CSEP Discussion Note-6
September 2021

Centre for Social and Economic Progress

CSEP

Independence | Integrity | Impact

Assessing the Criticality of Non-fuel Minerals in India

Rajesh Chadha and Ganesh Sivamani

Independence | Integrity | Impact

www.csep.org

Centre for Social and Economic Progress (CSEP)
CSEP Research Foundation
6, Dr Jose P. Rizal Marg, Chanakyapuri,
New Delhi - 110021, India

Recommended citation:
Chadha, R. & Sivamani, G. (2021). *Assessing the Criticality of Non-fuel Minerals in India* (CSEP Discussion Note 6). New Delhi: Centre for Social and Economic Progress.

The Centre for Social and Economic Progress (CSEP) conducts in-depth, policy-relevant research and provides evidence-based recommendations to the challenges facing India and the world. It draws on the expertise of its researchers, extensive interactions with policymakers as well as convening power to enhance the impact of research. CSEP is based in New Delhi and registered as a company limited by shares and not for profit, under Section 8 of the Companies Act, 1956.

Designed by Mukesh Rawat

Assessing the Criticality of Non-fuel Minerals in India*

Rajesh Chadha
Senior Fellow
Centre for Social and Economic Progress**
New Delhi, India

Ganesh Sivamani
Research Analyst
Centre for Social and Economic Progress
New Delhi, India

*The authors thank CSEP colleagues for their insightful comments on this discussion note. These have been highlighted in the future work section and shall be addressed in the upcoming working paper.

**Formerly Brookings India.

Table of Contents

List of Tables and Figures

1. Backdrop

Critical minerals refer to the mineral resources, both primary and processed, which are essential inputs for the production process of an economy and whose supplies are likely to be disrupted on account of non-availability or risks of unaffordable price spikes. These minerals lack substitutability and recycling processes. The global concentration of extraction and processing activities, governance regimes and environmental footprints in the resource-abundant countries adversely impact availability risks. While some such materials provide inputs to traditional industries, many are crucial for high-tech products required for clean energy, national defence, informational technology, aviation and space research.[1]

Geoscience Australia refers to critical minerals as "metals, non-metals and minerals that are considered vital for the economic well-being of the world's major and emerging economies, yet whose supply may be at risk due to geological scarcity, geopolitical issues, trade policy or other factors".[2] Australia's perspective on critical minerals assessments has been discussed by Whittle et al. (2020)[3]. The lack of the availability of these minerals may disrupt the supply and operations of an industry or the Australian economy. The criticality arises from monopolies of extraction or processing by one or a few countries. However, Australia is endowed with minerals that are deemed critical by other countries, and hence can impact global supplies.

The US National Science and Technology Council (USNSTC) defines critical minerals as "those that have a supply chain that is vulnerable to disruption, and that serve an essential function in the manufacture of a product, the absence of which would cause significant economic or security consequence". The strategic minerals refer to "a subset of critical minerals and are those that are essential for national security applications".[4]

The European Union refers to critical minerals as critical raw materials (CRM) that have "high importance to the economy of the EU and whose supply is associated with high risk". The criticality is judged by two main parameters, economic importance and supply risk.[5]

Critical minerals have highly complex global supply chains with a high degree of concentration in the extracting and processing countries resulting in high supply risks. For example, China produces 63% of the world's output of rare earth elements (REEs) and 45% of molybdenum. More than 70% of cobalt is mined in the Democratic Republic of Congo, with China having the majority ownership. Australia produces 55% of the world's lithium, with China as its major importer. South Africa mines 72% of the world's platinum output (International Energy Agency (IEA) Report, 2020).[6]

---

[1] https://csep.org/discussion-note/skewed-critical-minerals-global-supply-chains-post-covid-19/

[2] Skirrow, R.G., Huston, D.L., Mernagh, T.P., Thorne, J.P., Dulfer, H., & Senior, A.B. 2013. Critical commodities for a high-tech world: Australia's potential to supply global demand. Geoscience Australia, Canberra, (http://www.ga.gov.au/metadata-gateway/metadata/record/gcat_76526/).

[3] https://www.researchgate.net/publication/345780094_Minerals_Criticality_Assessment_from_an_Australian_Perspective

[4] https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/NSTC/csmsc_assessment_of_critical_minerals_report_2016-03-16_final.pdf

[5] https://op.europa.eu/en/publication-detail/-/publication/2d43b7e2-66ac-11e7-b2f2-01aa75ed71a1

[6] Kim, Tae-Yoon and Milosz Karpinski (2020), Clean energy progress after the Covid-19 crisis will need reliable supplies of critical minerals, International Energy Agency (IEA): https://www.iea.org/articles/clean-energy-progress-after-the-covid-19-crisis-will-need-reliable-supplies-of-critical-minerals

2. Critical Minerals Assessment for India

A Planning Commission Working Group on Mineral Exploration and Development (other than coal and lignite) submitted its report in 2011.[7] It highlighted the need for assured availability of minerals resources for India's industrial growth and emphasised the need for R&D and processing of Technology Metals and Energy Critical Minerals. In addition, there must be a clear focus on well-planned exploration and management of already discovered resources. The report analysed the minerals under eleven broad categories, including metallic, non-metallic, precious stones and metals, and strategic minerals. The strategic minerals included tin, cobalt, lithium, germanium, gallium, indium, niobium, beryllium, tantalum, tungsten, bismuth and selenium. The need to increase resource efficiency, finding substitutes and end-of-life recycling was emphasised.

The Ministry of Mines, Government of India, published a study on Rare Earths and Energy Critical Minerals: A Roadmap and Strategy for India (CTempo-CSTEP, 2012).[8] The report provides a review of India's production, consumption and reserves, and suggests policy initiatives and interventions required from the Government to push the growth of this sector. The supply chain for rare earth elements generally consists of exploration, mining, extraction and manufacturing. Necessary initiatives need to be taken for value-added refining, metal/ alloy production and manufacturing components for end-use.

Lele and Bhardwaj (2014) analysed the availability, requirement, utility and deficiency of strategic materials. Nine minerals were considered, viz. antimony, bismuth, beryllium, cobalt, germanium, lithium, nickel, tungsten and tin. The authors use Porter's Five Forces Model to assess the strength and attractiveness of markets of these minerals and risk factors based on psychometric assessment using the Likert Scale. However, Porter's model offers a qualitative analysis of the market, and hence, the results of this model are not considered conclusive. Further, Lele (2019) provides an extended discussion on India's need for Strategic Minerals.[9]

A study by the Department of Science and Technology and the Council on Energy, Environment and Water (DST-CEEW, 2016) highlighted the lack of research in India on ensuring mineral resource security for the manufacturing sector. The study made a pioneering attempt at computing the criticality index of 49 non-fuel minerals, including rare earth minerals.[10] A mineral is used in small quantities in a high-value-add manufacturing sector is more critical than a mineral used in large quantities in a low-value-add manufacturing sector. The supply-side risks for a mineral are based on the domestic endowment, geopolitical risks of the trade, substitutability and recycling potential. Thirteen minerals that would become most critical by 2030 were identified. Six of these were critical even in the reference year 2011.[11] One of the recommendations is that India should undertake institutional reforms outlined in the National Mineral Exploration Policy, NMEP 2016, including the creation of a not-for-profit National Centre for Mineral Targeting (NCMT), enhanced exploration and R&D in mining and mineral processing technologies, and strategic acquisition of mines abroad and signing of diplomatic and trade agreements.[12]

[7] https://niti.gov.in/planningcommission.gov.in/docs/aboutus/committee/wrkgrp12/wg_rep_min.pdf
[8] https://cstep.in/drupal/sites/default/files/2019-07/CSTEP_RR_rare_earths_energy_roadmap_July2012.pdf
[9] https://www.vifindia.org/sites/default/files/national-security-vol-2-issue-2-article-Alele.pdf
[10] Gupta, Vaibhav, Tirtha Biswas and Karthik Ganesan (2016), Critical Non-Fuel Mineral Resources for India's Manufacturing Sector: A Vision for 2030 (DST-CEEW): https://www.ceew.in/sites/default/files/CEEW_Critical_Non_Fuel_Mineral_Resources_for_India_Manufacturing_Sector_Report_19Jul16.pdf
[11] Minerals critical in 2011 as well as 2030 include chromium, limestone, niobium, rare earths (light), silicon and strontium. Minerals which would become critical by 2030 include rhenium, beryllium, rare earths (heavy), germanium, graphite, tantalum and zirconium.
[12] Ministry of Mines (2016), National Mineral Exploration Policy: Non-Fuel and Non-Coal Minerals: https://mines.gov.in/writereaddata/Content/NMEP.pdf

The proposed CSEP study shall evaluate the India-specific criticality of some of the non-fuel minerals. The present discussion note provides an illustration using 11 such minerals. Some of these minerals are deep-seated. While the DST-CEEW (2016) study was based on the EU methodology 2014[13], the updated CSEP study would use the EU methodology (2017).[14] Details are outlined in the methodology section.

3. Methodology

3.1 Indicators

This CSEP discussion note evaluates the criticality of eleven select minerals for their economic importance for India and import supply risks. The supply risks have been computed using the monopoly power of the minerals producing and sourcing countries by their respective governance and environmental regimes.

Table 1: Minerals Chosen: Uses and Rationale

Mineral	Major Uses	Critical for India in:		
		CEEW 2011 and 2030[15]	IBM Inventory 2015[16]	Planning Commission 2011[17]
Chromium	Alloys of steel, dyes	✓		
Cobalt	Alloys of steel, medical implements, batteries	✓	✓	✓
Copper	Electricity applications, pipes and pumps			
Iron	Steel			
Limestone	Cement	✓		
Lithium	Batteries (electric vehicles)		✓	
Niobium	Alloys of steel	✓	✓	
Heavy rare earths	Alloys of steel, alloys of aluminium	✓	✓	✓
Light rare earths	Ceramics, flint	✓	✓	✓
Silicon	Electronics components, steel manufacturing	✓		
Strontium	Alloys of aluminium	✓		

While copper ore and iron ore were not found to be critical in earlier reports, this study included these minerals due to their perceived economic importance. For the purpose of this study, heavy rare earths refer to yttrium and scandium, and light rare earths refer to cerium – these are the rare earth minerals produced and used in India.

3.2 Economic importance

The economic importance loosely measures the impact on the national economy of the concerned mineral no longer available in the supply chain. This is computed by taking an average of the value of mineral consumption in a particular sector weighted by that sector's GVA. The most recent Annual Survey of Industries (ASI 2017-18) was used for this component of economic importance.

[13] Report on the Critical Raw Materials for the EU, Report of the Ad hoc Working Group on defining critical raw materials, European Commission (2014).
[14] Methodology for establishing the EU list of critical raw materials, Guidelines, European Commission (2017).
[15] https://www.ceew.in/publications/critical-non-fuel-mineral-resources-india%E2%80%99s-manufacturing-sector
[16] https://ibm.gov.in/index.php?c=pages&m=index&id=900
[17] https://mines.gov.in/writereaddata/UploadFile/Report_of_working_group.pdf

The consuming sectors were all the manufacturing sectors (the broad sectors are given in Annex 1). For this study, the consumption of minerals was computed at the 5-digit level National Industrial Classification (NIC) 2008.[18] The information on inputs of mineral ores and their chemical and alloy forms has been sourced from the National Product Classification (NPC)[19]. Ideally, only the ore form of the mineral may be analysed. However, India does not extract and process some of the minerals. Therefore, the NPC reports the processed forms of these minerals. The list of NPCs of the minerals is given in Annex 2.

For the economic importance computation, the ease of substituting the mineral was also accounted for (Equation 1). For a highly substitutable mineral, the economic importance is lessened since there are alternatives available. This was done through a substitutability index which ranges from 0.6 to 1, where 0.6 represents a highly substitutable mineral, and 1 represents a mineral that is not substitutable. The substitutability index is computed by evaluating the cost and performance of the substitutes of each mineral (Table 2). This cost-performance score has been evaluated using published information on the feasibility of substitution, the performance of the substitutes, and the cost of the substitute (Annex 3). The substitutability index is the average cost-performance score weighted by the shares of mineral consumption by two-digit sectors (Equation 2).

The computation of the economic importance (EI) is given in Equation 1. is the share of the mineral consumption, is the GVA of the sector at a 5-digit level, and is the substitutability index. The result is scaled using the total manufacturing GVA at the 5-digit level.

Equation 1: Economic Importance

$$EI = \sum_{s} A_s Q_s \times \sigma_{EI}$$

Equation 2 shows the computation of the substitutability index, where is the share of mineral consumption in sector s, and is the cost-performance score for sectors.

Table 2: Cost-Performance Matrix

Cost of substitute \ Performance of substitute	Better	Similar	Reduced	No substitute
Much higher	0.8	0.9	1.0	1.0
Slightly higher	0.7	0.8	0.9	1.0
Similar or lower	0.6	0.7	0.8	1.0

Equation 2: Substitutability Index

$$\sigma_{EI} = \sum_{s} A_s \sigma_s$$

3.3 Supply risk

The supply risk indicator of the criticality assessment seeks to measure the vulnerability in the global mineral supply chains due to the level of concentration of mineral extraction in some countries and the quality of governance in these jurisdictions. This is done using the Herfindahl–Hirschman Index (HHI) to measure the concentration of the mineral extraction by country.[20] Two sets of producing countries are taken into account, the extracting countries and the countries from which India sources raw material.

[18] https://www.ncs.gov.in/Documents/NIC_Sector.pdf
[19] http://www.csoisw.gov.in/cms/cms/Files/124.pdf
[20] http://www.worldbhc.org/files/full%20program/A6_B6_LopezMorellNavarro.pdf

A higher HHI score for a mineral indicates fewer countries extract this mineral, thus leading to greater supply risk. Further, the supply risk becomes greater if the supplying countries have poor governance systems, and it gets partially offset if the supplying countries have better governance regimes. The quality of governance has been measured using the World Bank's Worldwide Governance Indicators (WGI)[21]. Country-wise, mineral extraction data is taken from World Mining Data (WMD)[22] and the United States Geological Survey (USGS)[23], where there is no data in WMD, and Indian sourcing of minerals is taken from the Indian Bureau of Mines and the World Bank WITS database[24].

The governance and market concentration supply risk is offset by two factors: the import reliance of the mineral in India and the rate of end-of-life recycling in the country. For a mineral with low import reliance, the global extraction concentration becomes less relevant. Similarly, for a mineral with high recycling in the country, the supply risk is lessened. The computation of the supply risk is given in Equation 3. Data on end-of-life recycling was taken from various published sources, including Indian government publications (Annex 4). Due to the lack of data availability on recycling rates of many minerals in India, instead of using the actual recycling rates, a score is given based on the level of recycling (Table 3).

Table 3: Recycling Scores

Level of recycling	Score
Almost no recycling	0.00
Some recycling	0.33
Mostly recycled	0.67
Almost all recycled	1.00

Equation 3: Supply risk

$$SR_G = \left[(HHI_{WGI})_{GS} \times \frac{IR}{2} + (HHI_{WGI})_{India} \times \left(1 - \frac{IR}{2}\right)\right] \times (1 - \rho)$$

SR_G is the supply risk taking governance issues into consideration. is the Herfindahl–Hirschman Index of mineral concentration, and accounting for the world governance indicators (Equation 4), is the end-of-life recycling rate of the mineral, ranging from 0 to 1, and represents the import reliance of the minerals (Equation 5). represents the concentration of global supply of minerals, while considers only the concentration of Indian sourcing.

Equation 4: Herfindahl-Hirschman Index

$$HHI_{WGI} = \sum_c S_c^2 WGI_c$$

The HHI is computed by taking summing the squares of the share of mineral extraction by country. In addition, the governance score of the countries is accounted for. In Equation 4, represents the share of mineral extraction in country c, and the world governance indicator score for country c. The HHI equation was used twice: the first to compute the concentration of global supply of minerals and the second to compute the concentration of Indian sourcing of mineral imports by country.

The WGI data give six dimensions of governance for each country: Voice and Accountability; Political Stability and Absence of Violence; Government Effectiveness; Regulatory Quality; Rule of Law; and Control of Corruption. These dimensions are measured on a range of -2.5 to 2.5. For this CMA study, the arithmetic mean of the scores was normalised (using a min-max transformation) with frontier values of

[21] https://info.worldbank.org/governance/wgi/
[22] https://www.world-mining-data.info/
[23] https://www.usgs.gov/centers/nmic/commodity-statistics-and-information
[24] https://wits.worldbank.org/

-2.5 and 2.5 such that all scores ranged from 0 to 100. Additionally, the scores were inverted, such that 0 represented the best-performing country and 100 the worst. This was done so that a higher score would increase the supply risk of the mineral.

Equation 5: Import Reliance

$$IR = \frac{import - export}{domestic\ production + import - export}$$

The computation of import reliance is given in Equation 5. The import reliance is 100% for some of the minerals which are not extracted in India. The IBM yearbook provided information on the self-reliance of some minerals considered in this study, which was used to find the import reliance (Annex 5).

In addition to the computation of supply risks due to quality of governance, the study attempted to evaluate the supply risks due to environmental risks. Equations 3 and 4 were used to compute the environmental supply risks () which would account for the extracting and supplying countries' performance on sustainability issues. The Environmental Performance Index[25] (EPI) was used for this indicator. However, it was seen that there is a high correlation between the EPI and WGI datasets (0.78 correlation), and an even higher correlation between and (0.98 correlation). Thus, only the governance supply risk results have been taken. Annex 6 provides the results of both.

4. Results

The results of the critical minerals assessment is given in Table 4. The supply risk and economic importance of the eleven minerals are shown, with higher values indicated in red and lower values in green. The supply risk broadly measures the concentration of mineral extraction and processing, and the economic importance broadly measures the share of manufacturing value add foregone in the absence of the mineral's availability.

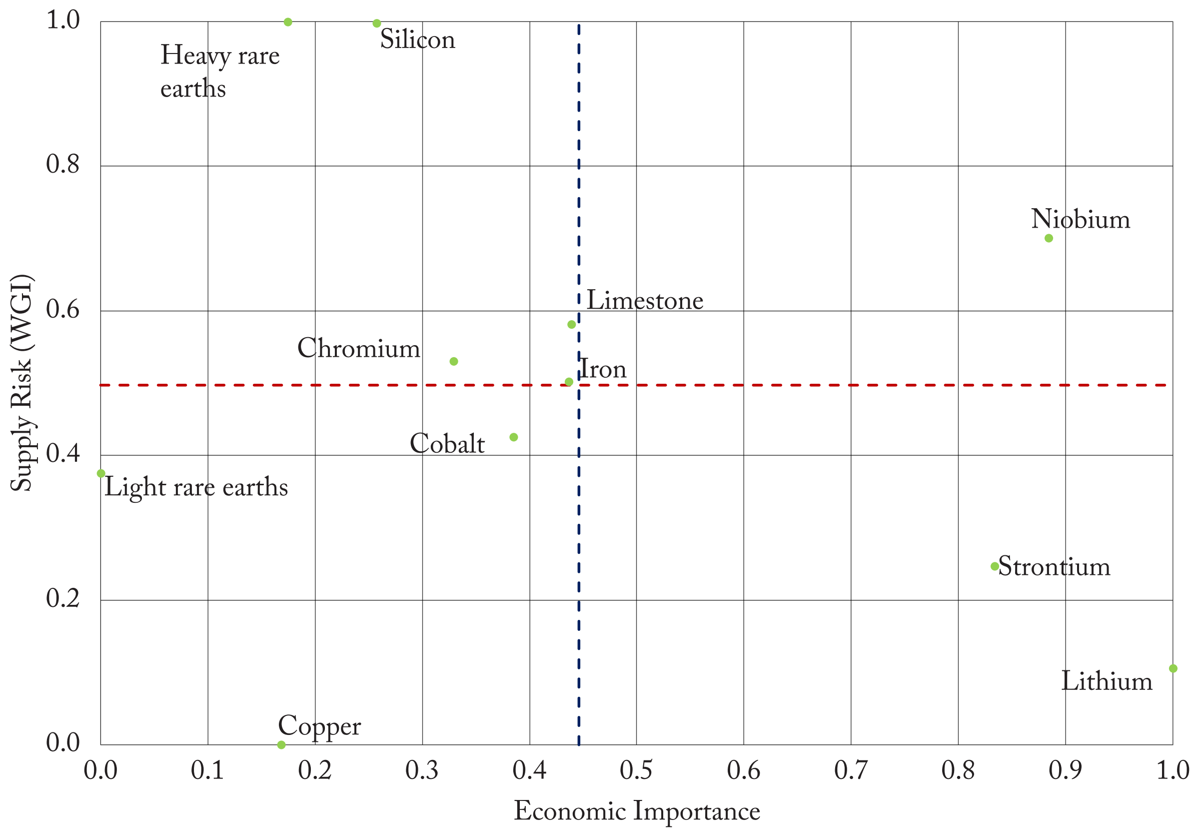
Table 4: Results of Critical Minerals Assessment

Mineral	Supply Risk (Governance)	Economic Importance
Chromium	23.8	1.0%
Cobalt	20.2	1.1%
Copper	5.8	0.6%
Iron	22.8	1.2%
Limestone	25.5	1.2%
Lithium	9.4	2.4%
Niobium	29.5	2.2%
Heavy rare earths	51.9	0.7%
Light rare earths	18.5	0.3%
Silicon	39.6	0.8%
Strontium	14.2	2.1%

The results from Table 4 are shown in a graphical form with the results normalised between 0 and 1 using the min-max transformation. The horizontal and vertical lines in the graph represent the average supply risk and economic importance scores respectively. Minerals in the upper-right quadrant are the most critical with high risk on both axes. In contrast, minerals in the lower-left quadrant are relatively less critical on both counts.

[25] https://epi.yale.edu/epi-results/2020/component/epi

Figure 1: Normalised Results of Critical Minerals Assessment



5. Future Work

- Extend the supply risk computation:
  - Include trade policy factors, such as the trade agreements with extracting and India-sourcing countries, tariffs, and export restrictions.
  - Substitutability affecting supply risk – this would account for the level of production, the criticality, and the production status (i.e., by-product or main product of mining) of the substitutes.
  - Fine-tune the computation considering domestic mineral availability and the grades of the imported minerals.
- Extend the economic importance computation:
  - Use the input-output table to compute the linkages of minerals with the national economy to improve the computation of the economic importance – this would include the indirect impact of the non-availability of a mineral in the economy. The current computation gives only the direct impact.
  - Strategic importance of the mineral-consuming sectors: national security, energy, infrastructure, food security.
- Short-term versus long-term analysis of criticality.
- Extension of the study to include more minerals, particularly of minerals required for industry 4.0 and clean energy technology required to meet India's climate change promises.
- This study may be repeated periodically to account for changes in mineral requirements and technology.

6. Concluding Remarks and Policy Highlights

The discussion note is a work in progress to understand the minerals' criticality in India's context. Each mineral has its risk profile in terms of economic importance, domestic and global availability, substitutability, recycling potential and changing technological dynamics and requirements for the future. Hence such studies are important for gauging the Indian economy's vulnerability to losing out on its desired objectives, including transformation toward electric vehicles, renewable energy, high-tech and IT equipment.

Eleven minerals have been identified for review. The analysis suggests that lithium, niobium and strontium have the highest economic importance, adjusted by their substitutability possibilities. The non-availability of any of the three shall impact more than 2% of the manufacturing-sector GVA. Four out of the eleven minerals have economic importance below 1%. These include light rare-earths (cerium), copper, heavy rare-earths (yttrium and scandium) and silicon. The remaining four, viz. chromium, cobalt, iron ore and limestone each affect 1 to 2% of the manufacturing sector GVA. While cobalt and strontium have some degree of substitutability, other minerals have very low substitution potential, with niobium being non-substitutable at all.

The supply risk, adjusted for the end-of-life recycling rate, is the highest for yttrium and scandium, followed by silicon. However, India does not have a recycling capacity for most of these minerals except for copper and iron, albeit low. Niobium, limestone, iron ore, chromium and cobalt face moderate supply risks, with copper and lithium at the lowest end.

The work-in-progress shall focus on energy and technology critical minerals. COVID-19 has been a wake-up call for monitoring the critical mineral supply chains to ensure adequate clean energy production and high-tech manufacturing.[26] However, the 21st-century need for clean energy and other high-tech equipment are proving to be a challenge due to the economic slump caused by COVID-19. Therefore, India needs to undertake serious research and build a policy framework of being self-reliant in clean energy and high-tech equipment by acting fast on exploring and excavating critical minerals and setting up investments in the downstream value chain of requisite manufacturing equipment at home.[27]

The results of the study will provide policy highlights on ensuring uninterrupted supplies of critical minerals through enhanced domestic mineral exploration and extraction, along with assured sources elsewhere. Particular attention should be given to the deep-seated minerals.[28] Import risks of critical minerals may be reduced through developing resilient supply chains, signing trade agreements, and acquiring mining assets abroad. In addition, the government-to-government engagement efforts through KABIL[29] need to be supplemented with the acquisition of private mines.

[26] https://www.business-standard.com/article/opinion/critical-minerals-for-critical-times-120060101653_1.html
[27] https://csep.org/discussion-note/skewed-critical-minerals-global-supply-chains-post-covid-19/
[28] https://www.financialexpress.com/opinion/to-improve-national-security-the-government-must-develop-mining/1556036/
[29] KABIL (Khanij Bidesh India Ltd.) is a joint venture between three public companies: NALCO, HCL, and MECL.

Annex 1: Manufacturing Sectors at NIC 2-digit level

NIC 2-digit	Description
10	Food products
11	Beverages
12	Tobacco products
13	Textiles
14	Wearing apparel
15	Leather and leather products
16	Wood and wood products except furniture
17	Paper products
18	Printing
19	Coke and refined petroleum
20	Chemicals and chemical products
21	Pharmaceuticals, medicinal chemical and botanical products
22	Rubber and plastics products
23	Other non-metallic mineral products
24	Basic metals
25	Fabricated metal products, except machinery and equipment
26	Computer, electronic and optical products
27	Electrical equipment
28	Machinery and equipment n.e.c.
29	Motor vehicles, trailers and semi-trailers
30	Other transport equipment
31	Furniture
32	Other manufacturing

Annex 2: National Product Classification for Manufacturing Sector (NPCMS)[30] Codes of Selected Minerals

NPC	Minerals	Description	Type
1429001	Chromium	Chrome lead	Ore
1429002	Chromium	Chrome ore and concentrate	Ore
1424001	Chromium	Chromium ore and concentrate	Ore
3424016	Chromium	Basic chromium sulphate	Chemical
4111300	Chromium	Ferro-chromium/ Ferro-chrome	Ferro
1429011	Cobalt	Cobalt ore and concentrate	Ore
3424023	Cobalt	Cobalt chloride	Chemical
3424024	Cobalt	Cobalt phosphate	Chemical
3425011	Cobalt	Cobalt acetate	Chemical
4111503	Cobalt	Ferro cobalt	Ferro
1421000	Copper	Copper, ores and concentrates	Ore
3422002	Copper	Copper oxide	Chemical
3424025	Copper	Copper sulphate	Chemical
3466204	Copper	Copper oxychloride	Chemical
1410001	Iron	Iron ores, Hematite	Ore
1410003	Iron	Iron ore, Magnetite	Ore
1410099	Iron	Iron ores n.e.c	Ore
3422004	Iron	Iron hydroxide	Chemical
3422005	Iron	Iron oxide	Chemical
1520006	Limestone	Lime stone	Ore
1520007	Limestone	Lime anbuz	Ore
1520008	Limestone	Lime powder	Ore
1520099	Limestone	manufacture of lime or cement; n.e.c	Ore
3424028	Lithium	Lithium bromide	Chemical
3424029	Lithium	Lithium carbonate	Chemical
3424030	Lithium	Lithium chloride	Chemical
3424031	Lithium	Lithium compounds	Chemical
4111506	Niobium	Ferro niobium	Ferro
3429000	Heavy rare earths	Compounds of rare earth metals, of yttrium or of scandium	Chemical
3899502	Light rare earths	Ferro cerium & others pyrotechnic products	Ferro
1513007	Silicon	Silica	Ore
3427001	Silicon	Alkali silicate	Chemical
3427003	Silicon	Calcium silicate hydrated	Chemical
3427005	Silicon	Potassium silicate	Chemical
3427008	Silicon	Sodium silicate	Chemical
4111513	Silicon	Ferro silicon	Ferro
1540015	Silicon	Silica clay	Ore
3416017	Silicon	Ethyl silicate	Chemical
3526050	Silicon	Magnesium trisilicate	Chemical
3421018	Strontium	Strontium nitrate	Chemical

[30] http://mospi.nic.in/sites/default/files/main_menu/national_product_classification/NPC-MS_21sep11.pdf

Annex 3: Cost-Performance Scores for Substitutability

Mineral	Substitutability Index
Chromium	0.901
Cobalt	0.802
Copper	0.898
Iron	0.896
Limestone	0.876
Lithium	0.946
Niobium	1.000
Heavy Rare Earth	0.938
Light Rare Earth	0.970
Silicon	0.944
Strontium	0.766

The substitutability index is the average cost-performance substitutability score weighted by the shares of mineral consumption by two-digit NIC sectors. Higher values indicate that the mineral is less substitutable in the economy, with a maximum score of 1.0 (not substitutable), and a minimum score of 0.6 (highly substitutable).

For various use cases of minerals, information was not easily available on its substitutability. In these cases, the end-use is given as 'INA' (information not available) and the cost-performance score is given as 1.0.

Mineral	End-Use	Substitutes	Notes	Cost / Performance
Chromium	Stainless steel[31] (24)	Silicon and aluminium[32] Phosphorous and tin[33] Molybdenum, silicon, and aluminium[34] Aluminium and manganese[35]	Chromium is price competitive and provides good material properties. 50% can be substituted for similar results.	0.9 Slightly higher cost and similar performance
	Basic chemical elements	INA		1.0
	Chemical products or preparations of a kind used in the textiles, paper, leather and like industries (20297)	Aluminium, zirconium, titanium, and synthetic organic compounds[36]	"80% of global leather production is chrome tanned. Alternatives are generally more expensive and produce different leather characteristics."[37] Need to investigate use in textiles and paper industries?	0.9 More expensive and different results
	Metal cable and other articles made of wire (25993)	INA	Nichrome – unable to find a direct substitute	1.0
	Other refractory articles (not elsewhere classified) (23919)	INA		1.0
	Machine tools for turning, drilling, milling, shaping, planning, boring, grinding etc. (28221)	Nickel-tungsten[38 39 40]	Similar performance, but price is unknown (assuming slightly higher)	0.8 Similar performance, slightly higher price
	Diverse parts and accessories for motor vehicles (29301)			

[31] https://www.aalco.co.uk/datasheets/Stainless-Steel-Alloying-Elements-in-Stainless-Steel_98.ashx
[32] https://inis.iaea.org/search/search.aspx?orig_q=RN:19054403
[33] https://www.pfonline.com/articles/identifying-new-alternatives-for-chromium-plating
[34] https://link.springer.com/article/10.1007/BF02833547
[35] https://link.springer.com/chapter/10.1007/978-3-319-16919-4_27
[36] https://www.afirm-group.com/wp-content/uploads/2019/09/afirm_chromium_VI_v2.pdf
[37] Ibid.
[38] https://www.sifcoasc.com/hard-chrome-plating-alternatives/
[39] https://www.sharrettsplating.com/blog/exploring-safer-alternatives-chrome-plating/
[40] https://www.sciencedirect.com/science/article/abs/pii/S0257897213012140

Mineral	End-Use	Substitutes	Notes	Cost / Performance
Cobalt	Hot-rolled and cold-rolled products of steel (24105)	Niobium / nitrogen / aluminium[41] for high-speed steel	Niobium is the best choice as cobalt will become more expensive due to demand in battery sector.	0.8 Reduced performance, lower cost.
	bone plates and screws, syringes, needles, catheters, cannula (32504)	Titanium (dentures)[42], ceramics / polymers / titanium alloys[43]	Titanium seems to be cheaper and performs better.	0.6 Better performance, lower cost.
	organic and inorganic chemical compounds n.e.c. (20119)	INA		1.0
	insecticides, rodenticides, fungicides, herbicides (20211)	INA		1.0
	Graphite products other than electrical articles (23994)	INA		1.0
	various other chemical products n.e.c. (20299)	INA		1.0
	tanning or dying extracts (20113)	Chromium / nickel / copper	Can be used in pigments / dyes[44]	0.7 Similar performance and similar price
	chemical products or preparations of a kind used in the textiles, paper, leather and like industries (20297)			
	other electrical equipment (27900)	INA		1.0
	Building of pleasure and sporting boats (30120)	INA		1.0
	motor vehicle electrical equipment (29304)			
	other plastics products (22209)	INA		1.0
	magnetic and optical media (26800)	Neodymium[45]	Provides savings, but different thermal properties.	0.8 Reduced performance, lower price.
	Other articles n.e.c. (32909)	INA		1.0

41 https://uu.diva-portal.org/smash/get/diva2:1225258/FULLTEXT02.pdf
42 https://www.sciencedirect.com/science/article/pii/S2352003516000022
43 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6384837/
44 https://www.afirm-group.com/wp-content/uploads/2018/01/afirm_metals_extractable.pdf
45 https://www.mceproducts.com/Knowledge_Base/Articles/About_Substituting_Magnet_Materials.htm

Mineral	End-Use	Substitutes	Notes	Cost / Performance
Copper	Copper metals (24201)	Aluminium / optical fibre / plastics[46]		0.9 Reduced performance, slightly higher price
	pumps, compressors, taps and valves (28132)	Polyethylene (PEX)[47] [48]		0.7 Similar performance, lower price
	electricity distribution and control apparatus (27104)	Aluminium[49]	Aluminium can be used instead of copper in wiring but with reduced electrical and thermal performances.[50]	0.8 Reduced performance, lower cost
	electric power distribution transformers etc (27102)			
	other electronic and electric wires and cables (27320)			
	fabricated metal products n.e.c. (25999)	INA		1.0
	insecticides, rodenticides, fungicides, herbicides (20211)	INA		1.0
	inorganic acids except nitric acid (20112)	INA		1.0
	diverse parts and accessories for motor vehicles (29301)	INA		1.0

46 https://ibm.gov.in/writereaddata/files/10142020121913Copper_2019_AR.pdf
47 https://www.sciencedirect.com/science/article/abs/pii/S0959652616311313
48 https://ibm.gov.in/writereaddata/files/10142020121913Copper_2019_AR.pdf
49 https://ibm.gov.in/writereaddata/files/10142020121913Copper_2019_AR.pdf
50 https://www.sciencedaily.com/releases/2011/02/110207124035.htm

Mineral	End-Use	Substitutes	Notes	Cost / Performance
Iron	basic iron and steel (2410)	Timber[51] / composites (Fibre Reinforced Plastics)[52] / bamboo[53] / aluminium / glass reinforced polyester (GRP)[54]	Use cases vary	0.9 Reduced performance, slightly higher price
	tubes, pipes and hollow profiles and of tube or pipe fittings of cast-iron/cast-steel (24311)	PEX / copper / PVC / brass[55]		0.7 Similar performance, similar price
	other iron and steel casting and products thereof (24319)	INA		1.0
	Portland cement, aluminous cement, slag cement and similar hydraulic cement (23942)	Alumina[56 57]	Fluxing agent.	0.7 Similar performance, similar price
	clinkers and cement (23941)			
	other structural metal products (24119)	INA		1.0
	parts and accessories of bodies for motor vehicles (29302)	Aluminium[58]		0.8 Similar performance, lower price
	Production of coke and semi-coke products (19101)	INA		1.0
	other structural metal products (25119)	Timber / plastics / composites[59]		0.8 Similar performance, slightly higher price

51 https://www.vox.com/energy-and-environment/2020/1/15/21058051/climate-change-building-materials-mass-timber-cross-laminated-clt
52 https://science.howstuffworks.com/engineering/structural/steel-best-material-for-building.htm
53 https://www.sciencedirect.com/science/article/pii/S2214509515300048
54 https://www.sciencedirect.com/science/article/abs/pii/S0921509305009512
55 https://www.thespruce.com/guide-on-how-to-choose-the-right-plumbing-pipe-844858
56 https://www.engr.psu.edu/ce/courses/ce584/concrete/library/construction/curing/Composition%20of%20cement.htm
57 https://www.hindawi.com/journals/amse/2016/1596047/
58 https://www.sciencedirect.com/science/article/pii/S2588840418300301
59 https://science.howstuffworks.com/engineering/structural/steel-best-material-for-building.htm

Mineral	End-Use	Substitutes	Notes	Cost / Performance
Limestone	Manufacture of cement, lime and plaster & articles of concrete, cement and plaster (2394 & 2395)	Pulverised fly ash (from coal) / Ground Granulated Blast-furnace Slag / silica / glass / plastic / gypsum[60 61 62]	Rather than finding substitute for limestone in cement, there are substitutes for the use of limestone-based cement.	0.9 Reduced performance, slightly higher cost
	Basic iron and steel (2410)	Dolomite[63 64 65]		0.8 Reduced performance, similar price
	organic and inorganic chemical compounds n.e.c. (20119)	INA		1.0
	Soap and detergents, cleaning and polishing preparations, perfumes and toilet preparations (2023)	INA		1.0
	prepared animal feeds (1080)	Calcium supplements[66] / dolomite	Dolomite is not appropriate for all animal feeds	0.9 Similar performance, much higher cost
	printing, writing and photocopying paper ready for use (17093)	Dolomite[67]		0.8 Similar performance, slightly higher cost
	tobacco products (1200)	INA		1.0
	other plastics products n.e.c. (22209)	INA		1.0

60 https://www.sciencedirect.com/topics/engineering/cement-replacement-material
61 https://www.constrofacilitator.com/alternative-cement-substitutes-materials/
62 https://www.specifyconcrete.org/blog/eco-friendly-alternatives-to-traditional-concrete
63 https://www.ispatguru.com/limestone-and-dolomite-flux-and-their-use-in-iron-and-steel-plant/
64 https://core.ac.uk/download/pdf/10208934.pdf
65 https://www.mdpi.com/2075-4701/8/9/686/pdf
66 https://www.feedipedia.org/node/59
67 www.sciencedirect.com/science/article/pii/S1110062116301611

Mineral	End-Use	Substitutes	Notes	Cost / Performance
Lithium	steam or other vapour generating boilers and hot water boilers other than central heating boilers (25131)	INA		1.0
	pharmaceuticals, medicinal chemical and botanical products (2100)	Other medication[68]	Some medicines use lithium – primarily mood disorders	0.9 Similar price, reduced performance
	refined petroleum products (1920)	INA		1.0
	basic chemicals (2011)	INA		1.0
	various other chemical products n.e.c. (20299)	INA		1.0
	glass and glass products (2310)	Magnesia[69], soda[70]		0.8 Reduced performance, similar price
Mineral	**End-Use**	**Substitutes**	**Notes**	**Cost / Performance**
Niobium	steel in ingots or other primary forms, and other semifinished products of steel (24103)	Tantalum[71], vanadium[72]		1.0 Reduced performance, much higher price
	hot- and cold-rolled products of steel (24105)			
	pig iron and spiegeleisen (24101)			

68 https://www.drugs.com/compare/lithium
69 https://www.researchgate.net/publication/223381925_The_influence_of_lithia_content_on_the_properties_of_fluorphlogopite_glass-ceramics_II_Microstructure_hardness_and_machinability
70 https://ceramics.onlinelibrary.wiley.com/doi/abs/10.1111/j.1151-2916.1943.tb15192.x
71 https://www.vanadiumprice.com/vanadium-and-niobium-substitute-date-april-26-2019/
72 https://www.worldscientific.com/doi/10.1142/9789813271050_0010

Mineral	End-Use	Substitutes	Notes	Cost / Performance
Light rare earths	Casting of iron and steel (2431)	Substitute not available[73]		1.0 No substitute available
Heavy rare earths	Manufacture of other non-ferrous metals (24209)	Substitute not available[74]		1.0 No substitute available
Heavy rare earths	organic and inorganic chemical compounds n.e.c. (20119)	INA		1.0
Heavy rare earths	paints and varnishes, enamels or lacquers (20221)	Chromium[75]		0.9 Reduced performance
Light rare earths	refractory bricks, blocks tiles and similar refractory ceramic constructional goods (23912)	INA		1.0
Light rare earths	hollow glassware (bottles, jars etc.) for the conveyance or packing of goods (23103)	Zirconium[76]		0.8 Similar performance, higher price
Light rare earths	articles of personal use such as cigarette lighters (32904)	INA	Used for flints.	1.0

[73] https://www.researchgate.net/publication/248269439_Effect_of_cerium_on_the_as-cast_microstructure_of_a_hypereutectic_high_chromium_cast_iron
[74] https://www.miragenews.com/tsu-suggested-how-to-replace-scandium-in-materials-for-shipbuilding/
[75] https://www.sciencedirect.com/science/article/abs/pii/S0026057607805472
[76] https://www.euspen.eu/knowledge-base/ICE12247.pdf

Mineral	End-Use	Substitutes	Notes	Cost / Performance
Strontium	allopathic pharmaceutical preparations (21002)	Phosphorous[77]	Treatment of osteoporosis[78]	0.7 Similar performance, similar price
	Aluminium from alumina and by other methods and products of aluminium and alloys (24202)	Sodium[79]		0.8 Reduced performance, lower price
	Casting of non-ferrous metals (24320)			
	parts and accessories of three wheelers and motorcycles (30913)	INA		1.0
	biscuits, cakes, pastries, rusks etc. (10712)	INA		1.0

[77] https://www.mayoclinic.org/diseases-conditions/osteoporosis/in-depth/osteoporosis-treatment/art-20046869
[78] https://pubmed.ncbi.nlm.nih.gov/27228273/
[79] https://www.chempap.org/file_access.php?file=356a763.pdf

Mineral	End-Use	Substitutes	Notes	Cost / Performance
Silicon	Manufacture of other textiles/ textile products (13999)	INA		1.0
	other iron and steel casting and products thereof (24319) basic iron and steel (241)	Aluminium / vanadium[80], manganese[81]	Substitute for deoxidiser[82] and strength and hardenability.	0.9 Much higher cost, similar performance
	non-metallic mineral products n.e.c. (239)	INA		1.0
	other chemical products (202)	INA		1.0
	basic chemicals, fertiliser and nitrogen compounds, plastics and synthetic rubber in primary forms (201)	Not substitutable[83] [84]		1.0
	glass and glass products (231)	Not substitutable		1.0
	Electrical equipment (27) electronic components (261)	Gallium / lithium[85]		0.8 Similar performances, slightly higher prices
	basic precious and other non-ferrous metals (242)	INA		1.0
	parts and accessories for motor vehicles (293)	INA		1.0
	special-purpose machinery (282)	INA		1.0
	other fabricated metal products (259)	INA		1.0
	general purpose machinery (281)	INA		1.0
	Food products (10)	Not substitutable[86]		1.0 Not substitutable
	paper and paper products (170)	INA		1.0
	allopathic pharmaceutical preparations (21002)	Not substitutable[87]		1.0 Not substitutable

80 https://www.sciencedirect.com/science/article/pii/B978008051135150011X
81 https://www.ispatguru.com/silicon-in-steels/
82 https://www.sciencedirect.com/topics/engineering/deoxidizer
83 https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.1062.6558&rep=rep1&type=pdf
84 https://www.atamexico.com.mx/wp-content/uploads/2017/11/AGRONOMY-POSTERS-19-Toharisman.pdf
85 https://news.mit.edu/2018/study-flexible-electronics-made-exotic-materials-1008
86 http://massamllc.com/newsite/wp-content/uploads/2013/12/Silicon-in-Animals-Carlslile.pdf
87 https://www.sciencedirect.com/science/article/pii/S0065774308610155

Annex 4: End-of-Life Recycling Rates

Mineral	Recycling Rate	Score
Chromium	5%[88]	0.00
Cobalt	5%[89]	0.00
Copper	20%[90]	0.33
Iron	35%[91]	0.33
Limestone	0% (INA)	0.00
Lithium	0% (INA)	0.00
Niobium	0% (INA)	0.00
Heavy Rare Earths	1%[92]	0.00
Light Rare Earths	1%[93]	0.00
Silicon	0%[94]	0.00
Strontium	0% (INA)	0.00

INA – Information not available

Annex 5: Mineral Import Reliance in India

Mineral	Import Reliance	Source
Chromium	0%	IBM Yearbook 2019[95]
Cobalt	100%	No mining
Copper	61%	IBM Yearbook 2019
Iron	0%	IBM Yearbook 2019
Limestone	0%	IBM Yearbook 2019
Lithium	100%	No mining
Niobium	100%	No mining
Heavy rare earths	13%	IBM Yearbook 2019
Light rare earths	100%	No mining
Silicon	17%	ASI
Strontium	100%	No mining

[88] https://factly.in/review-who-report-raises-concerns-about-the-effects-of-e-waste-exposure-on-child-health/
[89] Ibid.
[90] National Non-Ferrous Metal Scrap Recycling Framework, 2020
[91] Steel Scrap Policy
[92] https://digitalscholarship.unlv.edu/geo_fac_articles/284/
[93] Ibid.
[94] https://timesofindia.indiatimes.com/city/nagpur/tackle-solar-energy-waste-withrecycle-reuse-and-regenerate/articleshow/84510384.cms
[95] https://ibm.gov.in/?c=pages&m=index&id=1473

Annex 6: Supply Risks – Governance and Environmental

Mineral	Governance	Environmental
Chromium	23.8	29.1
Cobalt	20.2	16.9
Copper	5.8	8.0
Iron	22.8	25.0
Limestone	25.5	30.6
Lithium	9.4	10.6
Niobium	29.5	28.4
Heavy rare earths	51.9	56.8
Light rare earths	18.5	20.1
Silicon	39.6	43.3
Strontium	14.2	12.1

Correlation: 0.983

Independence | Integrity | Impact

Centre for Social and Economic Progress

6, Dr Jose P. Rizal Marg, Chanakyapuri, New Delhi - 110021, India

@CSEP_Org

@csepresearch

www.csep.org