.1016/j.exis.2021.100961.
64. Menegaki, M., and Damigos, D. (2020). A systematic review of the use of environmental economics in the mining industry. J. Sustain. Min. *19*, 254–271. https://doi.org/10.46873/2300-3960.1034.
65. Myllyvirta, L., Hasan, K., Kelly, J., Parapat, J., Adhinegara, B.Y., Rizqiana, A., Refani, F., Monica, L., Darmawan, J., and Utomo, W.T. (2024). Debunking the value-added myth in nickel downstream industry – Economic and health impact of nickel industry in Central Sulawesi, Southeast Sulawesi, and North Maluku (CREA and CELIOS).
66. Giang, A., Edwards, M.R., Fletcher, S.M., Gardner-Frolick, R., Gryba, R., Mathias, J.-D., Venier-Cambron, C., Anderies, J.M., Berglund, E., Carley, S., et al. (2024). Equity and modeling in sustainability science: examples and opportunities throughout the process. Proc. Natl. Acad. Sci. USA *121*, e2215688121. https://doi.org/10.1073/pnas.2215688121.
67. Parapat, J., and Hasan, K. (2023). Emerging Captive Coal Power: Dark Clouds on Indonesia's Clean Energy Horizon (CREA).
68. Auld, G., Betsill, M., and VanDeveer, S.D. (2018). Transnational governance for mining and the mineral lifecycle. Annu. Rev. Environ. Resour. *43*, 425–453. https://doi.org/10.1146/annurev-environ-102017-030223.
69. ICMM (2024). ICMM Guidance. https://guidance.miningwithprinciples.com/.
70. Nickel Institute (2023). Responsible sourcing and ESG due diligence. https://nickelinstitute.org/en/policy/nickel-life-cycle-management/responsible-sourcing-and-esg-due-diligence/.
71. ASI (2023). Aluminum Stewardship Initiative - Performance Standard V3.1.
72. Lambin, E.F., and Thorlakson, T. (2018). Sustainability standards: interactions between private actors, civil society, and governments. Annu. Rev. Environ. Resour. *43*, 369–393. https://doi.org/10.1146/annurev-environ-102017-025931.
73. More Junior, R., Franks, D.M., and Ali, S.H. (2015). Designing sustainability certification for greater impact: An analysis of the design characteristics of 15 sustainability certification schemes in the mining industry. https://www.evidensia.eco/resources/26/designing-sustainability-certification-for-greater-impact-an-analysis-of-the-design-characteristics-of-15-sustainability-certification-schemes-in-the-mining-industry/.
74. AngloAmerican (2024). Results of IRMA audit across our various mines reflect commitment in striving for highest levels of responsible metals production. https://singapore.angloamerican.com/our-stories/results-of-irma-audit-across-our-various-mines-reflect-commitment-in-striving-for-highest-levels.
75. Calderon, J.L., Bazilian, M., Sovacool, B., and Greene, S. (2020). Responsible or reckless? A critical review of the environmental and climate assessments of mineral supply chains. Environ. Res. Lett. *15*, 103009. https://doi.org/10.1088/1748-9326/ab9f8c.
76. Germanwatch (2022). An examination of industry standards in the raw materials sector. https://www.germanwatch.org/en/85063.
77. Institute for Energy Economics and Financial Analysis (2024). Will the new Indonesian Taxonomy for Sustainable Finance really serve its national interest? https://ieefa.org/resources/will-new-indonesian-taxonomy-sustainable-finance-really-serve-its-national-interest.
78. Igogo, T., Lowder, T., Engel-Cox, J., Newman, A., and Awuah-Offei, K. (2020). Integrating clean energy in mining operations: opportunities, challenges, and enabling approaches. Appl. Energy *300*, 117375.
79. Furnell, E., Bilaniuk, K., Goldbaum, M., Shoaib, M., Wani, O., Tian, X., Chen, Z., Boucher, D., and Bobicki, E.R. (2022). Dewatered and stacked mine tailings: a review. ACS EST Eng. *2*, 728–745. https://doi.org/10.1021/acsestengg.1c00480.
80. Wesselkämper, J., Dahrendorf, L., Mauler, L., Lux, S., and von Delft, S. (2024). Towards circular battery supply chains: strategies to reduce material demand and the impact on mining and recycling. Resour. Policy *95*, 105160. https://doi.org/10.1016/j.resourpol.2024.105160.
81. Innis, S., and Kunz, N.C. (2020). The role of institutional mining investors in driving responsible tailings management. Extr. Ind.

Soc. *7*, 1377–1384. https://doi.org/10.1016/j.exis.2020.10.014.

82. Franks, D.M., Stringer, M., Torres-Cruz, L.A., Baker, E., Valenta, R., Thygesen, K., Matthews, A., Howchin, J., and Barrie, S. (2021). Tailings facility disclosures reveal stability risks. Sci. Rep. *11*, 5353. https://doi.org/10.1038/s41598-021-84897-0.

83. Ford; Media Center (2023). PT Vale Indonesia and Huayou Sign Nickel Agreement with Ford Motor Co. Supporting Growth of the Global Sustainable EV Industry. https://media.ford.com/content/fordmedia/fna/us/en/news/2023/03/30/pt-vale-indonesia-and-huayou-sign-nickel-agreement-with-ford-mot.html.

84. LME (2023). Independent Review of Events in the Nickel Market in March 2022. file:///C:/Users/soft/Downloads/Independent%20Review%20of%20Events%20in%20the%20Nickel%20Market%20in%20March%202022%20-%20Final%20Report.pdf.

85. Hidayat, B., Jossi, K., Chu, K., and Meers, J. (2022). Investigating rainforest destruction: the nickel mines clearing Indonesian forests (Pulitzer Centre). https://pulitzercenter.org/stories/investigating-rainforest-destruction-nickel-mines-clearing-indonesian-forests.

86. Goodman, P.S., and Ifansasti, U. (2023). China's nickel plants in Indonesia created needed jobs, and pollution (N. Y. Times).

87. Ford Media Center (2023). Ford Taps Michigan for New LFP Battery Plant; New Battery Chemistry Offers Customers Value, Durability, Fast Charging, Creates 2,500 More New American Jobs. https://media.ford.com/content/fordmedia/fna/us/en/news/2023/02/13/ford-taps-michigan-for-new-lfp-battery-plant–new-battery-chemis.html.

88. Zhou, W., Cleaver, C.J., Dunant, C.F., Allwood, J.M., and Lin, J. (2023). Cost, range anxiety and future electricity supply: a review of how today's technology trends may influence the future uptake of BEVs. Renew. Sustain. Energy Rev. *173*, 113074. https://doi.org/10.1016/j.rser.2022.113074.

89. Clément, R.J., Lun, Z., and Ceder, G. (2020). Cation-disordered rocksalt transition metal oxides and oxyfluorides for high energy lithium-ion cathodes. Energy Environ. Sci. *13*, 345–373. https://doi.org/10.1039/C9EE02803J.

90. Tian, Y., Zeng, G., Rutt, A., Shi, T., Kim, H., Wang, J., Koettgen, J., Sun, Y., Ouyang, B., Chen, T., et al. (2021). Promises and challenges of next-generation "beyond Li-ion" batteries for electric vehicles and grid decarbonization. Chem. Rev. *121*, 1623–1669. https://doi.org/10.1021/acs.chemrev.0c00767.

91. Cheng, A.L., Fuchs, E.R.H., Karplus, V.J., and Michalek, J.J. (2024). Electric vehicle battery chemistry affects supply chain disruption vulnerabilities. Nat. Commun. *15*, 2143. https://doi.org/10.1038/s41467-024-46418-1.

92. Spence, E., and Listiyorini, E. (2024). Indonesia says its nickel supply will keep global prices low. Bloomberg.com.