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Existing research on the security of the supply of critical materials for clean energy generally aggregates information at the country level, a practice that obscures the extensive role of foreign direct investment (FDI) in the production of critical materials. FDI refers to an ownership stake in a company or project by an overseas investor. Here we establish a database for global mining of lithium, cobalt, nickel and platinum at company level, covering 240 countries and regions. We show that 47% of lithium, 71% of cobalt, 41% of nickel and 34% of platinum mined in 2019 were under FDI. We then explore how FDI may affect supply risks by proposing a supply risk index that allocates production of the critical materials to the country of origin of investors instead of the country where production is located. We present upper and lower bounds of the supply risk index that reflect scenarios where either all investors or only state investors prioritize the home-country demand, respectively. This study presents an approach for assessing the national supply risks of critical materials, considering the geographical allocation of FDI.

Clean energy technology deployment is rapidly expanding to address urgent climate challenges[1]. Compared with conventional energy technologies, clean energy applications require a wider range of materials, many of which are labelled 'critical materials'[2–5]: for example, lithium, cobalt, nickel and graphite for lithium-ion batteries[6,7], platinum group metals for electrolysers and fuel cells[8], and rare earth metals for permanent magnet motors[9]. Ensuring stable supplies of critical raw materials has become a prerequisite for sustainable energy transition[10–13].

These critical materials, however, often show significantly unbalanced production and consumption patterns. Their primary supply mostly originates from regions such as South America, Africa and Oceania[14], while their demand mainly concentrates in major economies such as the USA, the European Union (EU) and China. This makes consuming countries highly import-dependent and thus face challenges of potential materials supply disruption[15]. These risks have been widely discussed by studies using the methods of material flow analysis[9,16–19], criticality assessment[8,20–23] and complex network analysis[6,24,25].

Nevertheless, many studies that concentrate on import dependence overlook the heterogeneity and concentration of supply sources, thus failing to fully capture the distribution of risks. Moreover, previous studies generally centre on the national level and rarely address the company level. The usual focus overlooks that major economies are often home to multinational mining companies that have a certain proportion of property rights in overseas mines through foreign direct investment (FDI)[26]. FDI may alleviate supply shortage

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concerns of general material consumers of the home country through various channels. Examples include a proclivity to exploit enhanced downstream capacity in the home country[27], following of policy incentives that serve the home country's resource security (such as those in the US Inflation Reduction Act and EU Critical Raw Materials Act)[28], and favoring economic and national security interests of home-country investors, a channel that generally applies to state-owned companies[29].

Previous studies have shown the role of FDI in reducing raw material supply risks for some specific countries such as China and Japan[30–33]. Nevertheless, a comprehensive overview of FDI in global critical material markets is still not available. Note that while a country's FDI (for example, US investment) could reduce its domestic supply risk, it may also limit the raw material availability for other countries (for example, China and EU). Thus, it is vital to track FDI from a global perspective and systematically consider its impact on national supply risks.

Here we aim to address these gaps by mapping the global distribution of FDI and assessing its potential role in supply risk mitigation in the case of four critical materials: lithium, cobalt, nickel and platinum. These materials are selected because they are deemed critical for low-carbon mobility and power transition[34,35] while considering the availability of required data and our research expertise[8,19,36–39]. We first establish a company-specific global production database for these materials, including mine locations, operators, shareholders and corresponding FDI ownership hierarchy, and country affiliation of relevant companies. Then we trace the global production and trade network of the four materials for all countries and their dependent territories (240 regions in total) in 2019 when the latest data are available. The tracking focuses on the mining stage, while trade of lithium carbonate and platinum refined metals is also included given their common vertical integration of mining and refining processes. The two perspectives on production and international trade are thereafter presented: one by geographical location and the other by country of origin of the investors, which assumes that production control is proportional to the shareholders' ownership of equity. We further present a supply risk index (SRI) to quantify geopolitical supply risk faced by each country. Specifically, we derive an 'original SRI' and an 'adjusted SRI', respectively utilizing the two abovementioned perspectives. Our SRI considers both import dependency and supply concentration, assuming that importing is riskier than domestic production (this assumption necessitates further analysis as diversified imports could be more secure than concentrated domestic production).

We reveal significant differences between the geographical and company perspective of global production and trade networks of the four materials due to extensive FDI. We find that in the scenario whereby all investors follow the 'home-country priority' mode, FDI represents great potential for mitigating geopolitical supply risk for the USA's lithium, the United Kingdom's platinum, Japan's nickel, and China's lithium and cobalt. We also consider another scenario where only state investors prioritize home-country interests, reflecting their stronger ties to national interests compared with private investors. Here, the benefits of FDI are primarily evident in cobalt and nickel, dominated by Chinese state-owned enterprises. The comparison of the original SRI and the adjusted SRI represents the potential role of FDI in supply risk mitigation, with the reality situated somewhere between the two proposed scenarios. Our results highlight the importance of considering FDI in critical material supply security assessments.

Results

Global material production control database

Figure 1 shows the production control hierarchy of global FDI-related mines, and Supplementary Figs. 1–4 and Tables 1–4 contain further details. The location of a company's headquarters is defined as its country affiliation. The production 'control' is quantified on the basis of the company ownership of mine projects and subsidiaries (see Methods for details). In 2019, American companies controlled the largest amount of lithium mines overseas with a total production of 21 kt, mainly from Albemarle's Atacama mine in Chile, and its 49% ownership of Talison and FMC's Hombre Muerto mine in Argentina. Chinese companies came in second, controlling production of 15 kt in Australia and 3 kt in Chile, mainly from Tianqi's 51% ownership of Talison and 26% ownership of SQM, and Ganfeng's 43% ownership of Reed Industrial Minerals. These lithium companies, which engaged in both mining and refining operations, direct their overseas investments in minerals to primarily meet the demand for refining capacity in their respective home countries. Glencore, a Swiss company, controlled the two largest cobalt production mines in the Democratic Republic of the Congo (DRC), while Chinese companies came in second with 22 kt in total, mainly from China Molybdenum's 56% ownership of the Tenke Fungurume mine in DRC and Huayou Cobalt's Luiswishi mine in DRC. Chinese companies also controlled the largest overseas nickel supply, totalling 287 kt, mainly from Jinchuan and Tsingshan. Brazilian company Vale controlled the second-largest overseas nickel supply of 187 kt. British companies controlled most of overseas platinum production of 42 tons in total, which was mainly contributed by Anglo American Platinum. South African companies were the second-largest overseas platinum supply owner with 14 tons in total, mainly from Impala Platinum's Zimplats mine and Sibanye–Stillwater's Stillwater & East Boulder mine in the USA.

Impact of FDI on the production side

On the basis of the above company-specific database of the four materials, the national mineral production from a geographical perspective was 'reallocated' to derive the mineral production from a company ownership perspective (Fig. 1; see Methods for details). We find significant disparities between the physical geographical location of supply and supply ownership, as shown in Fig. 2 and Supplementary Tables 5–8.

Results indicate that 47% of lithium, 71% of cobalt, 43% of nickel and 34% of platinum in their corresponding global mine production are FDI-controlled in 2019. Major geographical producers of lithium were Australia, Chile, China and Argentina, with production shares of 52%, 22%, 12% and 7%, respectively. After reallocation, Chinese companies supplied the most lithium with a 33% share in total, followed by companies from Australia (26%), the USA (25%) and Chile (10%). The DRC dominated geographical cobalt production with a 69% share, while Swiss companies and Chinese companies were the top two cobalt suppliers from a company ownership perspective, with production shares of 29% and 17%, respectively. Production share of companies from the DRC was 11% after the reallocation. Indonesia, the Philippines and Russia were the top three geographical producers of nickel, with production shares of 34%, 13% and 11%, respectively. Chinese companies became the second-largest group of nickel suppliers after the reallocation, with a production share of 16%. South Africa, Russia and Zimbabwe were the top three geographical producers of platinum, with South Africa dominating due to its resource endowment. After reallocation, the production share of South African companies was 58%, remaining the largest supplier group. United Kingdom and Russian companies were the second and third largest production groups from a company ownership perspective, accounting for 23% and 13% of global platinum supply, respectively.

The Herfindahl–Hirschman Index (HHI) was utilized to quantify production concentration which ranges from 0 to 10,000, with larger numbers indicating greater concentration. HHI shows that production of lithium and platinum from both the geographic and company ownership perspectives, along with cobalt production geographically, is 'highly concentrated' (see Fig. 2 caption)[40]. Mining production for all four materials is more diversified from the company ownership perspective compared with the geographical perspective. Among the four materials, cobalt production concentration has the greatest difference between the two perspectives (Table 1). These two perspectives of the HHI can serve two categories of decision making: one would be

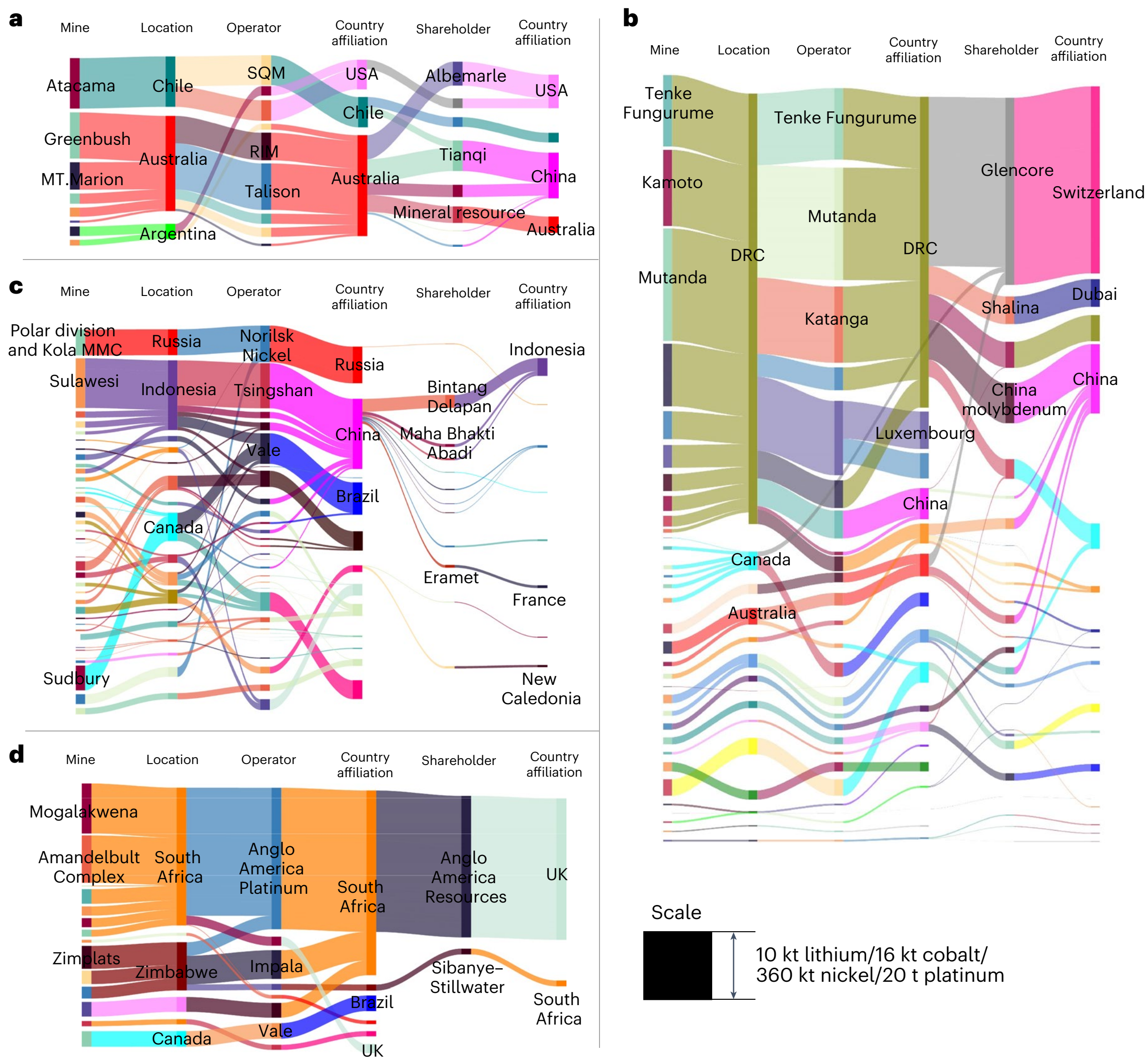

Fig. 1 | Locations, operators and shareholders of global FDI-related mines in 2019. a–d, Mine information for (**a**) lithium, (**b**) cobalt, (**c**) nickel and (**d**) platinum. Flow width is proportional to material production amount. Colours are coded by country affiliation, which is defined by the headquarter locations of companies. For clear visualization, only the names of the top three mines, companies and countries are shown.

suitable for scenarios where decision-making processes are exclusively managed by companies, the other is appropriate in circumstances where states hold that authority.

Impact of FDI on international trade

To explore the potential impacts of FDI on the import risks faced by each country, we 'adjusted' the global trade flows of lithium (minerals and lithium carbonates), cobalt (ores), nickel (ores) and platinum (ores and refined metals) by treating the overseas production controlled by a country's companies through FDI as that country's domestic production, as shown in Fig. 3. For example, China imported 48 kt lithium from Australia and Chinese companies controlled 15 kt lithium production in Australia. Thus, the 'adjusted trade flow' from Australia to China would be 33 kt. If the production controlled by FDI between trade partners is larger than the trade amount, the adjusted trade amount is set as 0. Details about adjusted trade flows are presented in Supplementary Table 9 and corresponding text notes in the Supplementary Information.

The findings indicate a significant overlap between partner countries for FDI and pivotal trade flows of clean energy materials, which were mainly from Australia to China for lithium (48 kt), the DRC to China for cobalt (75 kt), Indonesia to China for nickel (161 kt) and South Africa to the United Kingdom for platinum (14 tons). When FDI-controlled production between trade partners is subtracted, China's imports of lithium from completely external sources are reduced by 31%, cobalt by 25% and nickel by 45%. Meanwhile, the USA's lithium imports, Japan's nickel imports and the United Kingdom's platinum imports saw decreases of 88%, 58% and 35%, respectively. All other trade flows related to FDI were adjusted to zero. These trends underscore the concentration of clean energy materials trade in a handful of countries both from geographical and company ownership perspectives.

Quantifying supply risks at the country level

With a focus on the geopolitical factors, we developed the SRI to quantify the supply risk for these four critical materials faced by each country (see results of the top 10 SRIs in Fig. 4 and more details in Supplementary Figs. 9–12). The SRI comprises three sub-indicators: (1) import dependency, (2) share of national imports in total global imports and (3) likelihood of supply disruption. These sub-indicators were calculated mainly on the basis of the geographical production and international trade data of the four materials (Supplementary Figs. 5–8). The likelihood of supply disruption was calculated by further considering the

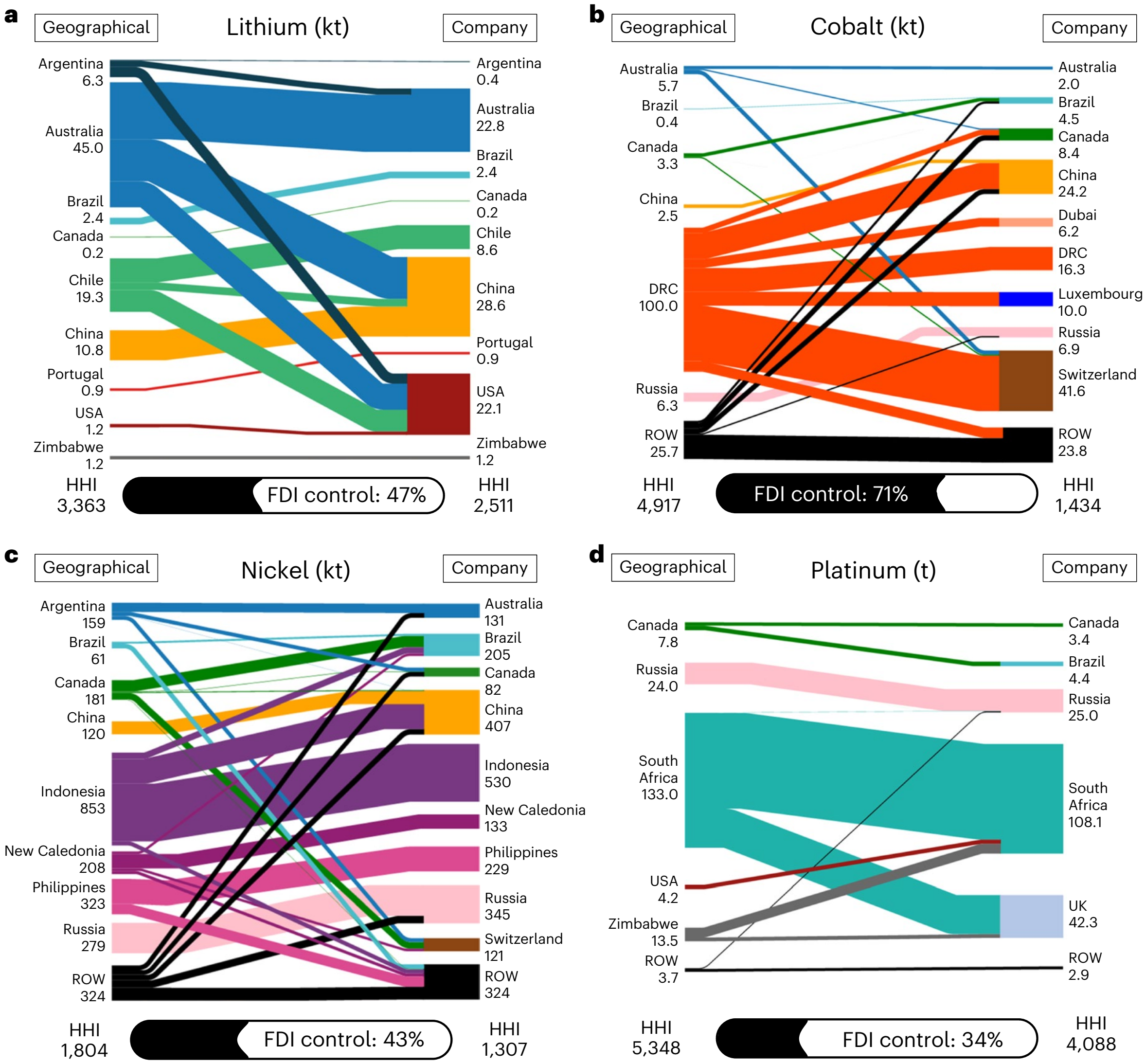

Fig. 2 | Material production from a geographical perspective (left) and a company ownership perspective (right). a–d, Mineral production of (**a**) lithium, (**b**) cobalt, (**c**) nickel and (**d**) platinum. The colours of the rectangles on both sides correspond to different countries. Flows represent production in the countries on the left controlled by the enterprises of the countries on the right. Flow width is proportional to the production in metallic mass content. Colours of flows correspond to country of origin of material production. 'FDI control' measures the proportion of the global mining production controlled by foreign companies. Here, the numerator excludes the output from transnational corporations in their home countries, while the denominator accounts for all production. The HHI was used to measure the mineral production concentration, as shown at the bottom of each panel (two sides for two perspectives). HHI was calculated as the sum of the squared market shares of each producer, with values ranging from 0 to 10,000. A higher HHI indicates greater market concentration. The US Department of Justice classifies an HHI below 1,500 as competitive, 1,500–2,500 as moderately concentrated and above 2,500 as highly concentrated[40]. ROW, rest of world.

supply concentration (quantified by the HHI using the production and trade data) and the political stability of suppliers. To explore the role of FDI in mitigating supply risk, we derived an 'adjusted SRI' on the basis of the adjusted international trade data (see Methods for details).

Of 240 countries and dependent regions studied, 43% were involved with imports of the four clean energy materials, with 85 countries for lithium, 39 for cobalt, 51 for nickel and 99 for platinum. China's cobalt supply risk was the highest, with an SRI of 88, followed by its nickel and lithium supply with SRIs of 51. Finland's cobalt supply risk, with an SRI of 47, ranks fourth. FDI had a significant impact in reducing supply risks for certain countries. The USA's lithium, United Kingdom's platinum, Japan's nickel, and China's lithium and cobalt saw SRI values drop by 63%, 33%, 21%, 15% and 11%, respectively. This is mainly due to a decline in import dependency for the USA's lithium from 67% to 8%, the United Kingdom's platinum from 100% to 65%, Japan's nickel from 100% to 42%, and China's lithium and cobalt from 83% to 55% and 97% to 73%, respectively. However, the impact of FDI was mixed concerning the sub-indicator 'likelihood of supply disruption'. For example, the likelihood of supply disruption of the United Kingdom's platinum decreased from 0.1 to 0.06, while China's lithium saw an increase from 0.22 to 0.35. Although FDI reduced supply risks for some countries, other nations importing the same commodities experienced heightened risk, creating a 'zero-sum' scenario. SRI values for lithium increased by 10% for 82 countries, cobalt by 8% for 38 countries, nickel by 18% for 50 countries and platinum by 2% for 92 countries after adjustment.

Discussion

Our analysis shows that transnational investment is widely involved in the production activities of lithium, cobalt, nickel and platinum. In the context of economic globalization, large mining companies

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Table 1 | Countries that are most affected by FDI on both the supply side and the demand side for the four critical materials

Material	Supply side			Demand side			Global production in 2019 (kt)	Supply concentration (measured by HHI)	
	Country	Domestic production controlled by FDI (kt)	Share of production controlled by FDI in total domestic production (%)	Country	Controlled overseas production (kt)	Reduction of SRI when considering FDI (%)		Geographical perspective	Company ownership perspective
Lithium	Australia	24	54	USA	21	63	87	3,363	2,511
Cobalt	DRC	84	84	China	22	11	144	4,917	1,434
Nickel	Indonesia	323	38	China	287	8	2,507	1,804	1,307
Platinum	South Africa	39 ton	29	United Kingdom	42 ton	33	186 ton	5,348	4,088

All values are in metallic content unit.

from economically advanced countries have a great impact on the supply of critical minerals. Quantitatively, we estimated that 47% of lithium, 71% of cobalt, 41% of nickel and 34% of platinum production were under FDI in 2019.

The market of critical materials is generally deemed to be vulnerable because it is geographically concentrated in a few countries that are not the major consumers, resulting in many countries being highly dependent on exports from limited sources. Taking into account company ownership leads to substantial changes in the roles of many countries in global material production and trade networks. Table 1 summarizes the countries that have been affected the most in each of the four critical materials. On the supply side, lithium in Australia, cobalt in the DRC, nickel in Indonesia and platinum in South Africa are the ones receiving the most overseas capital investment. Therefore, from the company ownership perspective, the influence of the host countries' priorities on production of these materials may not be as great as may be expected from the geographical perspective. Such variations contribute to significant differences in the supply concentration of the four materials between the two perspectives outlined in the HHI, especially for cobalt.

On the demand side, our supply risk assessment results indicate that the USA, the United Kingdom, Japan and China experience an overlap between their overseas investment and domestic demand. If the companies act at least partially in accordance with the interests of material supply security of the countries to which they belong, their overseas investments could, to a certain extent, alleviate the import risks faced by these consuming countries. Our SRI-based quantitative results consider the above scenario, which represents the upper bound of potential impact of FDI. In practical terms, FDI's role should be considerably smaller, given that companies prioritize shareholder profits over resource security of their origin countries. However, the alignment of corporate shareholders' interests with those of consumers in their home country can occasionally occur due to factors such as the integration of downstream capacities in the country of origin, policy incentives based on national security and the interests of state investors.

Here we differentiate between private and state investors and create an alternative scenario for evaluating the role of FDI in mitigating national supply risks. We find that private investors dominate the markets of selected materials, as outlined in Supplementary Table 10. In 2019, the mining production controlled by foreign state investors (including state-owned companies and government capital) was 9.1% for cobalt and 3.2% for nickel, with no involvement in lithium and platinum production. Among state investors, Chinese state-owned companies held the largest shares, controlling 5.2% of cobalt and 2.7% of nickel production in foreign assets. The other shares were mainly held by state investors from Kazakhstan (3.8% of cobalt) and South Korea (0.5% of nickel). These proportions could be interpreted as a lower limit for the role of FDI in geopolitical risk mitigation. A more precise quantification of the correlation between a company's country affiliation and decision-making priorities could be supported by future empirical analysis at the company level.

Meanwhile, FDI may reduce the availability of raw materials for other countries that do not have the ability to engage in foreign investment. Therefore, communication and cooperation among the multiple stakeholders at both the company and country levels are crucial to avoiding or de-escalating geopolitical tensions that may harm the global green transition.

We also reveal a certain mismatch between the supply controlled by FDI and import demand, especially for cobalt. There are 26 bilateral country pairs with FDI relationships for cobalt, but only 3 bilateral country pairs also have trade relationships. The potential for supply risk mitigation through FDI for cobalt is limited at present.

The extensive prevalence of FDI distribution indicates that, in addition to the domestic stakeholders in the exporting countries (for example, Australia, the DRC, Indonesia and South Africa), international private and state investors from major economies (for example, the USA, the United Kingdom and China) are major players whose actions can affect sustainable material supply. Cross-boundary investment and trade have significantly accelerated the development of mining industries in host countries but also come with many negative social and environmental externalities[41,42]. These impacts include, for example, water stress and pollution of lithium extraction from brine in Chile and Argentina, human rights issues in artisanal and small-scale mining of cobalt from the DRC and marine pollution issues from high-purity nickel processing by high-pressure acid leaching in Indonesia[11]. Such challenges could in part be resolved through ongoing and proposed public policies on the environment and human rights; thus, the compliance of domestic and international investors and adequate oversight by governments are indispensable[43]. The regulatory role of the state in offshore investment needs careful attention, especially for cobalt and nickel as many related mining projects are involved with government equities. Future research could explore the implications of foreign investment in mitigating the environmental and social impacts of local resource extraction, and compare them with the role of indigenous investment.

In the long term, recycling may change or even reverse the roles of resource exporting and importing countries[44]. Nickel and platinum recycling industries are relatively well established, with an end-of-life recycling rate of 60%[39] (ratio of recycled material to total material content of end-of-life products), while that of lithium and cobalt is much lower (1% and 15%, respectively)[15]. Nevertheless, government policies, together with the improvement of business models and economies of scale brought about by the potential ubiquity of lithium

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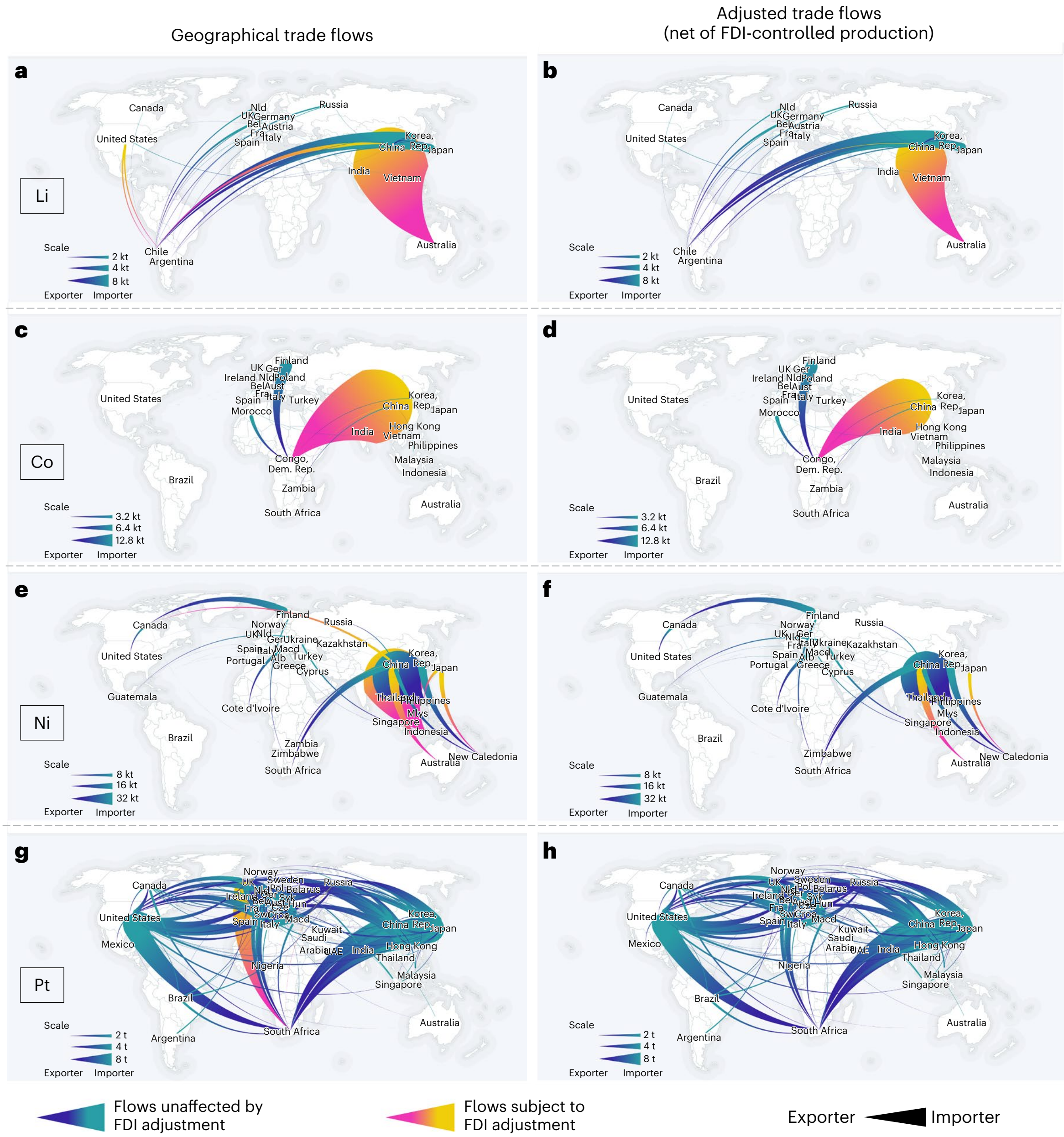

Fig. 3 | Geographical and adjusted trade network of the four clean energy materials in 2019. a–h, The geographical trade flows (left) and adjusted trade flows (right) of (**a**,**b**) lithium, (**c**,**d**) cobalt, (**e**,**f**) nickel and (**g**,**h**) platinum. Two coloured flows represent two trade types: one with corporate FDI between partners, subject to adjustment; the other without such investment, remaining unaffected. Adjusted trade flows were derived by subtracting material production controlled by importing country companies in exporting countries from the geographical trade flows. The flows are directed from the exporting country (narrow end) to the importing country (wide end). Flow width represents the trade amount in metallic content. Due to the large differences in trade value data among different countries, trade flows less than 0.01% of the maximum trade flow are not displayed. Ger, Germany; Nld, the Netherlands; Bel, Belgium; Fra, France; Spa, Spain; Mlys, Malaysia; Alb, Albania; Cze, Czech Republic; Grc, Greece; Svk, Slovakia; Swi, Switzerland; Croa, Croatia.

battery-powered products, are expected to markedly boost the recycling of lithium and cobalt in the future[45]. Technological evolution will contribute to altering global and national critical materials security as well. Clean energy technology development faces many uncertainties, for example, the commercialization of batteries with various innovative chemistry systems[46] and energy storage solutions for the power sector and long-range heavy-duty transportation[47]. For both investment and policymaking, it is essential to develop long-term strategies and to make timely production adjustments on the basis of evolving technological dynamics.

Various other materials, including copper, rare earth elements and so on, are also identified as critical minerals for clean energy technologies (see Supplementary Table 11). The availability of many of these raw materials presents a challenge comparable in severity to the materials discussed in this study (for example, the issue of lack of supply diversity[4]). The supply risk assessment model developed in this study can be extended to these critical minerals to evaluate the heterogeneous role of FDI in various markets. Aside from the minor caveats previously described for lithium and platinum, this study only focuses on upstream mining production. FDI also widely exists in the downstream of the industrial chain. The issue of highly concentrated supply is even more pronounced downstream than upstream. Currently, 60%–90% of the production capacity of intermediates, components, final products and recycled scraps are each dominated by top three producers[21,48]. The perspective and methods here could be applied across the entire industrial chain of clean energy technologies, although several challenges

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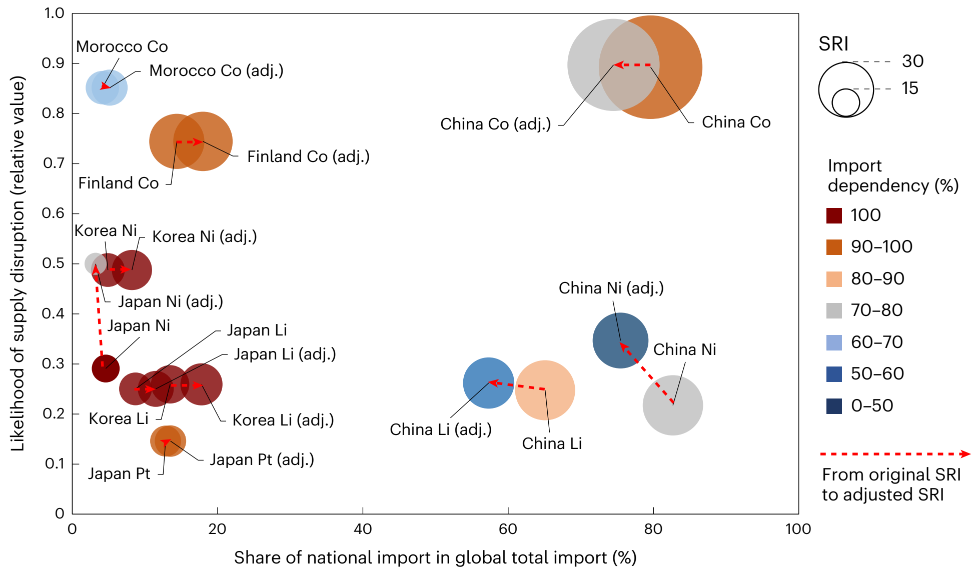

Fig. 4 | Top 10 supply risk indices. Circle size represents the value of SRI. The horizontal (share of national imports in total global import) and vertical (likelihood of supply disruption) axes represent two of the three sub-indicators used to calculate the SRI. The colour of the circle represents the third sub-indicator used to calculate the SRI: import dependency. The likelihood of supply disruption was derived from the supply concentration (measured using HHI) and the political stability of suppliers, which represents relative rather than actual probabilities in the interval 0–1. 'Adj.' stands for 'adjusted' SRI that considers the impact of FDI.

would need to be overcome. Challenges include collecting production and trade data from both the geographical and company ownership perspectives, establishing a comprehensive data-processing framework to transform and integrate raw data from various sources, and incorporating new functional modules to evaluate the vulnerability of energy technologies to supply restrictions at different stages.

Methods

System boundary

We chose four critical materials for clean energy transition in this Analysis: lithium, cobalt, nickel and platinum. We focused on the FDI related to primary supply, that is, the mining projects. To ensure that the assessment results are comparable across the different materials, we consistently considered the mining stage for all four materials when mapping the production flow. For lithium brines and platinum ores mining projects, these are often vertically integrated with refining facilities. This integration occurs because transporting these mineral products for international trade is generally unprofitable. It follows that our system coverage for international trade included both the mining and refining stages for lithium and platinum, and only the mining stage for cobalt and nickel. Therefore, under our framework, the selected commodity types encompassed ores, brines and lithium carbonates for lithium; ores for cobalt; ores for nickel; and ores and refined metals for platinum, as illustrated in Supplementary Fig. 13. These commodities are collectively referred to as 'materials' for reading convenience.

This study covered 193 sovereign states and their dependent territories (240 regions in total). The country classification was based on ISO 3166 (ref. 49). The temporal boundary of material production and international trade data was set to the year 2019 as it was the most recent year with sufficient data. The information about company FDI and ownership hierarchy was updated to the end of the first quarter of 2020.

Tracing material production and international trade

Production data for the four materials were adopted from the United States Geological Survey[14,50–53]. International trade data for material-related commodities were adopted from the United Nations Comtrade database and Customs databases of major countries, using the custom codes of corresponding commodities[54–57]. Material contents in relevant commodities were preliminarily determined on the basis of commodity industrial properties and amended on the basis of mass balance principles, which require the sum of national domestic production and imports to be approximately equal to the sum of exports and domestic consumption. We employed two main methods for balancing each country's inputs and outputs. The first method adjusts traded commodity values on the basis of production and consumption reports, aligning metal content with net trade differences, applicable in countries with detailed mineral reporting. The second method estimates metal unit production for countries lacking specific data, using physical tonnage and referencing trade values from major producers. The reliability of the database was verified by a series of related material flow analysis studies previously published by the authors[8,19,36–38].

Material production control quantification

Company 'control' is typically defined as the ability to influence substantial strategic decisions regarding operations and investments. Referencing the practices in existing literature[30], we quantified control using the companies' ownership of mine projects and subsidiaries. We assumed that control is proportionate to each shareholder's percentage of ownership. Then the control over material production could be attributed to the relevant companies on the basis of their equity ownership share structure. This approach was selected due to its capacity to provide a clear, visual representation of all stakeholders.

We established a critical material FDI database that collects the hierarchy of mine producers, relevant holding companies, intermediary companies and upstream parent companies. The database contains 32 lithium mines, 42 cobalt mines, 49 nickel mines and 31 platinum mines worldwide that are involved with FDI activities (note that lithium brine and platinum ore projects also tend to consolidate refining capacities). The information about mine production, owners and shareholders of these mines came from annual reports, public statements and news reports of relevant companies, consulting groups and information services platforms. The information about quantitative equity ownership relationships between companies and

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country affiliation of companies (defined by headquarter locations) was extracted from the ORBIS database of Bureau van Dijk, a professional analytics company[58]. The ORBIS database is a comprehensive global resource that offers detailed financial information on 45 million companies worldwide, including their trade descriptions, extensive corporate ownership structures, mergers and acquisitions deals and rumours, which are captured from hundreds of separate providers and Bureau van Dijk's own sources.

Here we only considered the companies that engaged in the production activities of the material-related industry chain, such as mining, chemical processing and downstream manufacture. The ownership of companies that are involved in investment capital in mines but not in the specific operating activities was classified to the country where the mine is located because these investment companies have relatively limited influence over the mine production activities. Our results were verified in comparison with those of relevant existing literatures[30,31,59]. Detailed data are transparently shown in Supplementary Figs. 1–4 and Tables 1–4.

Supply risk index calculation

Supply risk could be triggered by several factors, including accidental hazards of mining activities or the natural environment of the location (for example, natural disasters, epidemiological outbreaks), and intentional accidents caused by local communities or governments (for example, trade restrictions, strike procession). In this study, we focused on geopolitical supply risk, which we quantified using the 'SRI' indicator that we developed. As the country's influence over domestic supply against geopolitical factors is much stronger than its control over foreign supply, we considered domestic production as a 'risk-free' source of supply, although this assumption may not always align with reality[60]. Built upon existing literatures[61,62], the primary components of import risk that we considered encompassed national import dependence, supply concentration and political stability of foreign suppliers. We further modified the import risk assessment framework in these literatures to focus more on the national import structure. On the basis of these considerations, we calculated the SRI across three dimensions: (1) import dependency, (2) likelihood of supply disruption and (3) share of national import in total global import.

Import dependency measures the degree of dependence of a country on foreign supplies, as shown in equation (1). The higher the dependence on imports, the more unstable the supply structure of the country.

$$\mathrm{ID_i} = \frac{\mathrm{TIM_i}}{\mathrm{TIM_i} + \mathrm{PO_i}} \tag{1}$$

where $\mathrm{ID_i}$ is the import dependency of country i, $\mathrm{TIM_i}$ is the total import amount of country i, and $\mathrm{PO_i}$ is the domestic production of country i.

Likelihood of supply disruption measures the relative likelihood of disruption under different import combinations and was calculated using equation (2). This indicator was derived on the basis of the HHI and the regional political stability index. HHI is the sum of the square of the production shares of each producer[63]. A high HHI value represents high supply concentration, that is, a large likelihood of supply disruption. Further, we used the World Bank's Worldwide Governance Indicator (WGI) to reflect the impact of national-level government management on supply risk[64]. The WGI contains six measurement dimensions; we used the one called 'political stability and absence of violence/terrorism' for the year 2019 and converted it to the interval from 0 to 1, where a high value of the indicator reflects a low governance level.

$$\mathrm{LSD_i} = \sum_j \left(\frac{\mathrm{IM_{i,\,j}}}{\mathrm{TIM_i}}\right)^2 \times \mathrm{WGI_j} \tag{2}$$

where $\mathrm{LSD_i}$ is the likelihood of supply disruption, $\mathrm{IM_{i,j}}$ is the import of country i from country j, and $\mathrm{WGI_j}$ is the worldwide governance index (dimension of political stability and absence of violence/terrorism) of country j.

Other indices fulfil a role similar to that of the WGI, for example, the Policy Perception Index (PPI) developed by the Fraser Institute[65]. To examine the impact of varying indicator selections on the uncertainty of our results, we conducted identical calculations for SRI using the WGI and PPI. A comparison of the findings indicates that while there are discrepancies in the quantitative outcomes, the qualitative conclusions of this study largely remain consistent. Detailed information on these two indicators, along with a comparison of their results, can be found in Supplementary Fig. 14 and the accompanying explanatory text.

The share of national import in total global import measures the relative size of a country's total demand, as calculated following equation (3). A country with a larger share indicates that the country has more difficulty than other countries in adjusting its supply to meet the import demand[15].

$$\mathrm{IS_i} = \frac{\mathrm{TIM_i}}{\mathrm{GIM}} = \frac{\mathrm{TIM_i}}{\sum_i \mathrm{TIM_i}} \tag{3}$$

where $\mathrm{IS_i}$ is the share of the import of country i in the total global imports, and GIM is the total global imports.

The three aforementioned indicators were designed to encompass the three distinct dimensions of risk: (1) exposure, represented by import dependency; (2) hazard, represented by the likelihood of supply disruption and (3) vulnerability, represented by the share of national import in total global import. We adopted the methodology from a previous study[62] to integrate the three indicators into an overall risk index, SRI, by multiplying them and further normalizing them to a range of 0 to 100, using equation (4).

$$\mathrm{SRI_i} = (\mathrm{ID_i} \times \mathrm{IS_i} \times \mathrm{LSD_i})^{\frac{1}{3}} \tag{4}$$

where $\mathrm{SRI_i}$ is the supply risk index of country i.

To explore the impact of FDI on supply risk mitigation, we further proposed the concept of 'adjusted supply index'. In the evaluation of this index, we treated the production through FDI as a risk-free source of supply, similar to domestic production. The computational structure of the index is unchanged, that is, still based on a combination of sub-indicators in three dimensions. For the calculation of each sub-indicator detailed above, we subtracted the capacity controlled by FDI from the corresponding import amount and added it to the domestic production, as equations (5)–(8) show.

$$\mathrm{SRI_{adjusted,i}} = \left(\mathrm{ID_{adjusted,i}} \times \mathrm{IS_{adjusted,i}} \times \mathrm{LSD_{adjusted,i}}\right)^{\frac{1}{3}} \tag{5}$$

$$\mathrm{ID_{adjusted,i}} = \frac{\mathrm{TIM_i} - \sum_j P_{\mathrm{i,j}}}{\mathrm{TIM_i} - \sum_j P_{\mathrm{i,j}} + \mathrm{PO_i} + \sum_j P_{\mathrm{i,j}}} = \frac{\mathrm{TIM}_i - \sum_j P_{\mathrm{i,j}}}{\mathrm{TIM_i} + \mathrm{PO_i}} \tag{6}$$

$$\mathrm{LSD_{adjusted,i}} = \sum_j \frac{(\mathrm{IM_{i,j}} - P_{\mathrm{i,j}})^2 \times \mathrm{WGI_j}}{\left(\mathrm{TIM_i} - \sum_j P_{\mathrm{i,j}}\right)^2} \tag{7}$$

$$\mathrm{IS_{adjusted,i}} = \frac{\mathrm{TIM_i}}{\mathrm{GIM}} = \frac{\mathrm{TIM_i} - \sum_j P_{\mathrm{i,j}}}{\sum_i \left(\mathrm{TIM_i} - \sum_j P_{\mathrm{i,j}}\right)} \tag{8}$$

where $P_{\mathrm{i,j}}$ is the production controlled by country i through FDI in country j.

Limitations and uncertainties

Statistical biases and propagation errors in the underlying data lead to uncertainties in our results. We deemed data sources of geographical production and trade of raw materials to be relatively robust since they have been verified by a series of previously published research[15,19,36–38]. Similarly, the potential impact of the inaccuracies of data on property rights of mining enterprises due to unrecorded investments is limited because the ownership information has been verified by the authority database of Raw Materials Data[30]. While the potential flaws in model structure and parameters (for example, WGI) may make the quantitative results of the model partially inconsistent with reality, the qualitative conclusions still hold as verified by the results of calculations using other parameters with the same functions (Supplementary Fig. 14).

Our method of quantifying company control via ownership only might have overlooked nuanced factors such as discrepancy of government and private shareholders, country-specific government–business connections, subjective tendencies of decision makers and company-specific decision-making processes. Further studies are needed to accurately quantify the influence of investment and production decisions, considering the characteristics of the various stakeholders and their complex interaction processes. Compared with some studies that reassigned total control to companies surpassing certain ownership thresholds (for example, 20%) or to the highest ownership stakeholder[30], our approach might have overestimated minor shareholders' control while underestimating larger shareholders' influence in some cases. The uncertainties and suitability of these varying methodologies need to be examined in future studies.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The information on country affiliation of companies is from the ORBIS database of Bureau van Dijk[58]. The ownership hierarchy of mine owners and stakeholders was collected from annual reports, public statements and news reports of relevant companies, consulting groups and information services platforms. Geographical production and international trade of four materials are from the United Nations Comtrade database[54], United States Geological Survey Reports[14] and our previous studies[8,19,36,37,66]. Source data are available in Supplementary Information.

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Author contributions
X.S. and H.H. conceived the idea, conducted the analysis and wrote the paper. C.G., T.F. and G.L. wrote sections of the paper and provided guidance on the paper. D.X. and M.E. provided data for the analysis. I-Y.L.H., Z.L. and F.Z. reviewed and edited the paper. H.H. and G.L. supervised the work and secured funding for the project.

Competing interests
The authors declare no competing interests.

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Analysis

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Reducing supply risk of critical materials for clean energy via foreign direct investment

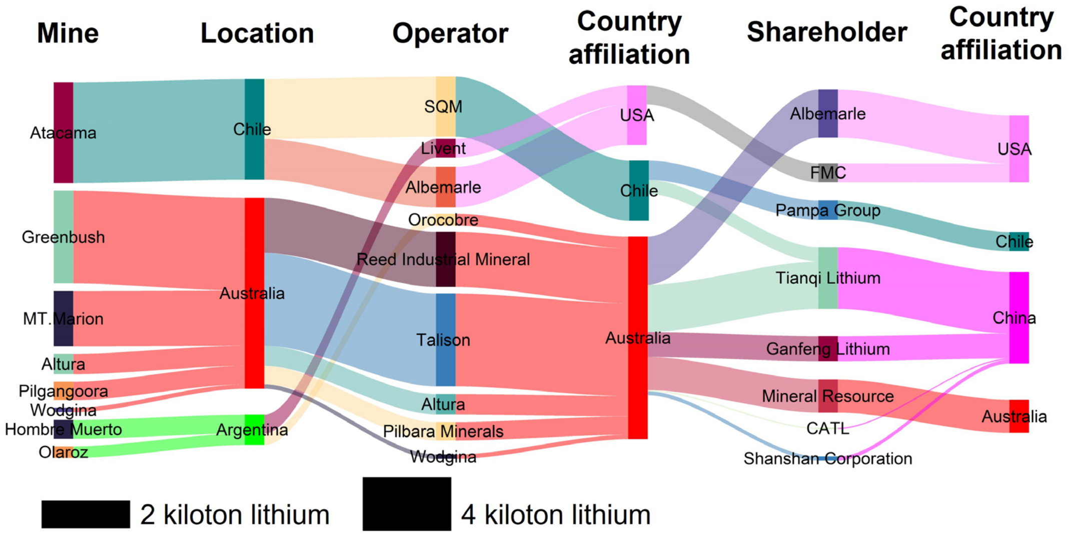

Figure S1. Locations, operators, shareholders, and country affiliation of lithium FDI-related mines in 2019. Flow width is proportional to material production amount. Unit is lithium metallic equivalent. Colors are coded by country affiliation. Underlying data is collected from multiple data sources, including company annual reports, press releases, international mining consulting industry reports, academic studies, and newspapers and is verified by the results in relevant literature[1-3]. The information about the company ownership and FDI was updated to the end of the first quarter of 2020. Subsequent changes in company ownership were not included in the system boundary of this study, e.g., Altura was acquired by Pilbara in 2021; Galaxy Resource and Orocobre merge to be Allkem in 2021; Livent merged with Allkem in 2023. The treatments for Figure S2-S4 are the same with that for Figure S1. Thus, the notes are not be repeated below.

In 2019, American companies controlled the largest amount of overseas lithium mines via FDI, with a total production of 21 kt, which includes 9 kt in Australia, 8 kt in Chile, and 4 kt in Argentina. Their FDI is mainly made up of Albemarle's Atacama mine in Chile (8 kt), its 49% ownership of Talison (owning Greenbush project in Australia with an output of 18 kt output), as well as FMC's Hombre Muerto mine in Argentina (4 kt). Chinese companies were the second largest overseas lithium mine owners, controlling production of 15 kt in Australia and 3 kt in Chile, due to Tianqi's 51% ownership of Talison and 26% ownership of SQM (owning the Atacama mine in Chile with an output of 12 kt), and Ganfeng's 43% ownership of Reed Industrial Minerals (owning the MT Marion mine in Australia with an output of 11 kt). Detailed underlying data of Figure S1 are listed in the Table S1.

Table S1. Global lithium FDI-related mine production, locations, operators, shareholders, companies' ownership hierarchy, and the countries to which the companies belong (data for 2019)

Mine	Production in 2019/ton Li content	Location	Operator	Country affiliation of operator	Shareholder 1	Country affiliation of shareholder 1	Ownership of shareholder 1	Shareholder 2	Country affiliation of shareholder 2	Ownership of shareholder 2
Atacama	7890	Chile	Albemarle	USA						
Hombre Muerto	3663	Argentina	Livent	USA	FMC	USA	100%			
Atacama	11703	Chile	SQM	Chile	Tianqi Lithium	China	24%	Pampa Group	Chile	32%
Olaroz	2254	Argentina	Orocobre	Australia						
Greenbush	18033	Australia	Talison	Australia	Tianqi Lithium	China	51%	Albemarle	USA	49%
MT.Marion	10707	Australia	Reed Industrial Mineral	Australia	Ganfeng Lithium	China	43.10%	Mineral Resource	Australia	56.90%
Pilgangoora	3569	Australia	Pilbara Minerals	Australia	Ganfeng Lithium	China	6.32%	CATL	China	7.16%
Altura	3945	Australia	Altura	Australia	Shanshan Corporation	China	19.41%			
Wodgina	864	Australia	Wodgina	Australia	ALB	USA	60.00%	Mineral Resource	Australia	40.00%
Sonora	0	Mexico	Bacanora	Mexico	Ganfeng Lithium	China	100%			
La Corne	0	Canada	North America Lithium	Canada	CATL	China	100%			
Manono	0	DRC	AVZ	Australia	Dathcom Mining	DRC	15%	Cominière	DRC	25%
					Huayou Cobalt **(Shareholder 3)**	China	7.45%	Tianyi Lithium **(Shareholder 4)**	China	8.17%
Arcadia	0	Zimbabwe	Prospect Resources	Australia	Sinomine Resource	China	6%			
Jadar	0	Serbia	Rio Tinto	Australia						

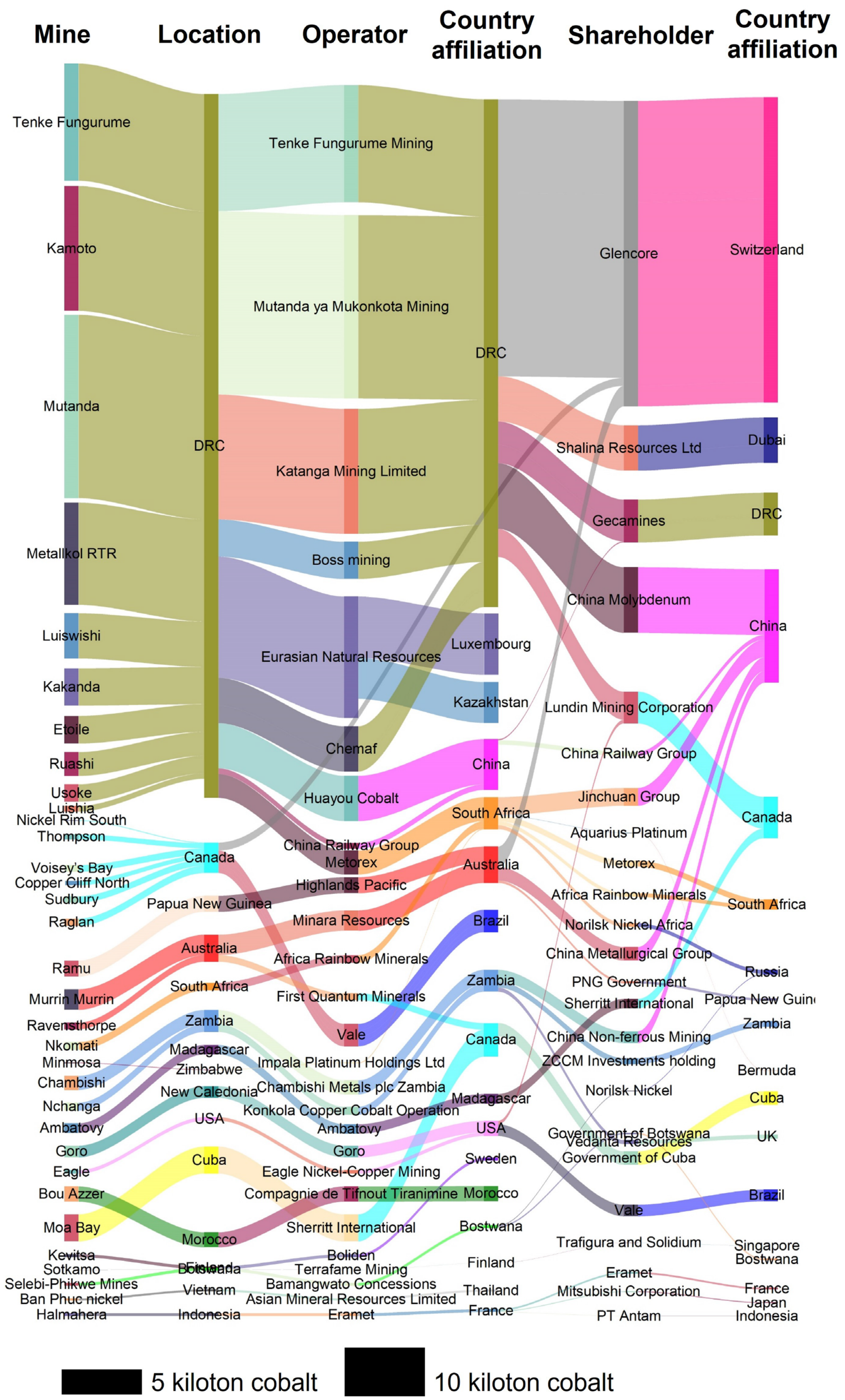

Figure S2. Locations, operators, shareholders, and country affiliation of cobalt FDI-related mines in 2019.

FDI in cobalt production exists mostly in the Democratic Republic of Congo (DRC). The Swiss giant Glencore controlled the largest two cobalt production mines in DRC, Mutanda (100% ownership) and Kamoto (75% ownership), with a total output of 38 kt in total in 2019. Coupled with the production from the Murrin Murrin mine in Australia (3 kt), and the Raglan mine and Nickel Rim South mine in Canada (1 kt), Glencore's cobalt output in 2019 reached 42 kt, making it the world's largest cobalt supplier. Chinese companies' control in foreign cobalt production was the second largest (22 kt in total), including 18 kt in DRC, 2 kt in Papua New Guinea, and 2 kt in Zambia. This control came mainly from China Molybdenum's 56% ownership of the Tenke Fungurume mine in DRC (16 kt), Huayou Cobalt's Luiswishi mine in DRC (6 kt), Jinchuan's 75% ownership of the Ruashi mine in DRC (3 kt), China Non-ferrous Mining's 85% ownership of the Chambishi mine in Zambia (2 kt), and China Metallurgical Group's 85% ownership of the Ramu mine in Papua New Guinea (2 kt). Another major foreign investor in the DRC is the British company Eurasian Natural Resources Corporation, which owns the Metallkol RTR mine (14 kt). Eurasian Natural Resources Corporation is the subsidiary of Eurasian Resource Group, which is a Luxembourg company while its 40% ownership belong to investors in Kazakhstan. Detailed underlying data of Figure S2 are listed in the Table S2.

Table S2. Global cobalt FDI-related mine production, locations, operators, shareholders, companies' ownership hierarchy, and the countries to which the companies belong (data for 2019).

Mine	Production in 2019/ton Co content	Location	Operator	Country affiliation of operator	Shareholder 1	Country affiliation of shareholder 1	Ownership of shareholder 1	Shareholder 2	Country affiliation of shareholder 2	Ownership of shareholder 2
Mutanda	25100	DRC	Mutanda ya Mukonkota Mining	DRC	Glencore	Switzerland	100%			
Tenke Fungurume	16053	DRC	Tenke Fungurume Mining	DRC	China Molybdenum	China	56%	Gecamines	DRC	20%
								Lundin Mining Corporation (**Shareholder 3**)	Canada	24%
Luiswishi	6200	DRC	Huayou Cobalt	China						
Kakanda	5100	DRC	Boss mining	DRC	Eurasian Natural Resources Corporation	UK	51%	Gecamines	DRC	49%
RTR	14000	DRC	Eurasian Natural Resources Corporation	UK	Eurasian Resources Group	Luxembourg	60%	Government of Kazakhstan	Kazakhstan	40%
Etoile	3800	DRC	Chemaf	DRC	Shalina Resources Ltd	Dubai	100%			
Ruashi Mine	3264	DRC	Metorex	South Africa	Jinchuan Group	China	75%	Metorex	South Africa	25%
Kamoto	17100	DRC	Katanga Mining Limited	Switzerland	Glencore	Switzerland	100%			
Usoke	2400	DRC	Chemaf	DRC	Shalina Resources Ltd	Dubai	100%			
Luishia	480	DRC	Miniere du Sud Katanga	DRC	Entreprise General Malta Forrest	DRC		Gecamines	DRC	
Luishia	770	DRC	China Railway Group	China	Gecamines	DRC	20%	China Railway Group	China	80%
Raglan	800	Canada	Glencore	Switzerland						
Voisey's Bay	710	Canada	Vale	Brazil						
Sudbury	706	Canada	Vale	Brazil						
Thompson	560	Canada	Vale	Brazil						
Copper Cliff North	485	Canada	Vale	Brazil						
Nickel Rim South	80	Canada	Glencore	Switzerland						
Murrin Murrin	2800	Australia	Minara Resources	Australia	Glencore	Switzerland	100%			

Ravensthorpe (Bandalup)	920	Australia	First Quantum Minerals	Canada						
Vermelho	0	Brazil	Horizonte Minerals	UK						
Moa Bay	3694	Cuba	Sherritt International	Canada	Government of Cuba	Cuba	50%			
Chambishi	1913	Zambia	Chambishi Metals plc Zambia	Zambia	China Non-ferrous Mining	China	85%	ZCCM Investments holding	Zambia	15%
Nchanga, Konkola	1085	Zambia	Konkola Copper Cobalt Operation	Zambia	Vedanta Resources	UK	51%	ZCCM Investments holding	Zambia	49%
Goro (VNC)	1600	New Caledonia	Goro	USA	Vale	Brazil	100%			
Ambatovy	1309	Madagascar	Ambatovy	Madagascar	Sherritt International	Canada	100%			
Kevitsa	420	Finland	Boliden	Sweden						
Sotkamo (formerly Talvivaara)	20	Finland	Terrafame Mining	Finland	Trafigura and Solidium	Singapore	100%			
Ramu	2191	Papua New Guinea	Highlands Pacific	Australia	China Metallurgical Group Corporation	China	85%	PNG Government	Papua New Guinea	15%
Nkomati	1065	South Africa	Africa Rainbow Minerals	South Africa	Norilsk Nickel Africa	Russia	50%	Africa Rainbow Minerals	South Africa	50%
Eagle	500	USA	Eagle Nickel-Copper Mining	USA	Lundin Mining	Canada	100%			
Halmahera/ Weda Bay	400	Indonesia	Eramet	France	PT Antam	Indonesia	10%	Mitsubishi Corporation	Japan	30%
								Eramet (**Shareholder 3**)	France	60%
Minmosa	88	Zimbabwe	Impala Platinum Holdings Ltd	South Africa	Aquarius Platinum	Bermuda	50%			
Selebi-Phikwe Mines	400	Botswana	Bamangwato Concessions	South Africa	Government of Botswana	Bostwana	50%	Norilsk Nickel	Russia	25.50%
Ban Phuc nickel mine and plant	277	Vietnam	Asian Mineral Resources Limited	Thailand						

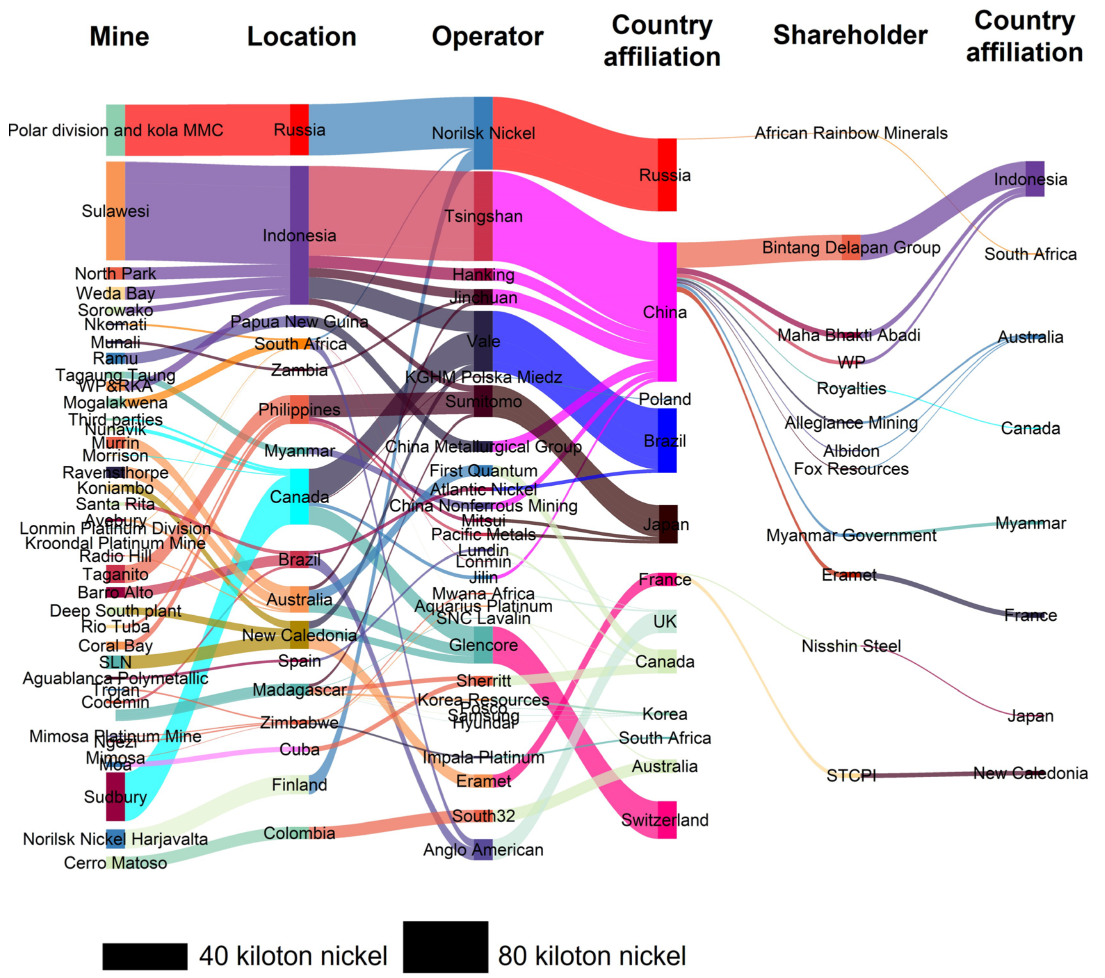

Figure S3. Locations, operators, shareholders, and country affiliation of nickel FDI-related mines in 2019. Flow width is proportional to material production amount. Unit is nickel metallic equivalent. Colors are coded by country affiliation.

Chinese companies (mainly Jinchuan and Tsingshan) controlled the largest overseas nickel supply, totaling 287 kt. Jinchuan controlled 60% of the WP & RKA mines in Indonesia (30 kt), 51% of Munali mine's production in Zambia (9 kt), and 11% of Avebury mine (9 kt) and 11% of Radio Hill mine (4 kt) in Australia. Tsingshan controlled 66% of the Morowali Industrial Park mine (250 kt) and 57% of the Weda Bay Industrial Park mine (40 kt) in Indonesia. Brazilian company Vale controlled the second largest overseas nickel supply of 187 kt, which mainly came from the Sudbury mine in Canada (97 kt), a 74% ownership of the Sorowako mine in Indonesia (79 kt), and the Deep South Plant mine in New Caledonia (23 kt). Detailed underlying data of Figure S3 are listed in the Table S3.

Table S3. Global nickel FDI-related mine production, locations, operators, shareholders, companies' ownership hierarchy, and the countries to which the companies belong (data for 2019).

Mine	Production in 2019/kiloton Ni content	Location	Operator	Country affiliation of operator	Operator ownership	Shareholder 1	Country affiliation of shareholder 1	Ownership of shareholder 1
INO (Sudbury, Raglan, Nikkelverk)	60	Canada & Norway	Glencore	Switzerland	100%			
Murrin Murrin	37	Australia	Glencore	Switzerland	100%			
Koniambo	24	New Caledonia	Glencore	Switzerland	100%			
Polar division and kola MMC	166	Russia	Norilsk Nickel	Russia	100%			
Norilsk Nickel Harjavalta	62	Finland	Norilsk Nickel	Russia	100%			
Nkomati	6	South Africa	Norilsk Nickel	Russia	50%	African Rainbow Minerals	South Africa	50%
Barro Alto	34	Brazil	Anglo American	UK	100%			
Codemin	9	Brazil	Anglo American	UK	100%			
Santa Rita	12	Brazil	Atlantic Nickel	Brazil	100%			
Mogalakwena	26	South Africa	Anglo American	UK	100%			
Lonmin Platinum Division	2	South Africa	Lonmin	UK	100%			
Trojan	5	Zimbabwe	Mwana Africa	UK	100%			
\	12	Brazil	Vale	Brazil	100%			
Sudbury	97	Canada	Vale	Brazil	100%			
Third parties	7	Canada	Vale	Brazil	100%			
Deep South plant	23	New Caledonia	Vale	Brazil	100%			
Sorowako	79	Indonesia	Vale	Brazil	74%			
Nunavik	12	Canada	Jilin	China	70%	Royalties	Canada	30%

Tagaung Taung	22	Myanmar	China Nonferrous Mining	China	50%	Myanmar Government	Myanmar	50%
Ramu	35	Papua New Guina	China Metallurgical Group	China	100%			
Munali	9	Zambia	Jinchuan	China	51%	Albidon	Australia	49%
Avebury	9	Australia	Jinchuan	China	11%	Allegiance Mining	Australia	89%
Radio Hill	4	Australia	Jinchuan	China	11%	Fox Resources	Australia	89%
WP&RKA	30	Indonesia	Jinchuan	China	60%	WP	Indonesia	40%
North Park	40	Indonesia	Hanking	China	53%	Maha Bhakti Abadi	Indonesia	48%
Morowali (IMIP)	250	Indonesia	Tsingshan	China	66%	Bintang Delapan Group	Indonesia	33%
Weda Bay (IWIP)	40	Indonesia	Tsingshan	China	57%	Eramet	France	43%
Cerro Matoso	40	Colombia	South32	Australia	100%			
Mimosa Platinum Mine	4	Zimbabwe	Aquarius Platinum	Australia	50%			
Kroondal Platinum Mine	0.5	South Africa	Aquarius Platinum	Australia	50%			
SLN	43	New Caledonia	Eramet	France	56%	STCPI	New Caledonia	34%
						Nisshin Steel	Japan	10%
Taganito	75	Philippines	Sumitomo	Japan	63%			
Coral Bay	25	Philippines	Sumitomo	Japan	100%			
Taganito	75	Philippines	Mitsui	Japan	15%			
Rio Tuba	27	Philippines	Pacific Metals	Japan	38%			
Sorowako	79	Indonesia	Sumitomo	Japan	26%			
Ambatovy	37	Madagascar	Sumitomo	Japan	28%			
Moa	33	Cuba	Sherritt	Canada	50%			
Ambatovy	37	Madagascar	Sherritt	Canada	40%			
Ambatovy	37	Madagascar	Korea Resources	Korea	18%			
Ambatovy	37	Madagascar	Posco	Korea	4%			
Ambatovy	37	Madagascar	Samsung	Korea	3%			
Ambatovy	37	Madagascar	Hyundai	Korea	2%			
Ambatovy	37	Madagascar	SNC Lavalin	Canada	5%			

Ravensthorpe	36	Australia	First Quantum	Canada	100%
Aguablanca Polymetallic	9	Spain	Lundin	Canada	100%
Ngezi	5	Zimbabwe	Impala Platinum	South Africa	100%
Mimosa	4	Zimbabwe	Impala Platinum	South Africa	50%
Morrison	3	Canada	KGHM Polska Miedz	Poland	100%

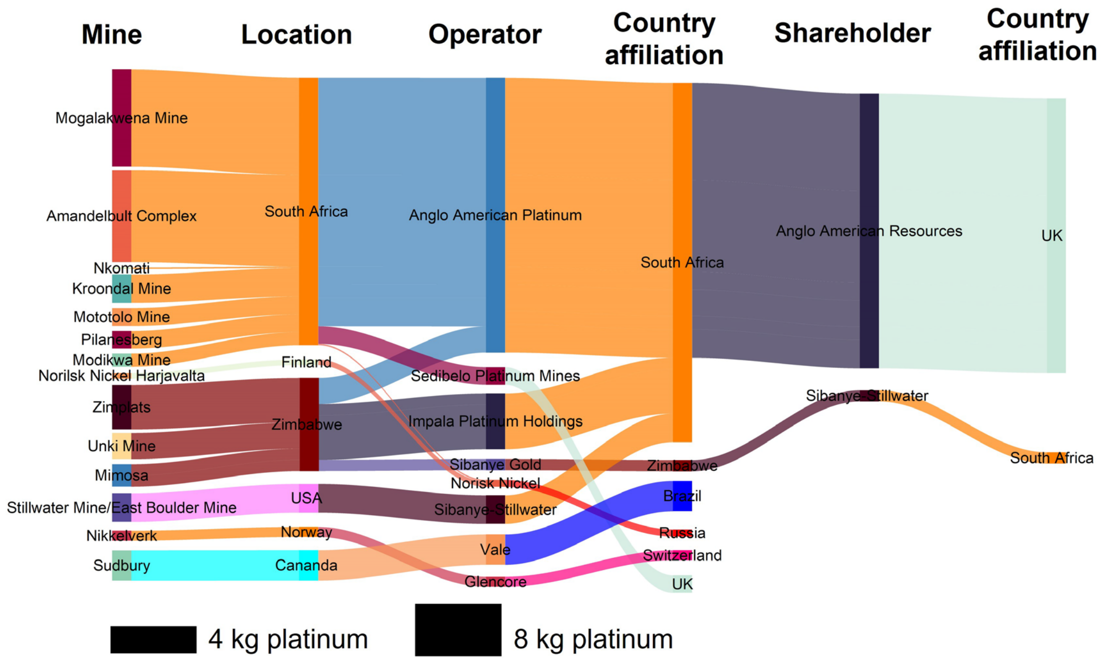

Figure S4. Locations, operators, shareholders, and country affiliation of platinum FDI-related mines in 2019. Flow width is proportional to material production amount. Unit is platinum metallic equivalent. Colors are coded by country affiliation.

British companies controlled the most overseas platinum production of 42 tons in total, which was mainly contributed by Anglo American Platinum, a subsidiary corporation of Anglo American Resource. The platinum supply controlled by Anglo American Resource located primarily in South Africa (Mogalakwena mine, 14 tons; Amandelbult Complex mine, 13 tons; Kroondal mine, 4 tons; Mototolo mine, 3 tons; Modikwa mine, 2 tons) and Zimbabwe (Unki mine, 4 tons). South African companies were the second largest overseas platinum supply owner with 14 tons in total, which was due to the Impala Platinum's Zimplats mine (6 tons) and 50% ownership of the Mimosa mine (4 tons) in Zimbabwe, as well as Sibanye-Stillwater's Stillwater & East Boulder mine in the USA (4 tons) and another 50% ownership of the Mimosa mine. Detailed underlying data of Figure S4 are listed in the Table S4.

Table S4. Global platinum FDI-related mine production, locations, operators, shareholders, companies' ownership hierarchy, and the countries to which the companies belong (data for 2019).

Mine	Production in 2019/kg Pt content	Location	Operator	Country affiliation of operators	Shareholder 1	Country affiliation of shareholder 1	Ownership of shareholder 1
Mogalakwena Mine	14060	South Africa	Anglo American Platinum Limited	South Africa	Anglo American PLC	United Kingdom	100%
Amandelbult Complex	13280	South Africa	Anglo American Platinum Limited	South Africa	Anglo American PLC	United Kingdom	100%
Mototolo Mine	2600	South Africa	Anglo American Platinum Limited	South Africa	Anglo American PLC	United Kingdom	100%
Unki Mine	3800	Zimbabwe	Anglo American Platinum Limited	Zimbabwe	Anglo American PLC	United Kingdom	100%
Modikwa Mine	1913	South Africa	Anglo American Platinum Limited	South Africa	Anglo American PLC	United Kingdom	100%
Kroondal Mine	4121	South Africa	Anglo American Platinum Limited	South Africa	Anglo American PLC	United Kingdom	100%
Mimosa	1630	Zimbabwe	Sibanye Gold Limited	Zimbabwe	Sibanye-Stillwater Limited	South Africa	100%
Mimosa	1630	Zimbabwe	Impala Platinum Limited	Zimbabwe	Impala Platinum Holdings Limited	South Africa	100%
Stillwater Mine/East Boulder Mine	4150	USA	Sibanye-Stillwater	USA	Sibanye-Stillwater Limited	South Africa	100%
Zimplats	6441	Zimbabwe	Impala Platinum Limited	Zimbabwe	Impala Platinum Holdings Limited	South Africa	100%
Pilanesberg	2551	South Africa	Sedibelo Platinum Mines Limited	South Africa	Sedibelo Platinum Mines Limited	United Kingdom	100%
Nikkelverk	1446	Norway	Glencore Nikkelverk AS	Norway	Glencore	Switzerland	100%
Norilsk Nickel Harjavalta	813	Finland	Norisk Nickel	Russia			
Nkomati	208	South Africa	Norisk Nickel	Russia			
Sudbury	4386	Cananda	VALE (Companhia Vale do Rio Doce)	Cananda	Vale	Brazil	100%

Table S5. Lithium mine production in 2019.

Country	Geographic	Company
Argentina	6300	383
Australia	45000	22841
Brazil	2400	2400
Canada	200	200
Chile	19300	8629
China	10800	28640
Portugal	900	900
USA	1200	22107
Zimbabwe	1200	1200
Total	**87000**	**87000**
HHI	**3363**	**2511**

The production in the geographic level is adopted from the USGS report for the year of 2021[4]. Unit in ton metallic equivalent. HHI, Herfindahl-Hirschman Index.

In 2019, the world's total lithium production was 87 kt, 47% of which was controlled by FDI. From a geographic perspective, Australia, Chile, China, and Argentina were the major primary producers, with production shares of 52%, 22%, 12%, and 7%, respectively. After the reallocation, China was the largest lithium supplier with its share of global supply rise from 12% to 33%. Australia became the second largest supplier with its supply share falling to 26%. The production share of the USA rises from 1% to 25%, making it the third largest lithium suppliers. The production share of Chile after reallocation drops to 10%, making it the fourth largest producer.

Table S6. Cobalt mine production in 2019.

Country	Geographic	Company
Australia	5740	2020
Brazil	400	4460
Canada	3340	8429
China	2500	24242
Cuba	3800	1953
Dubai	0	6200
DRC	100000	16352
Kazakhstan	0	6640
Luxembourg	0	9961
Madagascar	3400	2091
New Caledonia	1600	0
Papua new guinea	2910	1048
Philippines	5100	5100
Russia	6300	6935
South Africa	2100	2384
Switzerland	0	41605
USA	500	0
Others	6320	4592
Total	**144000**	**144000**
HHI	**4917**	**1434**

The production in the geographic level is adopted from the USGS report for the year of 2020[4]. Unit in ton metallic equivalent.

The global cobalt production was 144 kt in 2019, and 71% of which is controlled by FDI. From a geographical perspective, DRC dominated the global production, accounting for 69%, followed by Russia (4%) and Australia (4%). In the past two decades, almost all additional investment in cobalt production happened in the DRC, leading the supply share of DRC to grow to 10 times that of 1995. However, 84% of the production in the DRC is operated by foreign companies from Switzerland (45%), China (18%), Luxembourg (10%), Kazakhstan (7%), Dubai (6%), Canada (4%), and South Africa (1%). These ownerships made Switzerland and China the top two cobalt suppliers from a company ownership perspective, with a production share of 29% and 17%, respectively. The production share of DRC dropped to 11% after the allocation, making it the third largest supplier.

Table S7. Nickel mine production in 2019.

Country	Geographic	Company
Australia	159	131
Brazil	60.6	205
Canada	181	82
China	120	407
Indonesia	853	530
New Caledonia	208	133
Philippines	323	229
Russia	279	345
Switzerland	0	121
Other countries	323.5	324
Total	**2507**	**2507**
HHI	**1804**	**1307**

The production in the geographic level is adopted from the USGS report for the year of 2020[4]. Unit in kiloton metallic equivalent.

In 2019, the global nickel production was 2507 kt, 43% of which was controlled by FDI. From a geographic perspective, Indonesia, the Philippines, and Russia were the top three producers, with production shares of 34%, 13%, and 11%, respectively. From a company ownership perspective, Indonesia was still the largest producer although its production share decreased to 21%. After the allocation, China became the second largest producer with its production share increased from 5% to 16%. Russia and the Philippines became the third and fourth largest producers with a production share of 14% and 9%, respectively.

Table S8. Platinum mining production in 2019.

Country	Geographic	Company
Australia	97	97
Brazil	0	4386
Canada	7800	3414
China	1434	1434
Colombia	325	325
Ethiopia	3	3
Finland	813	0
Japan	1002	1002
Poland	56	56
Russia	24000	25021
Serbia	1	1
South Africa	133000	108117
UK	0	42325
USA	4150	0
Zimbabwe	13500	0
Total	**186000**	**186000**
HHI	**5348**	**4088**

The production in the geographic level is adopted from the USGS report for the year of 2020[4]. Unit in kg metallic equivalent.

The global platinum production was 186 tons in 2019, 34% of which was controlled by FDI. From a geographic perspective, 91% of platinum production was from the top three producers, South Africa (71%), Russia (13%), and Zimbabwe (7%). Due to its leading resource endowment, South Africa (home to 90% of the world's platinum mine reserves) has dominated the global platinum supply for decades. After the allocation, South Africa's production share falls to 58%, but it is still the largest supplier. From a company ownership perspective, the UK and Russia were the second and third largest producers, accounting for 23% and 13%, respectively, of global platinum supply.

Table S9. Trade flows adjusted based on FDI and corresponding trade values.

Material	Total global trade value (ton metallic content)	Bilateral trade flow amount	Trade flows related to FDI			
			Importer	Exporter	Original trade value (ton metallic content)	Adjusted trade value (ton metallic content)
Lithium	82,000	509	China	Australia	48,023	32,964
			Australia	Argentina	23	0
			China	Chile	3,121	339
			USA	Argentina	1,053	0
			USA	Chile	1,056	0
Cobalt	96,000	81	China	DRC	75,048	56,329
			China	Zambia	465	0
			South Africa	DRC	0	0
Nickel	458,000	188	Canada	Australia	0	0
			China	Australia	27,316	25,941
			China	Canada	6,005	0
			China	Indonesia	160,768	0
			China	Papua New Guinea	0	0
			China	Zambia	538	0
			France	New Caledonia	1	0
			Japan	Indonesia	243	0
			Japan	New Caledonia	12,882	8,582
			Japan	Philippines	7,512	0
			South Africa	Zimbabwe	4	0
Platinum	309	1312	Brazil	Canada	0.001	0.000
			Russian Federation	South Africa	0.249	0.041
			South Africa	USA	0.066	0.000
			South Africa	Zimbabwe	0.000	0.000
			Switzerland	Norway	0.040	0.000
			United Kingdom	South Africa	14.486	0.000

Commodities that have been considered for international trade in this study include: lithium ores, lithium brines, lithium carbonates, cobalt ores, nickel ores, platinum ores, platinum refined metals. Data are mainly adopted from United Nations Comtrade database and Customs databases of major countries, using the HS-Codes of corresponding commodities: lithium carbonate, 283691; cobalt ore, 260500; nickel ore, 260400; platinum refined metal, 711011, 711019, 711292[5-8]. The trade data of other commodities are derived from relevant buyer companies or information services platform[9] as these commodities do not have their specific six-digit HS-Codes. Material contents in relevant commodities are preliminarily determined based on commodity industrial properties and amended based on the mass balance principles, which requires the sum of national domestic production and imports is approximately equal to the sum of exports and domestic consumption. The reliability of the database and treatments has been verified by a series of related material flow analysis studies previously published by the authors[10-14].

We adjusted the global trade flows by treating the overseas production controlled by a country's companies through FDI as that country's domestic production. For example, China imports 48 kt lithium from Australia while meanwhile Chinese companies control 15 kt lithium production in Australia. Thus, the "adjusted trade flow" from Australia to China would be 33 kt. If the production controlled by FDI between trade partners is larger than the trade amount, the adjusted trade amount was set as 0.

In 2019, the total lithium trade reached 82 kt with 509 bilateral trade flows. Among them, five trade flows were related to countries with FDI, i.e., from Australia to China

(48 kt), from Chile to China (3 kt), from Argentina to the USA (1 kt), from Chile to the USA (1 kt), and from Argentina to Australia (0.02 kt). Correspondingly, their adjusted trade flows would be from Australia to China (33 kt), from Chile to China (0.3 kt), and 0 for all the remaining three trade flows. With these flows adjusted, China's lithium import decreased by 31% to 37 kt, despite still being the largest importer. The USA's lithium import was adjusted to 0.3 kt, which decreased by 88%.

The global trade of cobalt material reached 96 kt in 2019, with 81 bilateral trade flows in total. There were three trade flows related to countries with FDI, which were from DRC to China (adjusted to 56 kt from 75 kt), from Zambia to China (adjusted to 0 from 0.5 kt), and from DRC to South Africa (adjusted to 0 from 0.0002 kt). With these flows adjusted, China's cobalt import decreased by 25% to 57 kt.

Global nickel trade was 458 kt in 2019 with 188 bilateral trade flows. Eleven trade flows were related to countries with FDI. Among them five trade flows were China's import flows, which were from Indonesia (161 kt), Australia (27 kt), Canada (6 kt), Zambia (0.5 kt), Papua New Guinea (0.00005 kt). Three trade flows were Japan's trade flow which were from New Caledonia (13 kt), Philippines (8 kt), and Indonesia (0.2 kt). Another two trade flows were from Zimbabwe to South Africa (0.004 kt) and from New Caledonia to France (0.001 kt). After adjustment, the trade flows from Australia to China was 26 kt and from New Caledonia to Japan was 9 kt. The other trade flows were adjusted to 0. With these flows adjusted, China's nickel import decreased by 45% to 202 kt and Japan's nickel import decreased by 58% to 9 kt.

In 2019, the global platinum trade was 309 tons with 1312 bilateral platinum trade flows in total. Six trade flows were related to countries with FDI: from South Africa to the UK (14 tons), from South Africa to Russia (0.25 tons), from the USA to South Africa (0.07 tons), from Norway to Switzerland (0.04 tons), from Canada to Brazil (0.001 ton), and from Zimbabwe to South Africa (0.00001 tons). The trade flow from South Africa to Russia was adjusted to 0.04 tons, and all other trade flows subject to adjustment were adjusted to 0. After adjustment, the UK's platinum import decreased by 35% to 27 tons.

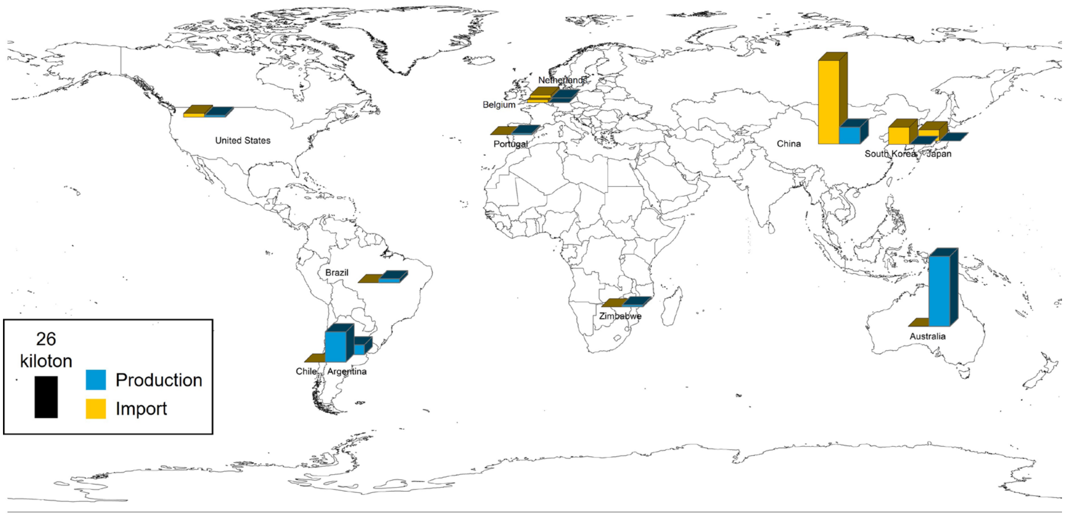

Figure S5. Lithium production and import by country. Unit is lithium metallic equivalent. Bar height is proportional to value. Yellow and blue bar represents imports and production, respectively. Underlying data is adopted from the authors' material flow analysis database which has been verified in previous studies[10,11,13,15-17]. Only values larger than 1% of global total production are shown here for clarity.

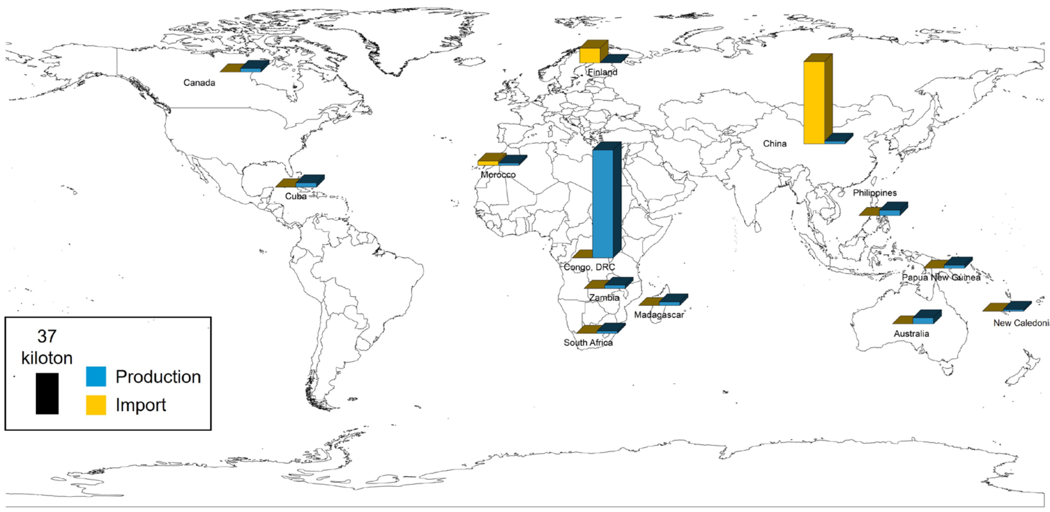

Figure S6. Cobalt production and import by country.

Unit is cobalt metallic equivalent. Other treatments are the same with Figure S5.

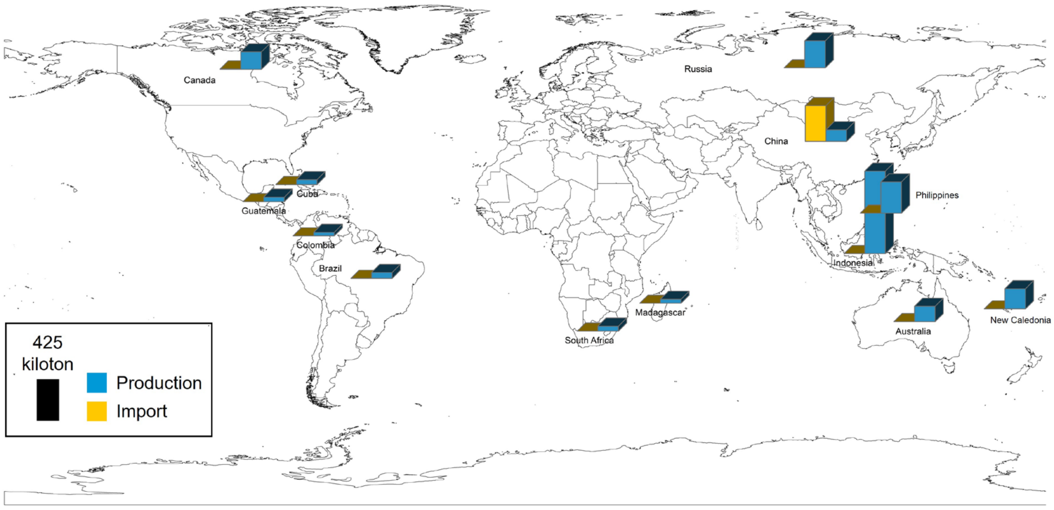

Figure S7. Nickel production and import by country.

Unit is nickel metallic equivalent. Other treatments are the same with Figure S5.

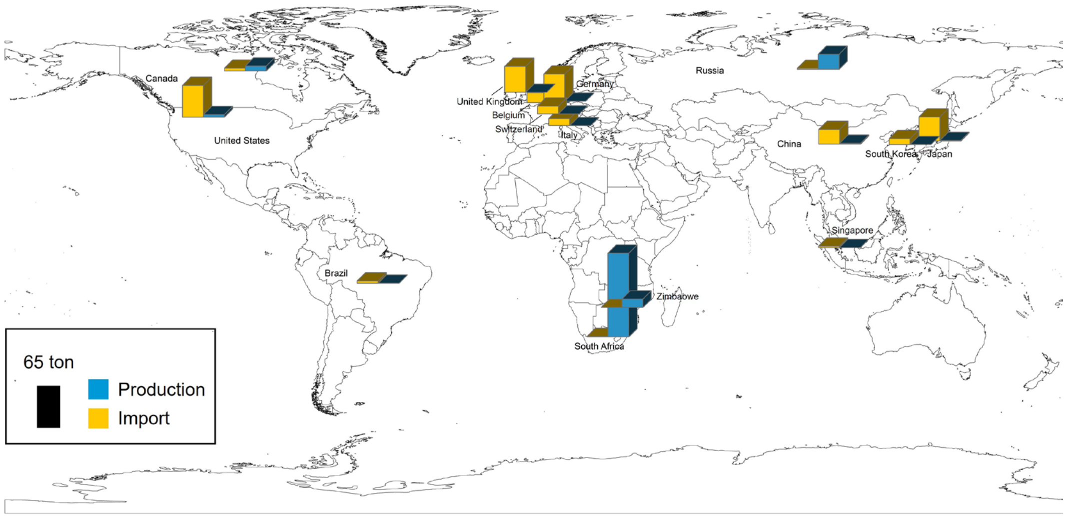

Figure S8. Platinum production and import by country.

Unit is platinum metallic equivalent. Other treatments are the same with Figure S5.

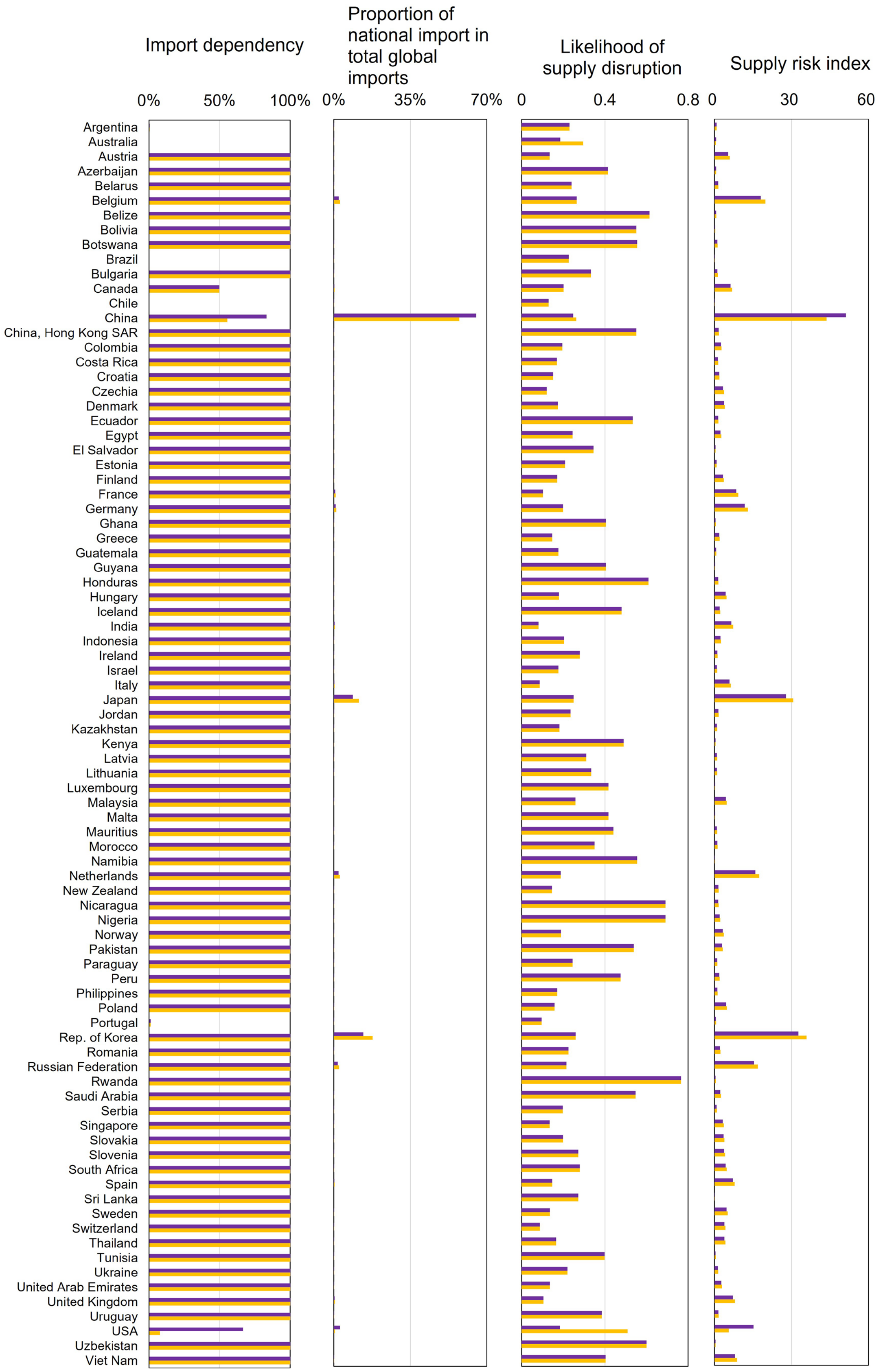

Figure S9. Original and adjusted supply risk index of lithium by country.

Figure S10. Original and adjusted supply risk index of cobalt by country.

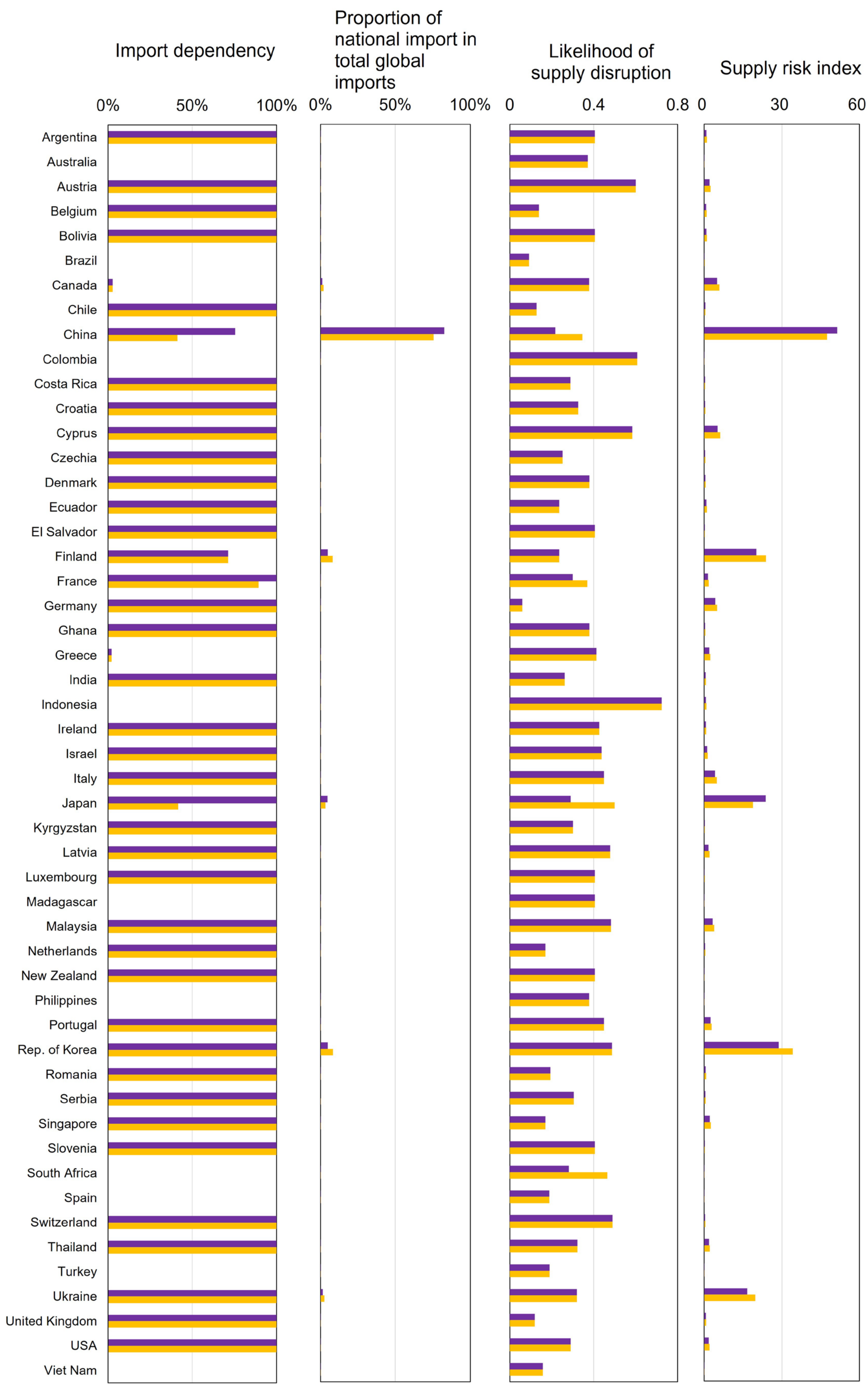

Figure S11. Original and adjusted supply risk index of nickel by country.

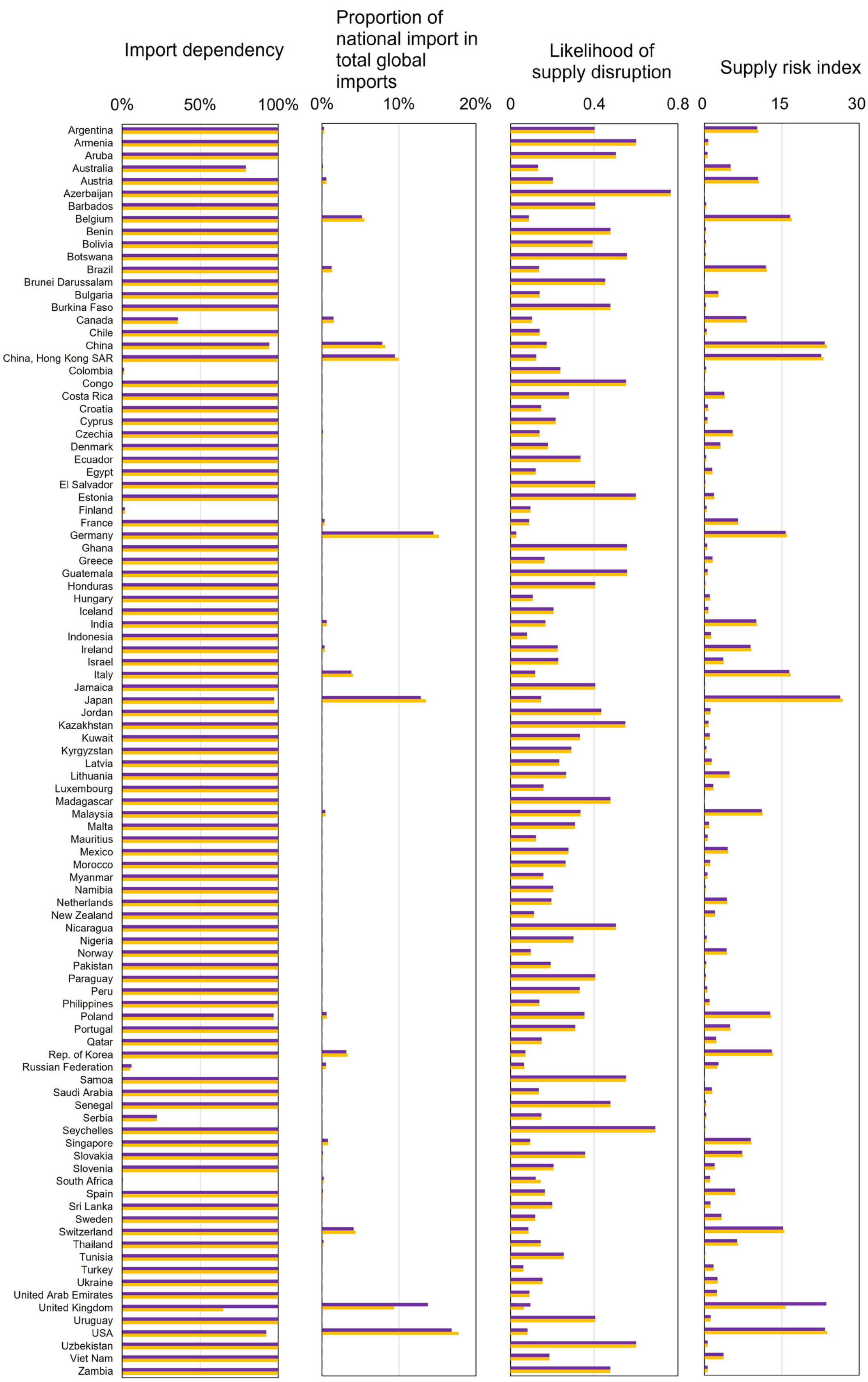

Figure S12. Original and adjusted supply risk index of platinum by country.

Figure S9-S12 show the quantification results of original and adjusted Supply Risk Index (SRI) of the four critical materials. Out of the 240 countries covered in this study, the number of countries facing supply risk (SRI greater than 0) are considerable (16%-41%), i.e., 85 for lithium, 39 for cobalt, 51 for nickel, and 99 for platinum. China's cobalt supply risk is the most notable, with an SRI of 88. This result is driven by the relatively large values of sub-indicators in all three dimensions. The SRIs of China's nickel supply and lithium supply are the second and third largest, respectively, with both values of 51. These values are mainly driven by China's large proportion of global total import and high import dependency. Finland's cobalt supply risk is the fourth largest with a value of 47, which is mainly driven by the high likelihood of supply disruption and import dependency. Other high SRI values are often driven by their high likelihood of supply disruption (e.g., Morocco's cobalt supply with an SRI of 29) or import dependency (e.g., South Korea's lithium supply with an SRI of 33).

When considering the impact of FDI, supply risks for USA's lithium, UK's platinum, Japan's nickel, and China's lithium and cobalt reduce the most significantly, with adjusted SRI values declining by 63%, 33%, 21%, 15%, and 11%, respectively. After stripping out the foreign capacity controlled by domestic companies, the USA's import dependency of lithium decreased from 67% to 8%. The UK's import dependency of platinum decreased from 100% to 65%. Japan's import dependency of nickel decreased from 100% to 42%. China's import dependency of lithium and cobalt decreased from 83% to 55% and from 97% to 73%, respectively.

The shares of national imports in total global imports for these countries show a similar trend as that of import dependency. Nevertheless, FDI played the opposite role in different countries' material supply in terms of the likelihood of supply disruption. For instance, the likelihood of supply disruption of UK's platinum decreased from 0.1 to 0.06, while that of China's lithium increased from 0.22 to 0.35. This observation can be attributed to the fact that more of China's imports from relatively stable countries has been adjusted.

It should be noted that, while the supply risks faced by the abovementioned countries dropped by considering the impact of FDI, the other countries that have the same commodity imports would face higher risk. After adjustment, the SRI value of lithium for 82 countries became 10% larger, that of cobalt for 38 countries became 8% larger, that of nickel for 50 countries became 18% larger, and that of platinum for 92 countries became 2% larger. This indicates a kind of "zero-sum" game in national supply risk: when import shares of some countries in the global total import became smaller by considering FDI, the shares of the other countries' imports in the global total import are magnified.

Table S10. Ownership type (private or state-owned) and headquarter location of companies with FDI in clean energy material production.

Company	Ownership type	Headquarter location
African Rainbow Minerals	Private	South Africa
Albemarle	Private	USA
Albidon	Private	Virgin Islands (UK)
Allegiance Mining	Private	Australia
Altura	Private	Australia
Ambatovy	Private	Madagascar
Anglo American Resource	Private	UK
Anglo American Platinum	Private	South Africa
Aquarius Platinum	Private	Australia
Atlantic Nickel	Private	Brazil
AVZ	Private	Australia
Bacanora lithium	Private	UK
Bamangwato Concessions	Private	South Africa
Bindura Nickel Corporation Ltd	State-owned	Zimbabwe
Bintang Delapan Group	Private	Indonesia
Boliden	Private	Sweden
Boss mining	Private	DRC
CATL	Private	China
Chambishi Metals plc Zambia	Private	Zambia
Chemaf	Private	UAE
China Metallurgical Group	State-owned	China
China Molybdenum	Private	China
China Nonferrous Mining	State-owned	China
China Railway Group	State-owned	China
Cominière	State-owned	DRC
Dathcom Mining	Private	DRC
Entreprise General Malta Forrest	Private	DRC
Eramet	Private	France
Eurasian Natural Resources Corporation	Private	UK
Eurasian Resources Group	Private	Luxembourg
First Quantum Minerals	Private	Canada
FMC	Private	USA
Fox Resources	Private	Australia
Galaxy Resource	Private	Australia
Ganfeng Lithium	Private	China
Gecamines	State-owned	DRC
Glencore Nikkelverk AS	Private	Norway
Glencore Public Limited Company	Private	Switzerland

Hanking	Private	China
Highlands Pacific	Private	Papua New Guinea
Horizonte Minerals	Private	UK
Huayou cobalt	Private	China
Hyundai	Private	Korea
Impala Platinum	Private	South Africa
Jilin	State-owned	China
Jinchuan	State-owned	China
Katanga Mining Limited	Private	Canada
KGHM Polska Miedz	Private	Poland
Konkola Copper Mines	Private	Zambia
Korea Resources	State-owned	Korea
Livent	Private	USA
Lonmin Limited	Private	South Africa
Lundin	Private	Canada
Maha Bhakti Abadi	Private	Indonesia
Managem	Private	Morocco
Metorex	Private	South Africa
Minara Resources	Private	Australia
Miniere du Sud Katanga	State-owned	DRC
Mitsubishi Corporation	Private	Japan
Mutanda ya Mukonkota Mining	Private	DRC
Mwana Africa	Private	UK
Nisshin Steel	Private	China
Norilsk Nickel	Private	Russia
Norilsk Nickel Africa	Private	South Africa
North America Lithium	Private	Canada
Northam Platinum Limited	Private	South Africa
Orocobre	Private	Australia
Pacific Metals	Private	Japan
Pampa Group	Private	Chile
Panoramic Resources	Private	Australia
Pilbara Minerals	Private	Australia
Posco	Private	Korea
Prospect Resources	Private	Australia
PT Antam	State-owned	Indonesia
Queensland Nickel Group	Private	Australia
Reed Industrial Mineral	Private	Australia
Rio Tinto	Private	Australia
Rio Tuba Nickel Mining Corporation/ Coral Bay Nickel Corporation	Private	Philippines
Royal Bafokeng Platinum Limited	Private	South Africa
Royalties	Private	Canada
Samsung	Private	Korea

Sedibelo Platinum Mines Limited	Private	UK
Shalina Resources Ltd	Private	UAE
Shanshan Corporation	Private	China
Sherritt	Private	Canada
Sibanye Gold Limited	Private	South Africa
Sibanye-Stillwater	Private	South Africa
Sinomine Resource	Private	China
Siyanda Resources Limited	Private	South Africa
SNC Lavalin	Private	Canada
South32	Private	Australia
SQM	Private	Chile
STCPI	Private	Caledonia
Sumitomo	Private	Japan
Talison	Private	Australia
Tenke Fungurume Mining	Private	DRC
Terrafame Mining	State-owned	Finland
Tharisa Minerals Limited	Private	South Africa
Tharisa PLC	Private	Cyprus
Tianqi Lithium	Private	China
Trafigura and Solidium	Private	Singapore
Tsingshan	Private	China
Vale	Private	Brazil
Vedanta Resources	Private	UK
Wodgina	Private	Australia
Xinjiang Xinxin Mining Industry	Private	China
Yuanjiang Nickel	State-owned	China
ZCCM Investments holding	State-owned	Zambia

Information about company ownership type and headquarter locations was mainly derived from the ORBIS database of Bureau van Dijk[18] and also supplemented and verified by public information from the companies' official website and annual reports. In this study, we defined the headquarter location of a company as its country affiliation.

Table S11. Critical minerals for clean energy technologies. REE, rare earth elements. PGM, platinum group metals. CSP, concentrating solar power. EV, electric vehicles.

	Copper	**Cobalt**	**Nickel**	**Lithium**	REEs	**Chromium**	**Zinc**	**PGMs**	Aluminium
Solar PV	√								√
Wind	√		√		√	√	√		√
Hydro	√					√	√		√
CSP	√		√			√	√		√
Bioenergy	√						√		√
Geothermal			√			√			
Nuclear	√		√			√			
Electricity networks	√								√
EVs and battery storage	√	√	√	√	√				√
Hydrogen			√		√			√	√

The content listed in the Table S11 are derived from the report of International Energy Agency (IEA)[19]. In this report, IEA has assessed the relative importance of nine critical minerals for various clean energy technologies, including copper, cobalt, nickel, lithium rare earth elements (REEs), chromium, zinc, platinum group metals (PGMs), aluminium. They categorized the importance level of critical minerals into three levels: high, moderate, and low. The " √ " symbol in the Table S11 represents minerals that are categorized as high or moderate importance in the IEA report.

Similar studies have been conducted by official organizations in major economies. Department of Energy (DOE) of the USA has determined the list of **critical materials for energy** to include the following in their newly released report [20]: aluminum, cobalt, copper, dysprosium, electrical steel, fluorine, gallium, iridium, lithium, magnesium, natural graphite, neodymium, nickel, platinum, praseodymium, silicon, silicon carbide and terbium. Joint Research Center (JRC) of European Commission has evaluated the importance and supply risks of various minerals for 15 key technologies across the five strategic sectors (renewable energy, electromobility, energy-intensive industry, digital, and aerospace/defense) in their recent report[21]. They finally selected the following materials as the **strategic and critical materials**: gallium, magnesium, REE, boron, PGM, lithium, bismuth, germanium, natural graphite, cobalt, titanium metal, silicon metal, tungsten, manganese, nickel, copper, niobium, phosphorus, strontium, scandium, vanadium, antimony, beryllium, arsenic, feldspar, hafnium, baryte, tantalum, aluminium, helium, fluorspar, phosphate rock. Seven materials appeared in the intersection of the critical mineral lists generated by these organizations (IEA, DOE, and JRC): **lithium, cobalt, nickel, copper, REE, PGM, aluminum** (REE and PGM are grouped together as one material, respectively). With reference to this list of overlapping material and taking into account the research expertise of the authors' team and the availability of relevant data, lithium, cobalt, nickel, and platinum were selected as study cases.

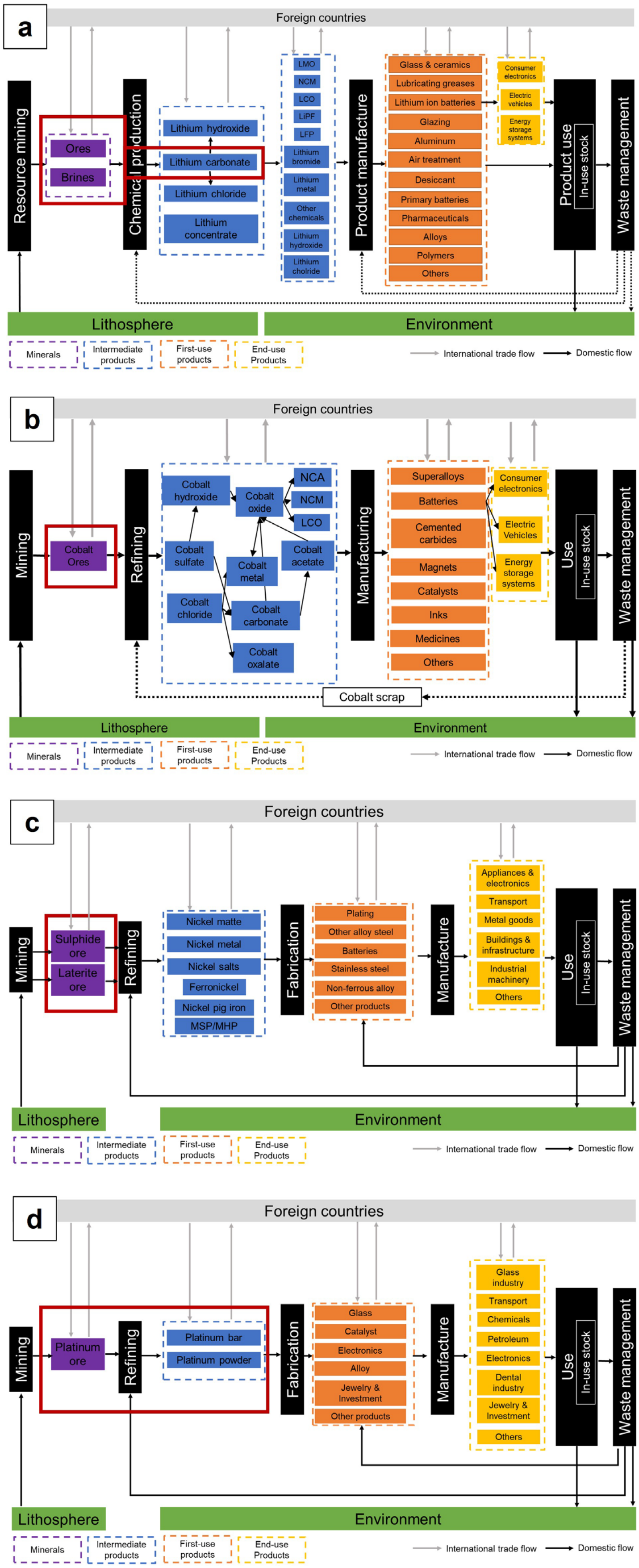

Figure S13. Life cycle of lithium (a), cobalt (b), nickel (c), and platinum (d).

Notes to Figure S13: The red boxes represent the commodities related to the four materials of interest covered in the system boundary of this study. Abbreviation: NCM, lithium nickel cobalt manganese oxide. NCA, lithium nickel cobalt aluminum oxide. LCO, lithium cobalt oxide. LMO, lithium manganese oxide. LFP, lithium iron phosphate. LiPF, lithium hexafluorophosphate. MSP/MHP, nickel mixed sulphides or hydroxides precipitates.

In this study, we explore the FDI associated with mining projects for four critical materials: lithium, cobalt, nickel, and platinum. Each of these materials has unique physicochemical properties, leading to varied mining and metallurgical processes. Lithium minerals contain both ore and brine forms. The output of the lithium ore mining project (mostly in Australia) is generally only lithium ores, which is then transported to the specialized refining plants (mostly in China) for subsequent processing. While for lithium brines, the output of corresponding mining projects (mostly in Chile and Argentina) is primarily lithium carbonates, as transporting lithium brine is not economically feasible. For cobalt and nickel, mining projects typically yield only ores and concentrates (ores and concentrates are classified as the same category in customs codes). Platinum presents a unique case; most platinum ores are not economical to transport due to their low concentration. As a result, platinum mining projects are often vertically integrated with refining operations in the same or nearby facilities[22]. The final products from platinum mine projects are refined metals, either in powder or bar form, following the concentration and smelting of the ores. Considering only the trade in minerals would overlook a significant portion of the outputs of lithium and platinum projects not accounted for in the risk assessment model. This gap means that the risks associated with importing lithium and platinum and the role of FDI in various countries may not be accurately measured. To provide a more comparable analysis across these different materials, we also track the international trade of some specific commodities in the refining stage of their life cycles, including lithium carbonate and refined platinum metals.

In summary, our focus is on the FDI related to mining projects for lithium, cobalt, nickel, and platinum. For lithium and platinum, some mining projects also include refining. We uniformly consider the mining stage for all four materials when mapping production flow. Regarding international trade flow, we cover both mining and refining stages for lithium and platinum, while only the mining stage is addressed for cobalt and nickel, as illustrated in Figure S13.

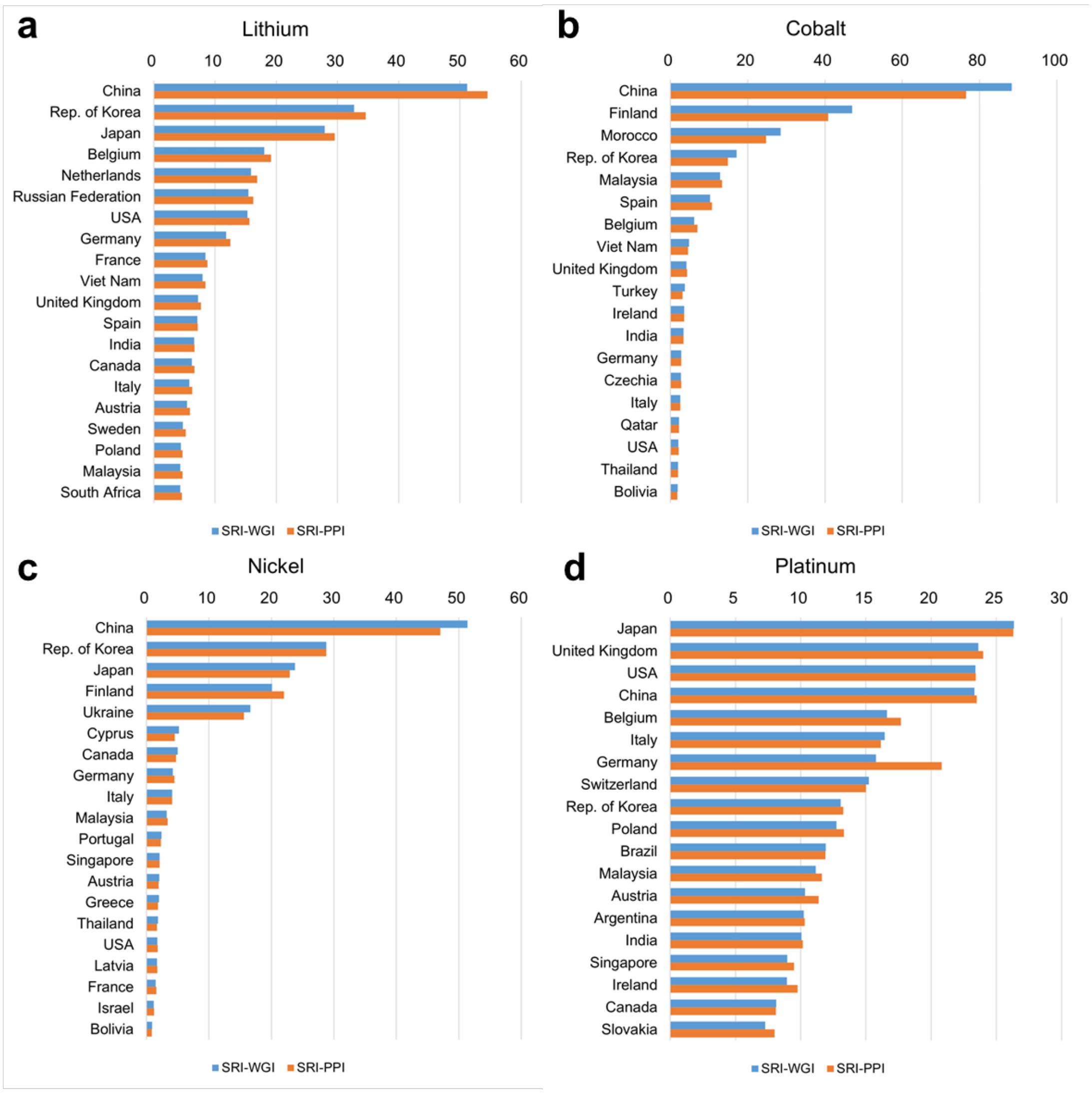

Figure S14. Quantitative results of supply risk index for lithium (a), cobalt (b), nickel (c), and platinum (d), using WGI and PPI, respectively.

The blue bars represent the SRI results based on the Worldwide Governance Indicators (WGI). The orange bars represent the SRI results using the Policy Perception Index (PPI). For simplicity in visualization, only the top 20 SRIs for each category of critical materials are displayed.

Both the WGI and PPI are widely used in existing literature to quantify regional policy stability for supply risk assessment[14,23,24]. The WGI is designed by the World Bank to assist researchers and analysts in evaluating broad trends in governance perceptions across various countries and over time[25]. The WGI comprises six consolidated governance indicators covering more than 200 countries and territories over the period 1996–2022: (1) Voice and Accountability; (2) Political Stability and Absence of Violence/Terrorism; (3) Government Effectiveness; (4) Regulatory Quality; (5) Rule of Law; (6) Control of Corruption. Generally, only the indicator - Political Stability and Absence of Violence/Terrorism is used for assessing the supply risk.

The PPI, previously referred as the Policy Potential Index, was developed by the Fraser Institute[26]. It provides a comprehensive assessment of the attractiveness of mining policies in a jurisdiction, and can serve as a report card to governments on how attractive their policies are from the point of view of an exploration manager. The PPI is a composite index that captures the opinions of managers and executives on the effects of policies in jurisdictions with which they are familiar. Its calculation includes the uncertainty concerning the administration, interpretation, and enforcement of existing regulations; environmental regulations; regulatory duplication and inconsistencies; taxation; uncertainty concerning disputed land claims and protected areas; infrastructure; socioeconomic agreements; political stability; labor issues; geological database; and security.

In this study, we opted for the WGI to reflect the regional policy stability as it is a more commonly used indicator for this purpose and offers results for a wider array of countries. We integrated the WGI with the HHI to quantify the Likelihood of Supply Disruption. Given that a higher WGI signifies lower risk, contrary to the numerical implication of the HHI, we employ equation (1) to transform the regional WGI values into deviation values. This sets the global WGI average at 0.5, where a larger value indicates a country with a higher risk.

$$WGI_{scaled} = \frac{-(WGI - WGI_{ave})}{stdev(WGI)} \times 0.1 + 0.5 \quad (1)$$

Where, WGI_{ave} is the global average value of WGI; $stdev(WGI)$ is the standard deviation of all countries' WGI; WGI_{scaled} is the scaled value of WGI.

To investigate the uncertainties associated with the chosen indicators, we also replicated the aforesaid calculation for assessing the SRI using the PPI. The Fraser Institute's report provides PPI results for approximately 30 countries, including some that are specific to regions within a single country (e.g., states in the United States). In instances where only region-specific PPI data were available, we calculated the country's PPI as the average of these regional values. For countries without specific PPI data, we assigned the global average as their PPI value.

The comparative results of using these two indicators are presented in Figure S14. These comparisons reveal that the SRIs for many countries show varying degrees of difference between the WGI and PPI assessments. The differences between these two kinds of SRIs range from 0.03% (for Korea's nickel supply risk) to 32% (for Germany's platinum supply risk), with an average of 4%. 93% of the SRIs have a variation of no more than 10% when calculated using the WGI and PPI. The majority of countries maintain their global SRI rankings. Despite the uncertainty in indicator selection, the qualitative conclusions of this study remain robust.

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Data collection	No software was used. The data was manually collected and download from publicly available source and deposited in the txt and Excel file.
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Human research participants

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Population characteristics	N/A
Recruitment	N/A
Ethics oversight	N/A

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Study description	This study collected the foreign direct investment, national production, and international trade data related to the lithium, cobalt, nickel, and platinum mining industry. These data are analyzed based on the "supply risk index" developed in this study.
Research sample	Only publicly available data is used for analysis. The information about country affiliation of companies is from the ORBIS database of Bureau van Dijk. The ownership hierarchy of mine owners and stakeholders are collected from annual reports, public statements, and news reports of relevant companies, consulting groups, and information services platforms. Geographical production and international trade of four materials are from United Nations Comtrade database, United States Geological Survey Reports, and our previous studies. Source data are available in the Supplementary Information document.
Sampling strategy	No sample-size calculation was performed because this study is an observational study of global lithium lithium, cobalt, nickel, and platinum mining industry
Data collection	The data was collected from publicly available source by direct download or copying. The data collection was conducted by the authors of this study without using specific software or coding work
Timing and spatial scale	The data was mainly collected from January 2020 to June 2020 and revised and reverified from June 2023 to September 2023.
Data exclusions	No data were excluded from the analyses.
Reproducibility	The results of this study can be easily reproduced through the steps described in the Methods section, using the source data provided in the Supplementary Information. The analysis could be conduced using Microsoft excel or similar software.
Randomization	Randomization is not relevant to this study because this study is an observational study of global lithium lithium, cobalt, nickel, and platinum mining industry.
Blinding	Blinding is not relevant to this study because this study is an observational study of global lithium lithium, cobalt, nickel, and platinum mining industry.

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