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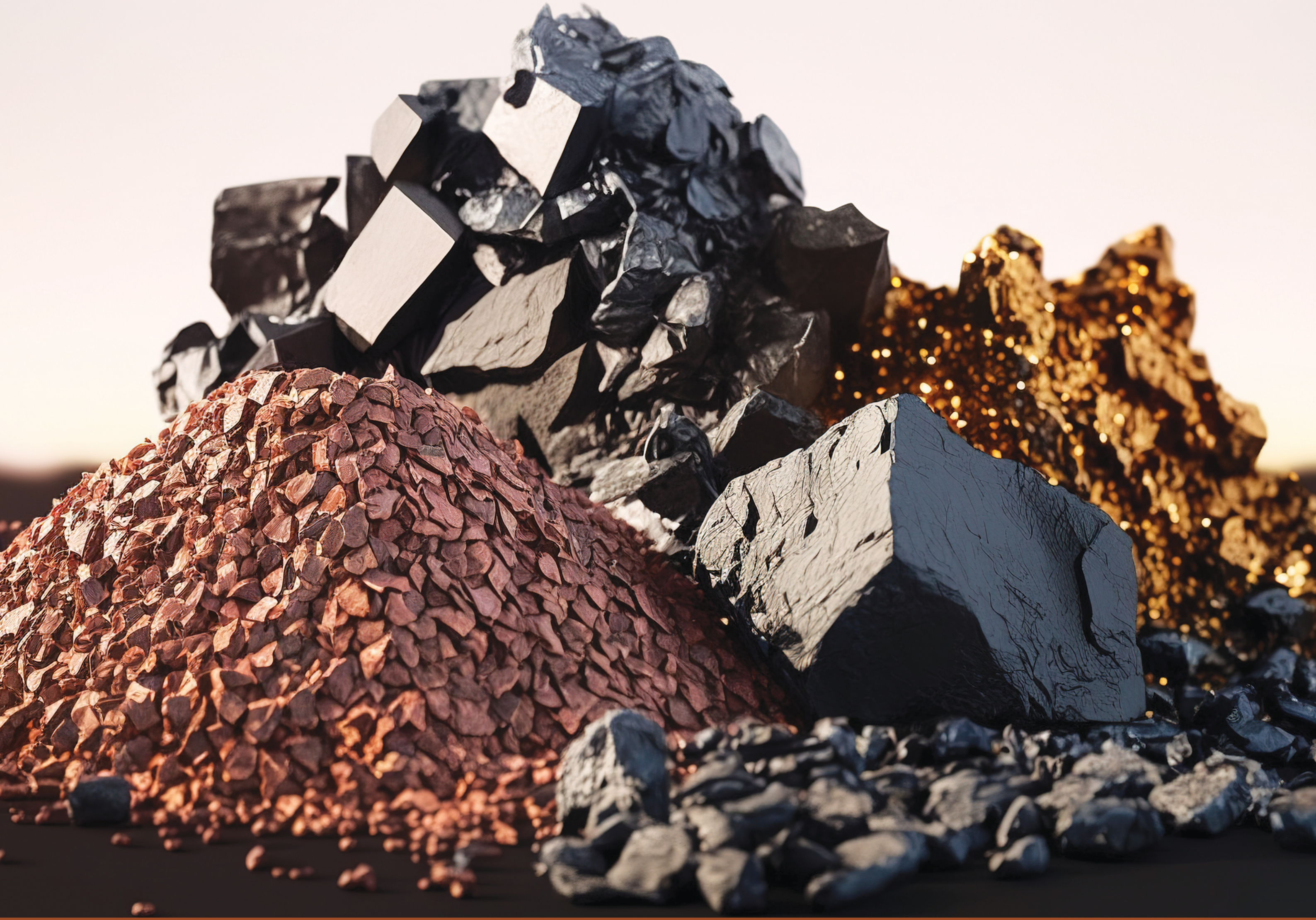
Assessing the Criticality of Minerals for India

2023



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Assessing the Criticality of Minerals for India

2023

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This study is the second edition of Part 1 of the earlier CSEP Working Paper - 19 titled *Critical Minerals for India: Assessing their Criticality and Projecting their Needs for Green Technologies*.

The authors thank Anuj Rajawat for the research assistance provided and CSEP colleagues for their insightful comments and suggestions. We also received valuable comments during the CSEP webinar held on this subject. We sincerely thank Rakesh Mohan and Bishwanath Goldar for their valuable comments and suggestions on the earlier drafts of this paper.

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Abstract

Critical minerals refer to mineral resources, both primary and processed, which are essential inputs in the production process of an economy, and whose supplies are likely to be disrupted due to the risks of non-availability or unaffordable price spikes. This paper extends the earlier assessment of 23 minerals for India by assessing the criticality levels of 43 select minerals for India based on their economic importance and supply risks, which are determined through the evaluation of specific indicators. Minerals such as antimony, cobalt, gallium, graphite, lithium, nickel, niobium, and strontium, among others, are critical for India. Many of these are required to meet green technologies, high-tech equipment, aviation, and national defence manufacturing needs. However, while India has a significant mineral geological potential, many minerals are not readily available domestically. Hence, India needs to develop a national strategy to ensure resilient critical minerals supply chains, which focuses on minerals found to be critical in this study.

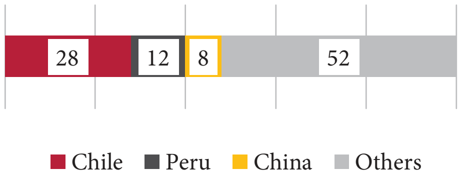
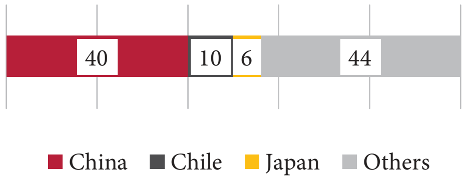
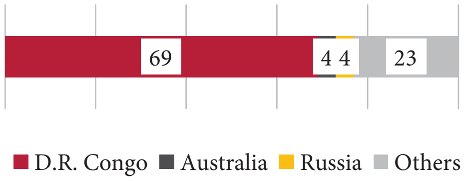
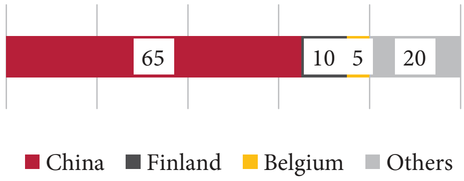
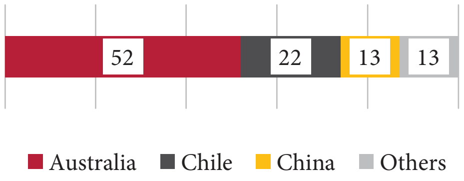
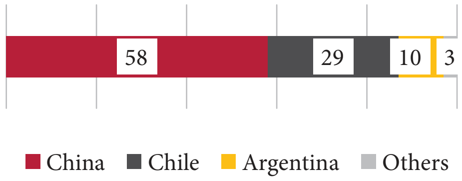
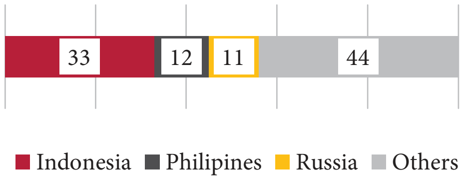
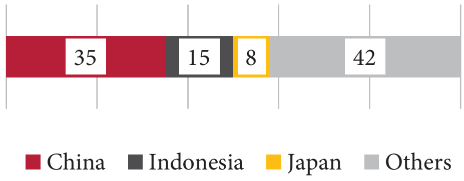
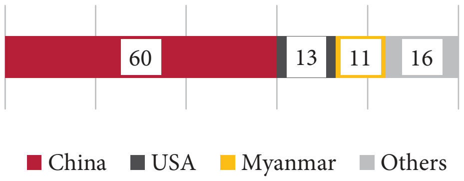
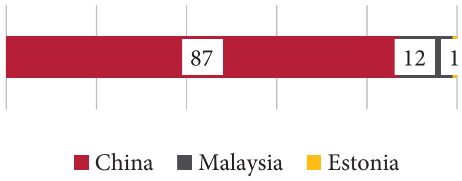
1. Backdrop

The present paper extends the earlier CSEP work (Chadha & Sivamani, 2022) assessing the criticality of minerals by including 20 additional minerals to the earlier 23. Critical minerals, also known as critical raw materials (CRMs), refer to mineral resources, both primary and processed, which are essential inputs in the production process of an economy, and whose supplies could be disrupted by non-availability or unaffordable price spikes. In addition, many of these minerals lack substitutability and recycling processes. While some are inputs for traditional industries, many are crucial for the high-tech products required for clean energy, national defence, informational technology, aviation, and space research. However, the global concentration of extraction and processing activities, the governance regimes, and environmental footprints in resource-abundant countries adversely impact availability risks (Chadha, 2020). Moreover, supply risks have intensified further after COVID-19 and the Russia-Ukraine war. Therefore, India must re-evaluate the criticality of minerals to guide a clear strategy and roadmap to secure resilient critical minerals supply chains.

The International Energy Agency (International Energy Agency (IEA), 2021b) has identified vulnerabilities in resilient supply chains of critical minerals required for the green transition, raising the risks of delayed or more expensive clean energy transitions. The major factors include the high geographical concentration of production and processing, long project development lead times, declining resource quality, growing environmental and social performance scrutiny, and higher exposure to climate risks.

Critical minerals have complex global supply chains with a high concentration in the extracting and processing countries, resulting in high supply risks. For example, China produces 60% of the world's rare earth elements (REEs) and 34% of molybdenum. Around 69% of cobalt is mined in the Democratic Republic of Congo, with China having a majority in processing (65%) of the global mineral supply. Australia produces 52% of the world's lithium, with China being a major importer and processor of 58% of the global supply. South Africa mines 72% of the world's platinum output. Table 1.1 shows the concentration of extraction and processing of some select minerals.

Table 1.1 Geographic Concentration of Extraction and Processing of Select Minerals

<table>
<tr><th>Mineral</th><th>Extraction (%)</th><th>Processing (%)</th></tr>
<tr><td>Copper</td><td> </td><td> </td></tr>
<tr><td>Cobalt</td><td> </td><td> </td></tr>
<tr><td>Lithium</td><td> </td><td> </td></tr>
<tr><td>Nickel</td><td> </td><td> </td></tr>
<tr><td>Rare earth elements</td><td> </td><td> </td></tr>
</table>

Source: International Energy Agency (2022)

India has been taking various measures towards climate change mitigation (Ministry of Environment, Forest and Climate Change, 2021). The Prime Minister's Council on Climate Change announced the National Action Plan on Climate Change (NAPCC) in 2008 to achieve sustainable development aligned with its economic and environmental objectives. In addition, it announced its Nationally Determined Contributions (NDC) in 2015 (Government of India, 2015), which aim to reduce the emission intensity of its GDP by 33-35% in 2030 from 2005 levels. The reduction commitment has further been revised to 45% post-COP26. In addition, India has announced a target of 500 GW of non-fossil-energy capacity and meeting 50% of its energy requirements from renewable energy by 2030. It has also proposed reducing its projected carbon emissions by one billion tonnes from 2021 to 2030. Critical minerals will play an essential role in achieving these goals.

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 (Mathai, 2020). The Russia-Ukraine war has further dented supply chains.

India needs to undertake serious research and build a policy framework for becoming self-reliant in clean energy and high-tech equipment by acting quickly on exploring and excavating critical minerals and setting up investments in the downstream value chains of requisite manufacturing equipment at home or through the foreign acquisition of mining and processing assets (Chadha, 2020). This paper aims to assess the criticality of 43 of these minerals.

2. Assessing the Criticality of Minerals and Raw Materials

Different countries define critical minerals in varying but broadly similar ways. For example, 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" (Skirrow, et al., 2013). In discussing Australia's perspective on critical minerals assessments, Whittle et al. (2020) conclude that the lack of availability of these minerals could disrupt manufacturing operations in Australia. Their criticality arises from the monopolies of extraction or processing by one or a few countries. Australia, in turn, is endowed with minerals deemed critical by other countries, which could 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". Strategic minerals are defined as "a subset of critical minerals and are those that are essential for national security applications" (National Science and Technology Council, 2016).

The European Union refers to critical minerals as critical raw materials (CRMs) 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 (European Commission, 2017). The EU has updated their CRM lists for 2014, 2017, and, most recently, 2020 (European Commission, 2020a).

Table 2.1 lists 56 raw materials and highlights those which are considered critical by some major global economies: the United States, European Union, Japan, Canada, Australia, China, Republic of Korea, and India. For India, the findings of both a Planning Commission report (Planning Commission, 2011) and the Department of Science and Technology & Council on Energy, Environment and Water (DST-CEEW) (Gupta, Biswas & Ganesan, 2016) are shown. Cobalt, lithium, and tungsten are assessed as critical by all eight economies (using the Planning Commission 2011 paper as the critical minerals list for India), while antimony, gallium, germanium, indium, niobium, rare earth elements, and tantalum are critical in seven economies.

Table 2.1: Critical Minerals for Selected Jurisdictions

Minerals	USA	EU	JPN	CAN	AUS	CHN	KOR	IND PC	IND DST
Aluminium	√	√		√		√			
Antimony	√	√	√	√	√	√	√		
Arsenic	√						√		
Barite	√	√					√		√
Beryllium	√	√	√		√		√	√	
Bismuth	√	√		√	√		√	√	
Borate		√					√		√
Caesium	√			√			√		
Chromium	√		√	√	√	√	√		√
Coal						√			
Coal-seam gas						√			
Cobalt	√	√	√	√	√	√	√	√	√
Coking coal		√							
Copper			√	√		√			
Diamond			√						
Fluorite	√	√	√	√		√			
Gallium	√	√	√	√	√		√	√	
Germanium	√	√	√	√	√		√	√	
Gold			√			√			
Graphite	√	√		√	√	√			
Hafnium	√	√			√		√		
Helium	√			√	√				
Indium	√	√	√	√	√		√	√	
Iron						√			
Lead			√						
Limestone									√
Lithium	√	√	√	√	√	√	√	√	√
Magnesium	√	√	√	√	√		√		
Manganese	√		√	√	√		√		
Molybdenum			√	√		√	√		√
Natural gas						√			
Natural rubber		√							
Nickel			√	√		√	√		

Minerals	USA	EU	JPN	CAN	AUS	CHN	KOR	IND PC	IND DST
Niobium	√	√	√	√	√		√	√	√
Oil						√			
Phosphorus		√	√			√	√		√
Platinum group metals	√	√	√	√	√		√		
Potash	√			√		√			√
Rare earth	√	√	√	√	√	√	√		√
Rhenium	√		√		√		√		
Rubidium	√								
Scandium	√	√		√	√				
Selenium							√	√	
Shale gas						√			
Silicon		√					√		√
Silver			√						
Strontium	√	√	√				√		√
Tantalum	√	√	√	√	√		√	√	
Tellurium	√			√			√		
Tin	√		√	√		√	√	√	
Titanium	√	√	√	√	√		√		
Tungsten	√	√	√	√	√	√	√	√	
Uranium	√			√		√			
Vanadium	√	√	√	√	√		√		√
Zinc			√	√					
Zirconium	√		√		√	√	√		

Source: Su & Hu (2022)

While each jurisdiction may use its methodology to assess the criticality of minerals for its economy, some common indicators are used across all frameworks, as shown in Table 2.2. The factors used for measuring the criticality of a mineral can be broadly categorised into supply-side and demand-side. The supply-side factors evaluate the criticality of a mineral from the countries supplying the raw (ore) or processed forms of minerals. The demand-side factors assess the criticality of a mineral based on the domestic situation. Some governments conduct these assessments periodically (usually every 2 to 3 years) to ensure they capture the most current information on geopolitics and economic needs.

Table 2.2: Indicators Used in Critical Minerals Assessments

Supply-side Factors	Demand-side Factors
• The geographic concentration of the mineral – at each stage of the supply chain (extraction, processing, and manufacturing) • Policies of the supplying countries – indicators related to the governance of a country, such as the World Governance Indicators • Relationship with supplying countries– measuring the strength of diplomatic/trade relationships with the supplying countries • Price volatility of the mineral	• Domestic consumption • Value Added by the industries consuming the mineral • Import reliance • Domestic stocks • End-of-life recycling rates • Substitutability of the mineral

2.1 Critical Minerals Assessments for India

The Planning Commission report (Planning Commission, 2011) highlighted the need for the assured availability of mineral resources for the country's industrial growth, stressing the need for the well-planned exploration and management of already discovered resources. It analysed 11 groups of minerals, viz. copper, lead & zinc, aluminium, cement & limestone, diamond & precious stones, gold & precious metals, dimensional & decorative stones, industrial/non-metallic minerals, beach sand minerals (including rare earth elements), *strategic minerals* and ferrous metals (copper was labelled a *strategic metal*, and rare earth elements as *strategic minerals)*. However, a separate group was designated *strategic minerals* (tin, cobalt, lithium, germanium, gallium, indium, niobium, beryllium, tantalum, tungsten, bismuth, and selenium) due to the limited availability of substitutes and the demand for them in high-technology products (such as LCD screens, hybrid cars, wind turbine magnets, and defence equipment). Consequentially, the report emphasised the need to increase their resource efficiency, identify substitutes, and develop end-of-life mineral recycling.

The Planning Commission report included strategies for reducing the criticality of minerals: trade agreements to secure supplies; establishing a national body responsible for sourcing minerals; incentivising domestic producers through fiscal measures; increasing resource efficiency, promoting recycling, and building a national stockpile of identified minerals.

The Ministry of Mines sponsored a study on rare earths, and energy-critical minerals (CSTEP & C-Tempo, 2012) reviewed India's production, consumption, and reserves and suggested policy initiatives and government interventions to propel the growth of the mining sector. The supply chain for minerals broadly consists of exploration, mining, processing, and manufacturing. The study also suggested that initiatives be taken in refining, metal/alloy production, and manufacturing components for end-use.

In their book on strategic minerals, Lele and Bhardwaj (2014) analysed the availability, requirements, utility, and deficiency of nine strategic minerals in India: antimony, bismuth, beryllium, cobalt, germanium, lithium, nickel, tungsten, and tin. They used Porter's Five Forces Model to assess the strength and attractiveness of the markets for these minerals and the risk factors based on psychometric assessment (using the Likert scale). Porter's model, however, offers a qualitative analysis of the market, and hence, the results are not considered conclusive. A subsequent study (Lele, 2019) discusses India's need for strategic minerals, the importance of these minerals for green energy transition, and the various challenges the sector faces, including in mining and processing. In addition, it recommends the need for research in recycling strategic minerals and finding appropriate substitutes.

A study sponsored by the Department of Science and Technology and the Council on Energy, Environment and Water (DST-CEEW) (Gupta, Biswas, & Ganesan, 2016) highlighted the lack of research in India related to ensuring mineral resource security for the manufacturing sector. It pioneered computing a criticality index for 49 non-fuel minerals, including rare earth minerals. A mineral used in small quantities in a high-value-add manufacturing sector is considered more critical than a mineral used in large amounts in a low-value-add manufacturing sector. The supply-side risks for a mineral are based on the domestic endowment, the geopolitical risks of its trade, and its substitutability and recycling potential. The study identified 13 minerals that would become most critical by 2030, of which 6 were critical even in 2011 (the reference year).[1] It recommended that India undertake the institutional reforms outlined in the National Mineral Exploration Policy (NMEP) 2016. These include the creation of a not-for-profit National Centre for Mineral Targeting (NCMT), enhanced exploration and R&D in mining and mineral processing technologies, strategic acquisition of mines abroad, and signing of diplomatic and trade agreements to ensure a constant supply of critical minerals (Ministry of Mines, 2016).

The National Mineral Policy of 2019 (Ministry of Mines, 2019) emphasises the need to explore fertiliser, strategic, and precious metals and stones, for which India mainly relies on imports.

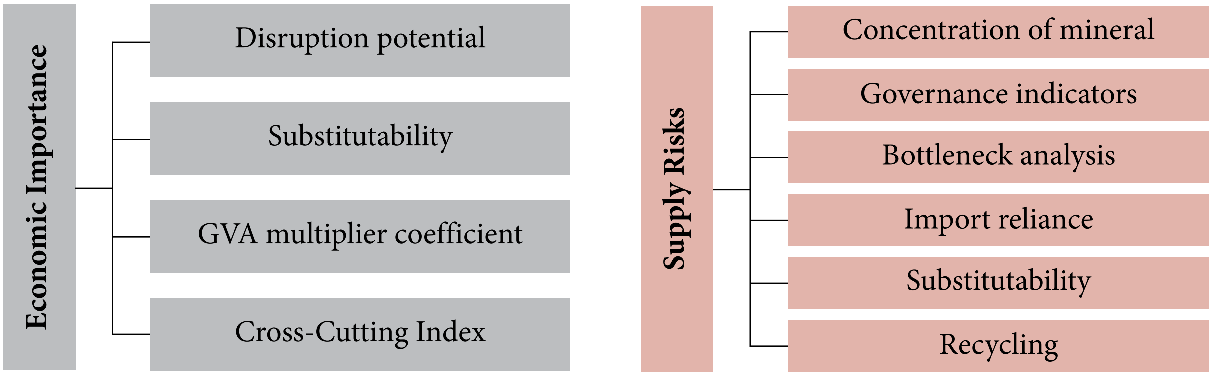
The CSEP working paper (Chadha & Sivamani, 2022) conducts a critical minerals assessment for India in 2019, a modified version of the EU assessment. The paper followed up on a discussion note, "Skewed Critical Minerals Global Supply Chains Post COVID-19" (Chadha, 2020), highlighting the importance of simultaneously developing the entire mineral value chain.

The present CSEP paper evaluates the criticality of 43 non-fuel minerals in India. Some are found in surficial deposits (such as iron ore and bauxite), while others are in deep-seated deposits (such as rare earth elements and copper). This study uses the EU methodology (European Commission, 2017) with some modifications.

3. Methodology

This study evaluates the criticality of 43 minerals based on two dimensions: economic importance for the Indian economy and supply risks. Figure 1 details the indicators used to compute the criticality computed for the two dimensions.

Figure 3.1 Dimensions and Indicators



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[1] Minerals that were critical in 2011 and will continue to be so in 2030 are chromium, limestone, niobium, light rare earths, silicon, and strontium. Minerals which would become critical by 2030 are rhenium, beryllium, heavy rare earths, germanium, graphite, tantalum, and zirconium.

3.1 Choice of Minerals

Table 3.1 and Figure 3.2 highlight the 43 minerals considered critical globally and in India and provide their key uses and the causes of their criticality. Many of the minerals included in this study are needed to manufacture clean energy technologies like wind turbines, solar PVs, and electric vehicles. Others are required for national defence, informational technology, aviation, and space research. Detailed information regarding the characteristics of the minerals and their respective criticality levels is provided in the Addendum to this paper.

The choice of minerals is based on minerals found critical in other jurisdictions and in the earlier studies for India. As the purview of this study is non-fuel minerals, seven fuel minerals (including uranium) listed in Table 2.1 have not been included, and natural rubber has been excluded as it is not a mineral. In addition, four minerals, viz. arsenic, caesium, rubidium, and tellurium, have not been considered as there is limited data on their consumption in India.

Table 3.1 Characteristics of Selected Minerals

Mineral	Uses	Type of Extraction	Main Producers	India Availability
Antimony	• Flame Retardants • Lead Alloy • Lead-Acid Batteries	Primary	China Tajikistan Russia	Reserves
Barium	• Drilling of Oil and Gas • Rubbers, Plastic and Paints	Primary	India China Morocco	Production
Bauxite	• Aluminium Production • Cement	Primary	Australia Guinea China	Production
Beryllium	• Automotive Components: Transport and Defence • Manufacturing of Machinery	Primary	United States China Madagascar	N/A
Bismuth	• Pharmaceuticals • Iron Casting	By-product	China Vietnam Japan	N/A
Boron	• Fertilisers • Glass and Ceramics	Primary	Turkey United States Chile	Resources
Chromium	• Stainless Steel and Alloy Steel • Dyes and Pigments	Primary	South Africa Kazakhstan India	Production
Cobalt	• Li-ion Batteries • Pigments and Dyes	By-product; co-product	Congo, D.R. Russia Australia	Resources
Copper	• Electronic Components • Automotive Industry	Primary	Chile Peru China	Production

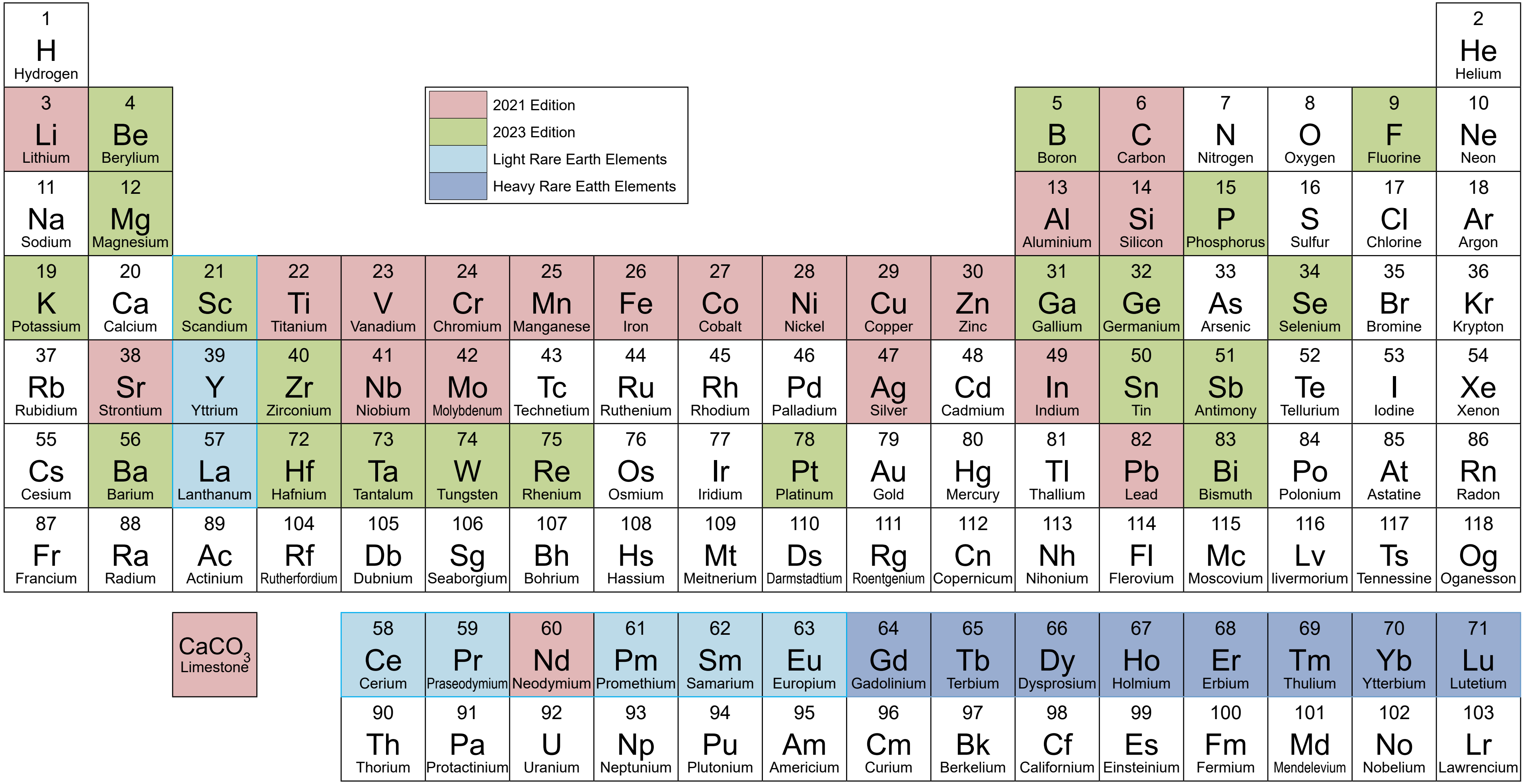
Fluorite	● Refrigerators and Air Conditioners ● Aluminium Production	Primary	China Mexico Mongolia	Production
Gallium	● Integrated Circuits ● LEDs	By-product	China Russia Ukraine	Potential
Germanium	● Fibre and Infrared Optics ● Solar Cells	By-product	China Russia Japan	N/A
Graphite	● Lubricants ● Batteries	Primary	China Brazil Madagascar	Production
Hafnium	● Nuclear Reactors ● Alloying Agents for Magnesium, Cobalt, Chromium	By-product; co-product	France United States Russia Ukraine	N/A
Heavy rare earths	● Electrical Equipment ● Alloying Agent for Iron and other ferrous metals	Primary; co-product	Myanmar Australia Russia	Some Resources
Indium	● Electrical Components and Semiconductors	By-product	China South Korea Japan	N/A
Iron	● Construction ● Automotive Industry	Primary	Australia Brazil China	Production
Lead	● Batteries ● Defence	Co-product	China Australia Mexico	Production
Light rare earths	● Electronic Appliances ● Pharmaceuticals	Primary; co-product	China United States Myanmar	Some Resources
Limestone	● Cement and Concrete ● Paper, Plastics and Rubber	Primary	China United States India	Production
Lithium	● Batteries ● Lubricant ● Glass and Ceramics	Primary	Australia Chile China	Potential
Magnesium	● Aluminium Alloys ● Automotive Industry	Primary	China Turkey Brazil	Production
Manganese	● Alloyed in Steel and Aluminium ● Batteries	Primary	South Africa Gabon Australia	Production

Molybdenum	● Alloys of Steel ● Pigments and Dyes	Primary	China Chile United States	Production
Neodymium	● Magnets ● Glass	Primary	China United States Myanmar	N/A
Nickel	● Construction ● Automotive Industry	Primary	Indonesia Philippines Russia	Resources
Niobium	● Construction ● Automotive Industry	Primary	Brazil Canada Russia	N/A
Phosphorus	● Animal Feed ● Fertilisers	Primary	China Morocco United States	Production
Platinum group metals	● Automotive Catalysts ● Jewellery	Primary	South Africa Russia Zimbabwe	Resources
Potash	● Fertilisers ● Water Softeners	Primary	Canada Russia Belarus	Resources
Rhenium	● Superalloys ● Aerospace	By-product	Chile United States Poland	N/A
Scandium	● Aluminium Alloys ● Electronics	Primary; by-product	China Russia United States	N/A
Selenium	● Electrolytic Manganese ● Glass	By-product	China Japan Germany	N/A
Silicon	● Paints ● Aluminium Alloys	Primary	China Russia Brazil	Production
Silver	● Jewellery ● Paints	By-product	Mexico China Peru	Production
Strontium	● Magnets ● Pyrotechnic Applications	Primary	Spain Iran China	N/A
Tantalum	● Electronic Micro-capacitors ● Medical Technology	Primary; co-product	Congo, D.R. Brazil Rwanda	N/A
Tin	● Solders ● Metal Packaging	Primary	China Indonesia Myanmar	Production

Titanium	● Paints ● Polymers	Primary; co-product	China South Africa Mozambique	Production
Tungsten	● Construction ● Aeronautics	Primary	China Vietnam Russia	Resources
Vanadium	● Alloys in Iron and Steel ● Batteries	Co-product	China Russia South Africa	Resources
Zinc	● Zinc Galvanising of metals ● Alloys in copper, Aluminium, Magnesium	Co-product	China Peru Australia	Production
Zirconium	● Nuclear Reactor Fuels ● Ceramics Industry	Primary	Australia South Africa China	Production

Sources: European Commission (2020b), European Commission (2020c), Reichl & Schatz (2022), India Bureau of Mines (2022)

Figure 3.2 Selected Minerals in the Periodic Table

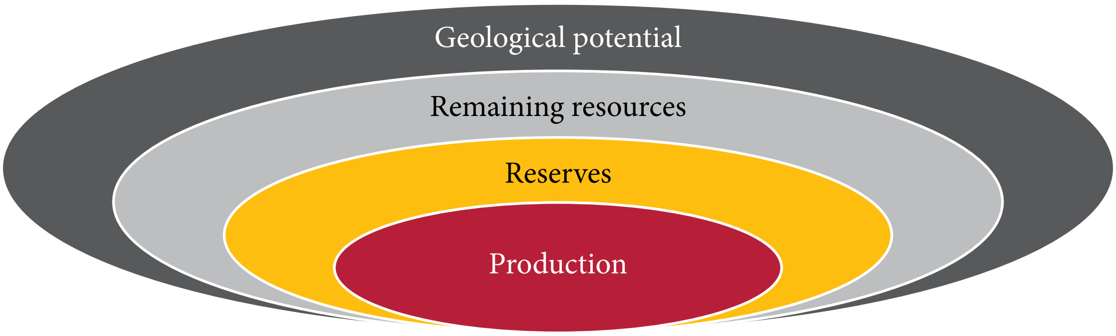


🟥 2021 Edition
🟩 2023 Edition
🟦 Light Rare Earth Elements
▦ Heavy Rare Eatth Elements

1 H Hydrogen																	2 He Helium
3 Li Lithium	4 Be Berylium											5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
11 Na Sodium	12 Mg Magnesium											13 Al Aluminium	14 Si Silicon	15 P Phosphorus	16 S Sulfur	17 Cl Chlorine	18 Ar Argon
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton
37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon
55 Cs Cesium	56 Ba Barium	57 La Lanthanum	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
87 Fr Francium	88 Ra Radium	89 Ac Actinium	104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110 Ds Darmstadtium	111 Rg Roentgenium	112 Cn Copernicum	113 Nh Nihonium	114 Fl Flerovium	115 Mc Moscovium	116 Lv livermorium	117 Ts Tennessine	118 Og Oganesson
		$CaCO_3$ Limestone		58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium	71 Lu Lutetium
				90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 No Nobelium	103 Lr Lawrencium

The geologic availability of selected minerals in India derives from four categories: production, reserves, remaining resources, and geological potential. Figure 3.3 describes the classification of the geological mineral inventory (India Bureau of Mines, 2022). The outermost ring shows the geological mineral potential of 0.53 million km^2 has been identified as obvious geological potential (OGP) in India, of which only 10% has been explored in detail (Press Information Bureau, 2021). Reconnaissance or prospecting is initially required to quantify a mineral occurrence as a resource. The next step involves general and detailed exploration to determine the quantity of economically mineable resources, referred to as mineral reserves, which can then be allocated for mineral production.

Figure 3.3 Graphical Representation of Geographical Inventory Classification (not to scale)



Source: Indian Bureau of Mines (2022)

India's geology is often likened to Western Australia and eastern Africa due to the sub-continent being a part of the Gondwana supercontinent until around 180 million years ago. However, due to the lack of exploration, India has not been able to discover its full mineral wealth. For example, Western Australia is rich in nickel and lithium, but there have been limited nickel resources found in India, and and some recent lithium finds.

Box 3.1 Lithium Discovered in Jammu & Kashmir, India

The Geological Survey of India (GSI) is responsible for the geological mapping of the country, conducting exploration activities and assessments of mineral resources. In their 62nd Board meeting held in early February, the GSI declared its findings of various critical minerals, including 5.9 million tonnes of lithium resources. This represents the fifth-largest inventory in the world.

The identified lithium has been classified as 'inferred resources', or a G3 level under the United Nations Framework Classification, implying that both reconnaissance and prospecting stages have been completed. Next, general exploration (G2) and detailed exploration (G1) will be required to fully understand the nature of the lithium deposits, including the ore grade. Feasibility and economic viability studies should simultaneously be undertaken. It would thus take time to convert these inferred lithium resources to economically mineable resources – i.e., mineral reserves.

While the discovery of lithium in India is welcome news for the country's future self-reliance, various steps are required to convert the resource into a functioning mine. First, a detailed exploration of the block will be required, which may take several months to years, depending on the complexity of the deposit. The government has indicated that it will auction the mineral block sometime soon, allowing the winning firm to explore and mine the lithium. The processes for more detailed exploration, developing a mining plan, and obtaining clearances can take five years or more and would depend on several factors, including engineering requirements and other local idiosyncrasies.

Hence, the lithium deposit found in 2023 may only bear its fruit sometime close to 2030. The government, for its part, can help streamline the process by ensuring the timely allocation of the mineral block and provision of the requisite clearances.

Source: Chadha & Sivamani (2023)

The criticality of various rare earth elements (REEs) has been considered in this study. REEs are a set of 17 heavy metals with diverse applications in industry. Based on their atomic numbers, they can be classified as light or heavy: those with atomic numbers 57 to 61 are labelled as light, while numbers 62 and greater are considered heavy. Although yttrium and scandium do not fall within this range of atomic numbers, they are typically considered REEs as they occur in the same ore deposits as other REEs and share similar chemical properties. The groupings of heavy and light REEs have been considered for this study's criticality assessment. Still, scandium – mainly used as an aluminium alloy – has been assessed as a separate mineral as it does not fall under either broad grouping. Neodymium, too, has been considered separately from the other light REEs due to its importance in manufacturing permanent magnets (used in machinery and electronics like turbines and mobile phones). India produces some quantities of yttrium, cerium, neodymium, praseodymium, and lanthanum, primarily through the extraction and processing of monazite, a phosphate mineral containing REEs and traces of thorium.

3.2 Economic Importance

The economic importance (EI) dimension measures a mineral's importance for a country's manufacturing sector. It measures the impact on this sector if a mineral becomes unavailable in a country's supply chain. Four indicators are used to compute the EI of each mineral [Eq. (3.1)]. The first indicator is the *disruption potential*, which measures the impact on the gross value added (GVA) if the mineral becomes unavailable in the country's supply chain. The *substitutability index*, the second indicator, measures the cost and performance of substitutes for the mineral, if any, in each of the mineral's end-use applications. The third indicator is the *GVA multiplier coefficient*, which measures the mineral's impact on manufacturing GVA (both direct and indirect), accounting for linkages between sectors of the economy and computed using sectoral GVA multipliers. The fourth is the *cross-cutting index*, which signifies the diversity of a mineral's use across manufacturing sectors.

$$EI = \left(\sum_{s} A_s Q_s \right) \times \sigma_{EI} \times \mu \times \kappa \qquad 3.1$$

Eq. (3.1) is used to compute the economic importance of each mineral, where:

A_s is the share of the mineral's consumption in sector s to its total consumption;
Q_s is the GVA share of sector s to total manufacturing GVA;
σ_{EI} is the substitutability index of the mineral;
μ is the mineral's GVA multiplier coefficient;
κ is the mineral's cross-cutting index.

Disruption Potential

The study uses the average values from the three most recent Annual Survey of Industries (ASI) – 2017-18, 2018-19[2], and 2019-20 to compute various indicators. Unit-level ASI data for these three years are used to reduce the influence of outliers and smoothen the industry's mineral consumption. The ASI includes industry statistics for the organised sector (see Annex 1 for the 2-digit level of classification of manufacturing sectors). While data are available for mineral consumption in the unorganised sector through the Unincorporated Non-Agricultural Enterprises (Excluding Construction) Survey, the latest report is for 2015-16 and hence is not considered in this study[3]. In addition, the ASI data relies on survey responses from each unit (factory) on their material inputs, which may contain uncertainties in the consumption data of minerals. Hence, some input values may be underestimated.

For this study, the domestic and imported consumption of minerals has been computed using ASI data at the 5-digit level of classification of the National Industrial Classification (NIC) (Central Statistical Organisation, 2008). Sectoral GVAs are also computed at the 5-digit level of NIC from the unit-level data and verified against the results published in the ASI reports. Information on the types of mineral ores and their chemical and alloy forms has been taken from the National Product Classification (NPC) (Central Statistics Office, 2011a). Both the ore and semi-processed forms of each critical mineral have been accounted for, as not all minerals are processed in any single country (Annex 2 lists the NPCs of the minerals that have been considered).

Some NPC codes aggregate multiple minerals, such as 3936800, which refers to scrap antimony and chromium. Since it is not feasible to find the mineral-wise usage share for these codes, the total consumption amount has been allocated to each mineral to which the codes refer. Indium, neodymium, and hafnium are not available as separate commodities in the NPC list, so the average values of the industry-wise use of these minerals have been taken from the EU report on CRMs.

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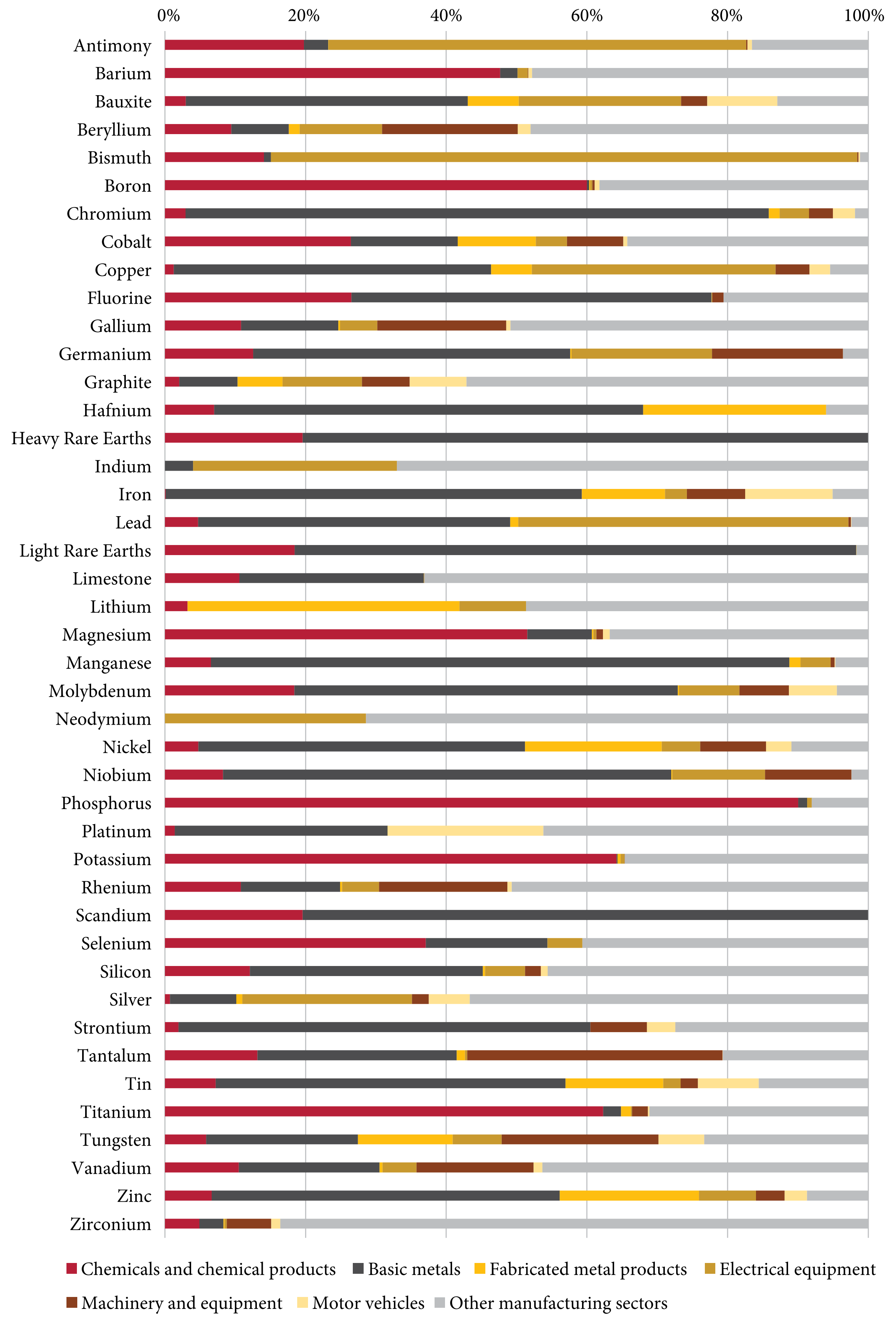
[2] The 2018-19 ASI was published in September 2021 and used a different method for computing GVA, which includes rent received for buildings and excludes expenses on R&D. This results in a higher overall GVA compared to that computed using the previous method. For this study, the computation given in the documentation has been used.

[3] India's unincorporated manufacturing sector accounted for ~9% of total manufacturing output in 2019-20.

Figure 3.4 Share of Mineral Consumption by 2-digit NIC Code



Source: Annual Survey of Industries

Substitutability Index (for economic importance)

The substitutability index, the second indicator of EI, is a measure that dampens the economic importance of a mineral if it has substitutes. The substitutability index is computed by assigning a score based on each substitute's cost and performance (Table 3.2) for each broad end-use case. A similar scoring matrix has been used in the EU's methodology. This study extends the matrix further by including an additional condition of when the substitute is better than the mineral (but may not be used if it is cost-prohibitive). Each mineral's processed form and end-use are considered when evaluating the scores of substitutes (e.g., infrastructure for steel and structural components for aluminium). The cost-performance scores are estimated using published information on the existence of substitutes and their relative costs and performances compared to the mineral. The scores range from 0.6 to 1.0, where 0.6 indicates a highly substitutable mineral and 1.0 indicates a mineral that is not substitutable. The substitutability index is the average cost-performance score weighted by the shares of mineral consumption by the 2-digit level of NIC sectors [see Eq. (3.2) and Annex 3 for mineral-wise results].

Table 3.2 Cost-Performance Score Matrix

Performance of Substitute / Cost of Substitute	Better	Similar	Lower	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

$$\sigma_{EI} = \sum_{s} A_s \sigma_s \qquad (3.2)$$

Eq. (3.2) is used to compute the substitutability index, where:
σ_{EI} is the substitutability index;
A_s is the share of the mineral's consumption in sector s to its total consumption in all sectors;
σ_s is the cost-performance score for sector s.

Gross Value Added Multiplier Score

The third component in the EI dimension is the GVA multiplier score. These scores are computed using the GVA multipliers from the CSEP Input-Output Table for India 2019-20[4] (Annex 4). The GVA multiplier is defined as the ratio of the sum of the direct and indirect GVA changes to the direct GVA change due to a unit increase in final demand. Sectors with high GVA multipliers are considered economically more important, as they have a higher potential to increase returns to the factors of production.

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[4] The CSEP Input-Output Table for 2019-20 has been constructed as part of a broader research project to construct an Environmentally-Extended Social Accounting Matrix for India.

$$\nu = \sum_{s} A_s \nu_s Q_s \tag{3.3}$$

Eq. (3.3) is used to compute the GVA multiplier, where:

ν is the mineral's GVA multiplier;

A_s is the share of the mineral's consumption in sector s to its total consumption in all sectors;

ν_s is the GVA multiplier for sector s;

Q_s is the GVA share of sector s to total manufacturing GVA.

For each mineral's GVA multiplier, a GVA multiplier score, , is assigned, which may increase the economic importance of the mineral (Table 3.3). The computed GVA multiplier and score for each mineral are given in Annex 4.

Table 3.3 GVA Multiplier Score

Mineral GVA Multiplier	GVA Multiplier Score
< 0.2	1.0
≥ 0.2 & ≤ 0.4	1.1
≥ 0.4	1.2

Cross-Cutting Index

The cross-cutting index (CCI) is the fourth indicator used to compute the EI of a mineral. Cross-cutting minerals are those that are consumed by various sectors. Minerals consumed by a larger number of industries are considered more economically important, as a sudden interruption in their supply would hit more industries. In contrast to the disruption potential, which focuses on the GVAs of the mineral-consuming sectors, the CCI measures the concentration of a mineral's use in different sectors. To compute the CCI, the Herfindahl–Hirschman Index (HHI) (The United States Department of Justice, 2018), a measure of concentration, has been applied to the ASI's sectoral mineral consumption data at the 3-digit level of NIC [Eq. (3.4)].

$$HHI = \sum_{c} S_i^2 \tag{3.4}$$

Eq. (3.4) is used to compute the concentration of mineral consumption by industry, where:

HHI is the level of industry-wise concentration of mineral consumption;

S_i is the share of mineral consumption in industry .

A 3-digit level of NIC has been chosen to compute the concentration level, and a CCI, is assigned to each mineral (Table 3.4 and Annex 6: Cross-Cutting Index).

Table 3.4 Cross-Cutting Index

HHI	Range	CCI
Highly cross-cutting	0 ≤ HHI < 0.15	1.2
Moderately cross-cutting	0.15 ≤ HHI < 0.25	1.1
Less cross-cutting	0.25 ≤ HHI	1.0

3.3 Supply Risk

The supply risk (SR) dimension of the criticality assessment seeks to measure the vulnerabilities a country may face from global mineral supply chains due to the geographic concentration of mineral extraction or processing in some countries and weighted by the quality of governance in the respective jurisdictions. The World Bank publishes the *World Governance Indicators* (WGI), which view the quality of governance by country (World Bank, 2023). Weights may also be assigned based on other factors, such as Yale University's Environmental Protection Index (EPI) (Yale Center for Environmental Law & Policy, 2022) or the Mining Investment Attractiveness Index (Fraser Institute, 2022). Mineral supply risks are also impacted by end-of-life recycling rates, substitutability, and the degree of self-reliance.

$$SR_G = \left[(HHI_{WGI})_{GS} \times \frac{IR}{2} + (HHI_{WGI})_{IS} \times \left(1 - \frac{IR}{2}\right)\right] \times (1 - \rho) \times \sigma_{SR} \times \epsilon \tag{3.5}$$

Eq. (3.5) is used to compute the supply risk of each mineral, where:

SR_G is the supply risk accounting for governance indicators;
HHI_{WGI} is the Herfindahl-Hirschman Index of mineral concentration, accounting for governance indicators;
GS is the global supply of extracted or processed minerals;
IS is the Indian sourcing of extracted or processed minerals;
ρ is the end-of-life recycling rate of the mineral;
IR is the import reliance of the minerals;
σ_{SR} is substitutability in the supply risk dimension;
ϵ is the self-sufficiency adjustment factor. 1

Governance-Weighted Mineral Concentration

A key factor that affects a mineral's supply risk is the geographic concentration of mining (extraction) or processing. Minerals extracted or processed in just one or a few countries are considered more critical. For example, the Democratic Republic of Congo mines 69% of the global cobalt supply, so any disruption in the country would significantly impact the associated supply chain. Another example is Indonesia, accounting for 33% of global nickel mining, which has been taking measures to ban the exports of nickel ore to encourage domestic processing (International Energy Agency, 2022). On the other hand, China has a monopoly on the extraction and processing of REEs, and any trade policy changes could affect global supplies of these metals.

The Herfindahl-Hirschman Index (HHI) measures the concentration of mineral extraction or processing by country. Global extraction and processing data are both considered, and the stage in which the concentration is higher is used to compute the supply risk [this is discussed further in section (f) below on bottleneck analysis]. Additionally, the Indian sourcing of raw and processed minerals is considered – for minerals where there is no import reliance, Indian sourcing becomes the only important factor. This mineral concentration is weighted by the supplying country's governance performance. Poorly-governed countries supplying minerals would imply higher supply risks than well-governed countries.

A similar exercise may be repeated based on the concentration of mineral extraction or processing done by companies rather than countries. For example, while the Democratic Republic of Congo produces the majority of cobalt globally, the countries of incorporation of the cobalt-producing companies may be located in countries other than Congo (Leruth, Mazarei, Régibeau, & Renneboog, 2022).

a) Global Mineral Production

Country-wise mineral extraction data have been sourced from *World Mining Data* (WMD) (Reichl & Schatz, 2022); data from the United States Geological Survey (2022) have been used for minerals not reported in WMD. For computing the HHI, the per cent share of mineral production by country has been used.

b) Global Mineral Processing

Global mineral processing data has been sourced from the EU study (European Commission, 2020a). For minerals with no information on processing shares by country, the bottleneck is assumed to be in the extraction stage.

c) Indian Sourcing of Minerals

Data on where India is sourcing its minerals from is taken from the World Bank's WITS database for 2021 (World Bank, 2021). The database provides gross import values based on the Harmonised Series (HS) codes. Relevant HS codes have been selected for each mineral, reflecting its raw or semi-processed forms.

d) World Governance Indicators

The quality of governance in each country has been accounted for using the World Bank's Worldwide Governance Indicators (WGI) (World Bank, 2021). The WGI data provide six dimensions of governance: voice and accountability; political stability and the absence of violence; government effectiveness; regulatory quality; rule of law; and control of corruption. These dimensions are measured in the range of -2.5 to +2.5. For this study, the arithmetic means of the scores have been normalised using a min-max transformation, so scores range from 0 to 100. The scores were then inverted so that 0 represents the best-performing country and 100 the worst; this was done to ensure that a higher score (less well-governed) would indicate a higher supply risk.

e) Environmental Protection Index

A country's degree of environmental protection can also be used to weigh the concentration of mineral extraction or processing, as has been done with the WGI. The Environmental Performance Index (EPI) 2022 (Yale Center for Environmental Law & Policy, 2022) provides data on a country's state of sustainability. With greater importance being assigned to mitigating environmental externalities, there may be increasing deterrents to doing business in countries with poor ecological outcomes, leading to higher supply risks of minerals being mined in these jurisdictions.

To compute the environmental-weighted supply risks, the HHI_{WGI} is replaced with HHI_{EPI} in Eq. (3.5). However, a high correlation has been noted between the WGI and EPI datasets, possibly due to better-governed countries paying greater attention to environmental protection. The correlation between the two datasets is 0.757, and the resultant mineral-wise supply risks have a 0.96 correlation. Annex 7 shows the difference in supply risk scores when using the EPI to weight mineral concentration compared to using the WGI. Hence, this study considers only the WGI to compute the supply risk.

f) Bottleneck Analysis

This study uses a bottleneck analysis to determine whether to consider the extraction or processing stages to assess the governance-weighted geographic concentration of minerals [Eq. (3.6)]. The higher of the two values is used to compute the supply risk.

$$HHI_{WGI} = \sum_{c} S_c^2 WGI_c \tag{3.6}$$

Eq. (3.6) is used to compute the HHI of geographic mineral concentration (for either the extraction or processing stages), weighted by the country's WGI, where:

HHI_{WGI} is the governance-weighted mineral concentration;
S_c is the share of mineral extraction or processing in country c;
WGI_c is the world governance indicator score for country c.

Table 3.5 shows the results of the bottleneck analysis. Stage 1 refers to a bottleneck in the extraction stage (i.e., higher governance-weighted mineral concentration in mining countries), while Stage 2 refers to a bottleneck in the processing stage. The bottleneck stage can vary between global supply and Indian sourcing of minerals.

Table 3.5 Results of the Bottleneck Analysis

Mineral	Global Supply – Bottleneck Stage	Indian Sourcing – Bottleneck Stage
Antimony	2	1
Barium	1	1
Bauxite	1	1
Beryllium	1	2
Bismuth	1	2
Boron	2	2
Chromium	2	1
Cobalt	1	1
Copper	2	1
Fluorine	1	2
Gallium	1	2
Germanium	1	2
Graphite	1	1
Hafnium	2	2
Heavy Rare Earths	1	2
Indium	1	2
Iron	2	1
Lead	2	1
Light Rare Earths	1	2
Limestone	1	1
Lithium	2	2
Magnesium	2	2
Manganese	2	2
Molybdenum	1	1

Neodymium	1	2
Nickel	1	1
Niobium	2	1
Phosphorus	2	2
Platinum	2	2
Potassium	1	2
Rhenium	2	2
Scandium	1	2
Selenium	1	2
Silicon	1	2
Silver	1	2
Strontium	1	1
Tantalum	1	1
Tin	2	1
Titanium	2	1
Tungsten	1	1
Vanadium	1	1
Zinc	2	2
Zirconium	1	2

End-of-life Recycling Rates

The end-of-life recycling rates (EOL-RR) of minerals impact their supply risks. Minerals with a high EOL-RR will have a dampened supply risk since the requirements for such minerals can be met by recovering the materials from waste rather than relying on imports. Each mineral is assigned a score (Annex 8) based on its recycling levels in India (Table 3.6). Theoretically, this score should be based on the end-of-life recycling *input* rate, which reflects the share of a mineral's recycled input. However, there is no data for this either by mineral or overall in India, so the average global 6% recycling input rate has been assumed (Willi Haas, 2015).

The data on end-of-life recycling rates have been taken from various published sources, including Indian government publications. In the case of gaps in recycling rates for some minerals, the worst-case scenario of no recycling (i.e., leading to higher supply risks) has been assumed for those minerals.

Table 3.6: Recycling Scores

Level of Recycling	Score
Almost no recycling	0.00
Some recycling	0.02
Mostly recycled	0.04
Almost all recycled	0.06

Import Reliance and Self-Sufficiency

A mineral's import reliance (IR) refers to a country's dependence on imports for its commodity needs and ranges from 0%-100% (i.e., from not reliant on imports to fully reliant on imports for domestic needs). The self-sufficiency of a mineral is computed as 100% — IR. Minerals with low import reliance will have lower supply risks and vice versa.

$$IR = \frac{M - X}{P + M - X} \tag{3.7}$$

Eq. (3.7) is used to compute the import reliance (IR) for each mineral, where:

IR is the import reliance;
M is the value of imports;
X is the value of exports;
P is the value of domestic production.

For minerals with no extraction in India, the IR is 100%, and for minerals where India's exports are greater than its imports, the IR is 0%. A mineral with no import reliance does not necessarily mean that there are no imports but that the value of exports is greater than the value of imports.

As Eq. (3.5) indicates, the IR term is used as a weighting factor between the concentration of global supply and the Indian sourcing of minerals. For minerals with no import reliance, only the Indian sourcing countries are considered. On the other hand, if there is complete reliance on imports, both the global supply and Indian sourcing concentrations are considered. Table 3.7 provides examples of how import reliance affects the weights given to global supply and Indian sourcing used in Eq. (3.5).

Table 3.7 Impact of Import Reliance on Weight of Global Supply and Indian Sourcing Mineral Concentrations – Indicative Examples

Import Reliance (%)	Global Supply Weight (%)	Indian Sourcing Weight (%)
0	0	100
20	10	90
40	20	80
50	25	75
60	30	70
80	40	60
100	50	50

Data on import reliance has been taken from various sources, including the *Indian Bureau of Mines (IBM) Yearbook* (Indian Bureau of Mines, 2021), which has information on the degree of India's self-sufficiency for some minerals considered in this study. Such information has been used to compute import reliance.

The methodology used in this study modifies the supply risk equation used in the EU Methodology Guidelines 2017 by including a 'self-sufficiency index', which dampens the supply risk by a factor proportional to the mineral's self-sufficiency. Eq. (3.8) has been used to normalise the mineral self-sufficiency between 0.6 and 1.0, where 0.6 indicates high self-sufficiency and 1.0 indicates low or no self-sufficiency. Mineral-wise values and scores of import reliance and self-sufficiency are given in Annex 9.

$$\epsilon = IR \times 0.4 + 0.6 \tag{3.8}$$

Eq. (3.8) is used to compute the self-sufficiency index for each mineral, where:

ϵ is the self-sufficiency index;
IR is the import reliance of the mineral in per cent terms.

No country is fully self-sufficient in its needs for mineral resources, and trade policy plays an important role in their availability across countries. This is particularly relevant for critical minerals since these have relatively more complex global supply chains with high degrees of monopoly in their extraction and processing. The endowed countries may distort free trade by imposing export taxes or quotas for various reasons, including benefitting their downstream industries, arm-twisting impoverished countries, or resorting to other trade war measures. While export taxes are permitted under the multilateral WTO discipline, quantitative restrictions on exports are not, except for short-term emergent reasons like domestic shortages. India could face such situations in its import of critical minerals. The present paper does not incorporate this aspect due to a lack of data on mineral-wise export restrictions imposed by India's sourcing countries. However, the work shall be extended after data has been collated from various sources.

Substitutability Index (for supply risks)

The substitutability index of each mineral has also been computed in the context of supply risks. While in the case of economic importance, a mineral's substitutability index was calculated using the cost-performance of each substitute, in the case of supply risks, the substitutability index measures the relative ease of mining substitutes. High levels of substitutability dampen the supply risk as it would be relatively easy to acquire substitutes through mining.

The ease of mining the substitute has been computed by taking the geometric mean of the scores of two factors: whether the mineral and its substitute are primary minerals or mined as by-products or co-products (Table 3.8); and the level of production of the substitute (Table 3.9 and Annex 10).

Table 3.8 Mineral Extraction of Substitutes Scores

Substitute Mineral	Primary	Both	Co-product/By-product
Primary	1.0	1.0	1.0
Both	0.9	0.9	1.0
Co-product/by-product	0.8	0.9	1.0

An example of co-products is lead and zinc, which are typically found together. An example of a by-product is a mineral, like cobalt, often produced as a by-product of copper and nickel mining. When the mineral is a primary product, there is no reduction in the supply risk, regardless of the substitute type. However, if the mineral is a co-product or by-product, and the substitute is a primary product, the supply risk substitutability falls. Minerals that are co-products and by-products are likely to face some constraints in their supply chains due to difficulties in their extraction and processing.

Table 3.9 Production Level of Substitutes Scores

Substitute	Score
Less production	1.0
More production	0.9

The production level of the substitute is also considered: when a substitute has a higher production level than the mineral, the supply risk is reduced due to the relatively greater availability of the substitute. However, when computing this indicator, an assumption is made that the substitute would replace the mineral in equal weight, which may not be the case.

$$\sigma_{SR} = \sqrt{\left(\sum_{s} A_s \sigma_{BC}\right)\left(\sum_{s} A_s \sigma_P\right)} \tag{3.9}$$

Eq. (3.9) is used to compute the supply risk substitutability index, where:

σ_{SR} is the supply risk substitutability index;
A_s is the share of mineral consumption in sector s;
σ_{BC} is the co-/by-production score;
σ_P is the production substitutability.

3.4 Choice of Adjusting Factors

Certain indicators can be considered 'adjusting factors' that either augment or dampen the economic importance and supply risk dimensions. The quanta of adjustments have been chosen by the authors based on earlier studies using similar methodologies. Nevertheless, there is scope to change these values based on the specifications of the stakeholder. For example, the cost-performance scoring matrix used to determine the substitutability (economic importance) indicator can be changed such that the largest dampening factor becomes 0.9 instead of 0.6. This would have the effect of reducing the impact that substitutability has on the economic importance dimension.

4. Results

The computed values for economic importance and supply risks have been normalised between 0 and 100 using the min-max transformation and based on the theoretical minima and maxima for each dimension. The normalised results of the economic importance and supply risks of the 43 considered minerals are shown in Table 4.1. Higher values in each dimension are shaded in darker colours.

The results have been depicted in graphical form in Figure 4.1. While there is no literature on the appropriate cut-off for criticality, this study attempts to estimate this. Along the normalised supply risk dimension, the cut-off has been chosen as 10.0. For economic importance, the cut-off has been chosen as 4.6. This threshold has been derived by applying a 10% cut-off for each indicator and computing the normalised economic importance. This differs from the supply risk threshold, as the range of supply risk scores is much higher than that for economic importance.

Minerals in the upper-right quadrant are the most critical, with high risks on both dimensions; those in the lower-left quadrant are relatively less critical on both counts. Table 4.2 shows the grouping of minerals by quadrant based on the criticality cut-offs of each dimension.

Table 4.1 Results of Critical Minerals Assessment

Mineral	Economic Importance	Supply Risks
Antimony	7.20	32.98
Barium	5.15	12.64
Bauxite	10.03	7.59
Beryllium	5.28	17.87
Bismuth	1.55	35.36
Boron	15.90	12.94
Chromium	14.80	15.59
Cobalt	7.16	29.14
Copper	5.46	6.03
Fluorine	13.62	10.10
Gallium	4.71	33.23
Germanium	2.88	26.86
Graphite	7.55	13.76
Hafnium	10.22	13.36
Heavy Rare Earths	4.27	11.49
Indium	3.68	15.07
Iron	15.55	10.99
Lead	4.18	8.89
Light Rare Earths	4.31	11.49
Limestone	15.27	14.71
Lithium	15.72	10.25
Magnesium	17.10	26.39
Manganese	12.80	17.43
Molybdenum	11.19	9.61
Neodymium	2.95	10.96
Nickel	14.46	12.93
Niobium	12.61	29.76
Phosphorus	7.81	12.48
Platinum	9.54	16.64
Potassium	17.23	3.54
Rhenium	4.45	13.46
Scandium	3.24	25.62
Selenium	6.21	3.64
Silicon	8.35	6.27
Silver	5.45	4.93
Strontium	20.87	10.99
Tantalum	2.79	12.83
Tin	7.75	19.18
Titanium	7.30	4.84
Tungsten	5.36	25.76
Vanadium	4.45	12.01
Zinc	9.92	3.59
Zirconium	2.68	7.16

Figure 4.1 Normalised Results of the Critical Minerals Assessment

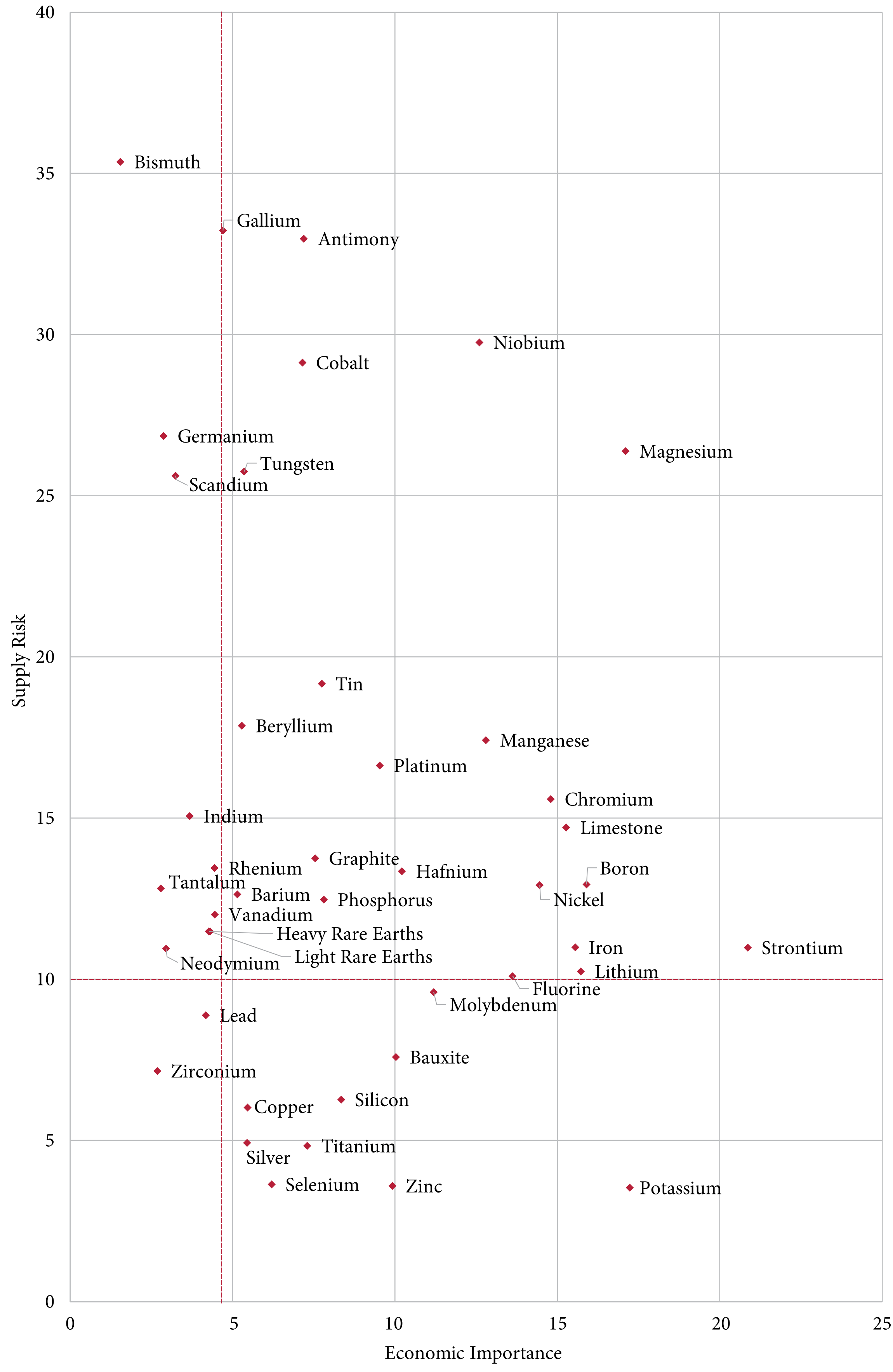

Table 4.2 Critical Minerals

#	High Economic Importance	High Supply Risk	Both Dimensions High
1	Bauxite	Bismuth	Antimony
2	Copper	Germanium	Barium
3	Molybdenum	Heavy Rare Earths	Beryllium
4	Potassium	Indium	Boron
5	Selenium	Light Rare Earths	Chromium
6	Silicon	Neodymium	Cobalt
7	Silver	Rhenium	Fluorine
8	Titanium	Scandium	Gallium
9	Zinc	Tantalum	Graphite
10		Vanadium	Hafnium
11			Iron
12			Limestone
13			Lithium
14			Magnesium
15			Manganese
16			Nickel
17			Niobium
18			Phosphorus
19			Platinum
20			Strontium
21			Tin
22			Tungsten

This study has analysed the criticality of 43 minerals for the Indian economy. For each of these, it deduces a risk profile in terms of economic importance, domestic and global availability, substitutability, recycling potential, changing technological dynamics, and requirements for the future. Such a study is relevant for gauging India's vulnerability to losing out on its manufacturing potential and transformation to green technology use, including renewable energy and electric vehicles.

The analysis suggests that the most critical minerals with relatively high economic importance and supply risks for India are antimony, barium, beryllium, boron, chromium, cobalt, fluorine, graphite, hafnium, iron, limestone, lithium, magnesium, manganese, nickel, niobium, phosphorus, platinum, strontium, tin and tungsten. Those which are critical based on economic importance are bauxite, copper, molybdenum, potassium, selenium, silicon, silver, titanium, fluorine, gallium, iron, lithium, molybdenum, potassium, silicon, strontium, titanium and zinc; while bismuth, germanium, heavy rare earths, neodymium, rhenium, scandium, tantalum and vanadium are associated with high supply risks.

A mineral may appear less critical if India does not import its raw or processed forms but imports only types of machinery with the mineral embedded. For example, this study shows that rare earth elements have high supply risks but low economic importance. However, various imported high-technology equipment have embedded rare earth elements. Additionally, while a mineral may not be critical for India when conducting this assessment, domestic or global changes could impact its criticality in the future.

5. Policy Implications: Concluding Remarks

5.1 Challenges for India

Global

Post COVID-19 and the Russia-Ukraine war, there are significant risks to the supply chains of critical minerals. There are four major risks that the world is currently facing:

- China, the most dominant player in the critical mineral supply chains, is still struggling with COVID-19-related lockdowns. As a result, the extraction, processing and exports of critical minerals are at risk of slowdown.
- Russia is one of the major producers of nickel, palladium, titanium sponge metal, and the rare earth element scandium. Ukraine is one of the major producers of titanium. It also has reserves of lithium, cobalt, graphite, and rare earth elements, including tantalum, niobium, and beryllium. The war between the two countries has implications for these critical mineral supply chains.
- As the balance of power shifts across continents and countries, the critical mineral supply chains may get affected due to the strategic partnership between China and Russia. As a result, developed countries have jointly drawn up partnership strategies, including the Minerals Security Partnership (MSP) and G7's Sustainable Critical Minerals Alliance, while developing countries have missed out.
- There will be an increase in the demand for several critical minerals as India and the rest of the world transition towards renewable power generation and electric vehicles. The manufacturing of renewable energy technologies would require increasing quantities of minerals, including copper, manganese, zinc, and indium. Likewise, moving to electric vehicles would require increasing quantities of minerals, including copper, lithium, cobalt, and rare earth elements. However, India does not have many of these minerals, and its requirements may be higher than its current reserves, necessitating reliance on foreign partners to meet domestic needs. Additionally, setting up new exploration, extraction, and processing activities would be time-consuming.

Domestic

India has an untapped potential for mineral wealth, and domestic policies can enable their sustainable extraction:

- Many critical and strategic minerals constitute part of the list of atomic minerals in the Mines and Minerals (Development and Regulation) (MMDR) Act, 1957. However, the present policy regime reserves these minerals only for public sector undertakings. Some of these minerals are beryl and other beryllium-bearing minerals, lithium-bearing minerals, minerals of the rare earths group containing uranium and thorium, niobium-bearing minerals, titanium-bearing minerals and ores, tantalum-bearing minerals, zirconium-bearing minerals and ores, and beach sand minerals.

- Given the increasing importance of critical and strategic minerals, there is an imperative need to create a new list of such minerals in the MMDR Act. The list may include minerals such as molybdenum, rhenium, tungsten, cadmium, indium, gallium, graphite, vanadium, tellurium, selenium, nickel, cobalt, tin, the platinum group of elements, and fertiliser minerals such as glauconitic, potash, and phosphate (without uranium). These minerals must be prospected, explored, and mined on priority, as any delays may hinder India's emissions reduction and climate change mitigation timeline.
- The reconnaissance and exploration of minerals must be encouraged, with particular attention given to deep-seated minerals (Mathai, 2019). This will call for a collective effort by the government, junior miners, and major mining companies. An innovative regime must be devised to allocate critical mineral mining assets, including deep-seated minerals. Private explorers, including 'junior' explorers, could play a much more significant role if adequately incentivised.
- India needs to determine where the mid- and down-stream processing and assembly of critical minerals-embedded equipment will occur. Currently, India relies on global supplies of various processed critical minerals, as there are limited domestic sources.

5.2 Strategies for India

Objectives of India's Critical Minerals Strategy

India requires a critical minerals strategy comprising measures aimed at making the country *AatmaNirbhar* (self-reliant) in critical minerals needed for sustainable economic growth and green technologies for climate action, national defence, and affirmative action for protecting the interests of the affected communities and regions. In addition, India must actively engage in bilateral and plurilateral arrangements for building assured and resilient critical mineral supply chains.

The assessment of critical minerals for a jurisdiction needs to be updated every three years to keep pace with changing domestic and global scenarios; this is a good global practice that India needs to follow, beginning with the list of minerals identified in this study. We also need to project the country's critical mineral requirements for the near future, which would provide early warning signals of critical mineral supply chains that must become more resilient.

A national critical minerals strategy for India, underpinned by the minerals identified in this study, can help focus on priority concerns in supply risks, domestic policy regimes, and sustainability. Table 5.1 highlights some of the strategies major global economies employ to secure their CRM needs.

Table 5.1: Strategies for Creating Resilient Critical Mineral Supply Chains

Supply Resilience of Critical Minerals	Favourable Policy Regime	Sustainability
● International coordination ● Stockpiling ● Investment in foreign assets	● Geological surveys ● Tax incentives or financing ● Promotion of end-of-life recycling ● Investment in research and development ● Policy regime	● Environmental standards ● Gender equity ● Transparency

Source: International Energy Agency (2022)

Progress has been made in securing India's critical mineral supply chains, including the signing of the Australia-India Economic Cooperation Trade Agreement (Department for Foreign Affairs and Trade (DFAT), 2022), which eliminates tariffs on most critical minerals, including zirconium, titanium, cobalt, and nickel. In addition, the government has set up KABIL[5] to ensure a consistent supply of critical and strategic minerals through government-to-government (G-to-G) negotiations and acquiring mining assets abroad. KABIL has already expressed interest in establishing lithium extraction projects in Argentina (ANI, 2022). Apart from these measures, the private sector must look outside the country to secure critical mineral supply chains for their industries.

India must also consider what role to play in the downstream critical mineral value chains. China, for example, has developed an efficient domestic lithium processing industry, which benefits from being a part of a larger supply chain, economies of scale, and years of expertise. If India is to compete in this market, substantive investments and additional skills will be required – perhaps with the help of strategic partners like Australia. Environmental and social externalities must also be considered for mining and processing operations. For example, lithium processing consumes large quantities of water, and the waste streams may contaminate the air, water, or land, which would have adverse health impacts on local communities. India may simultaneously consider owning foreign assets in critical mineral supply chains.

Creating Knowledge Networks

With critical minerals emerging as a new area of academic interest, the government could channel funds to institutions engaged in studying critical and strategic minerals and, in the long term, consider establishing an institution dedicated to this area.

The processing technologies for critical and strategic minerals are not widely available in India. Therefore, the country needs to utilise its vast network of scientific and technical institutions to identify the necessary technologies and develop these domestically. Here, the role of the Department of Scientific and Industrial Research, the Ministry of Science and Technology, the Ministry of Education, and higher education institutes, such as the Indian Institute of Technology (Indian School of Mines), Dhanbad, can be crucial.

Knowledge networks should also be established with other countries looking to secure their critical minerals supply chains. The MSP, for example, of which India is not currently a part, seeks to strengthen information-sharing across partner countries, increase investment in securing CRM supply chains, and develop recycling technologies (International Energy Agency, 2022). It would be to India's benefit to participate in such multilateral organisations. For example, a "G20 Critical Minerals Security Partnership" (G20-CMSP) could be created through an active partnership between the developing and the developed member countries. The CMSP should ensure a resilient supply chain of critical minerals, including stockpiles of various minerals stored in different member countries as per their respective comparative advantages in extraction and processing.

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[5] KABIL (Khanij Bidesh India Ltd.) is a joint venture between three public companies: NALCO, HCL, and MECL.

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Annexes

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 for furniture
17	Paper products
18	Printing
19	Coke and refined petroleum
20	Chemicals and chemical products
21	Pharmaceuticals, medicinal chemicals 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 not elsewhere classified
29	Motor vehicles, trailers and semi-trailers
30	Other transport equipment
31	Furniture
32	Other manufacturing

Source: National Industrial Classification

Annex 2: National Product Classification for Manufacturing Sector (NPC-MS) 6 Codes of Selected Minerals

NPC	Mineral(s)	Type
3425006	Antimony	Chemical
4160301	Antimony	Processed
4160399	Antimony; Bismuth; Chromium; Manganese	Processed
3936800	Antimony; Chromium	Scrap
3424019	Arsenic	Chemical
3527010	Arsenic	Chemical
3421003	Barium	Chemical
3424013	Barium	Chemical
3424014	Barium	Chemical
3424015	Barium	Chemical
3425007	Barium	Chemical
3425008	Barium	Chemical
1423001	Bauxite	Ore
1423002	Bauxite	Ore
1423003	Bauxite	Ore
1423099	Bauxite	Ore
1611001	Bauxite	Ore
3423108	Bauxite	Chemical
3423109	Bauxite	Chemical
3424001	Bauxite	Chemical
3424002	Bauxite	Chemical
3424005	Bauxite	Chemical
3424006	Bauxite	Chemical
3936301	Bauxite	Scrap
3936399	Bauxite	Scrap
4143101	Bauxite	Processed
4143102	Bauxite	Processed
4143103	Bauxite	Processed
4143199	Bauxite	Processed
4143201	Bauxite	Processed
4143299	Bauxite	Processed
4153101	Bauxite	Processed
4153102	Bauxite	Processed
4153199	Bauxite	Processed
4153201	Bauxite	Processed
4153202	Bauxite	Processed
4153203	Bauxite	Processed
4153204	Bauxite	Processed

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

NPC	Mineral(s)	Type
4153205	Bauxite	Processed
4153299	Bauxite	Processed
4153301	Bauxite	Processed
4153302	Bauxite	Processed
4153399	Bauxite	Processed
4153401	Bauxite	Processed
4153402	Bauxite	Processed
4153403	Bauxite	Processed
4153404	Bauxite	Processed
4153499	Bauxite	Processed
4153501	Bauxite	Processed
4153502	Bauxite	Processed
4153503	Bauxite	Processed
4153504	Bauxite	Processed
4153505	Bauxite	Processed
4153599	Bauxite	Processed
4153601	Bauxite	Processed
4153602	Bauxite	Processed
4153603	Bauxite	Processed
4153699	Bauxite	Processed
3424003	Bauxite; Fluorine	Chemical
1611099	Bauxite; Phosphorus	Ore
3424004	Bauxite; Phosphorus	Chemical
3936701	Beryllium	Scrap
4160101	Beryllium	Processed
4160201	Beryllium	Processed
4160299	Beryllium; Cobalt; Gallium; Germanium; Hafnium; Indium; Magnesium; Molybdenum; Niobium; Rhenium; Tantalum; Titanium; Tungsten; Vanadium; Zirconium	Processed
3936799	Beryllium; Cobalt; Magnesium; Molybdenum; Tantalum; Titanium; Tungsten; Zirconium	Scrap
4141301	Beryllium; Copper	Processed
4160199	Beryllium; Gallium; Hafnium; Indium; Rhenium; Tungsten; Vanadium; Zirconium	Processed
4160303	Bismuth	Processed
4160304	Bismuth	Scrap
4160305	Bismuth	Processed
3423112	Boron	Chemical
3423113	Boron	Chemical
3423115	Boron	Chemical
3427002	Boron	Chemical
3427007	Boron	Chemical
3427099	Boron	Chemical

NPC	Mineral(s)	Type
3423199	Boron; Magnesium	Chemical
1424001	Chromium	Ore
1429001	Chromium	Ore
1429002	Chromium	Ore
3422017	Chromium	Chemical
3424016	Chromium	Chemical
3424060	Chromium	Chemical
3922001	Chromium	Scrap
4160307	Chromium	Processed
4111300	Chromium; Iron	Ferro
4111501	Chromium; Iron	Ferro
4111509	Chromium; Iron	Ferro
4121301	Chromium; Iron	Processed
4121303	Chromium; Iron	Processed
4121304	Chromium; Iron	Processed
4122102	Chromium; Iron	Processed
4122103	Chromium; Iron	Processed
4126501	Chromium; Iron	Processed
4126502	Chromium; Iron	Processed
3424049	Chromium; Potassium	Chemical
1429011	Cobalt	Ore
3424023	Cobalt	Chemical
3425011	Cobalt	Chemical
3936703	Cobalt	Scrap
4160104	Cobalt	Processed
4160105	Cobalt	Processed
4160106	Cobalt	Processed
4160107	Cobalt	Processed
4160203	Cobalt	Processed
4111503	Cobalt; Iron	Ferro
3422099	Cobalt; Iron; Lead; Manganese; Zinc	Chemical
3424024	Cobalt; Phosphorus	Chemical
1421000	Copper	Ore
3422002	Copper	Chemical
3424025	Copper	Chemical
3936102	Copper	Scrap
3936199	Copper	Scrap
4141100	Copper	Processed
4141201	Copper	Processed
4141202	Copper	Processed
4141299	Copper	Processed
4141302	Copper	Processed

NPC	Mineral(s)	Type
4141303	Copper	Processed
4141304	Copper	Processed
4141306	Copper	Processed
4141307	Copper	Processed
4141399	Copper	Processed
4151101	Copper	Processed
4151102	Copper	Processed
4151199	Copper	Processed
4151201	Copper	Processed
4151202	Copper	Processed
4151203	Copper	Processed
4151204	Copper	Processed
4151299	Copper	Processed
4151301	Copper	Processed
4151303	Copper	Processed
4151304	Copper	Processed
4151399	Copper	Processed
4151402	Copper	Processed
4151403	Copper	Processed
4151499	Copper	Processed
4151501	Copper	Processed
4151502	Copper	Processed
4151503	Copper	Processed
4151504	Copper	Processed
4151599	Copper	Processed
4151602	Copper	Processed
4151603	Copper	Processed
4151604	Copper	Processed
4151699	Copper	Processed
4151306	Copper; Nickel	Processed
4151404	Copper; Nickel	Processed
4151605	Copper; Nickel	Processed
4151302	Copper; Nickel; Silver; Zinc	Processed
4151307	Copper; Silver	Processed
3936101	Copper; Zinc	Scrap
4141305	Copper; Zinc	Processed
4151305	Copper; Zinc	Processed
4151401	Copper; Zinc	Processed
4151601	Copper; Zinc	Processed
4151606	Copper; Zinc	Processed
4151608	Copper; Zinc	Processed
3415002	Fluorine	Chemical

NPC	Mineral(s)	Type
3424008	Fluorine	Chemical
3424061	Fluorine	Chemical
3424072	Fluorine	Chemical
4160108	Gallium	Processed
4160204	Gallium	Processed
4160119	Gallium; Germanium; Hafnium; Indium; Niobium; Rhenium; Vanadium	Scrap
4160205	Germanium; Hafnium; Indium; Niobium; Rhenium; Vanadium	Processed
3795000	Graphite	Product
3799000	Graphite	Product
4295005	Graphite	Product
4695001	Graphite	Product
4695002	Graphite	Product
4695003	Graphite	Product
4695099	Graphite	Product
3429000	Heavy rare earths; Light rare earths; Neodymium; Scandium	Chemical
1410001	Iron	Ore
1410003	Iron	Ore
1410099	Iron	Ore
3422004	Iron	Chemical
3422005	Iron	Chemical
3934002	Iron	Scrap
3934003	Iron	Scrap
3935001	Iron	Scrap
3935099	Iron	Scrap
4111101	Iron	Processed
4111103	Iron	Processed
4111104	Iron	Processed
4111105	Iron	Processed
4111199	Iron	Processed
4111502	Iron	Processed
4111504	Iron	Processed
4111515	Iron	Processed
4111599	Iron	Processed
4111601	Iron	Processed
4111699	Iron	Processed
4111701	Iron	Processed
4111702	Iron	Processed
4111703	Iron	Processed
4111704	Iron	Processed
4111705	Iron	Processed
4111706	Iron	Processed
4111799	Iron	Processed

NPC	Mineral(s)	Type
4112101	Iron	Processed
4112103	Iron	Processed
4112104	Iron	Processed
4112105	Iron	Processed
4112106	Iron	Processed
4112107	Iron	Processed
4112108	Iron	Processed
4112109	Iron	Processed
4112110	Iron	Processed
4112199	Iron	Processed
4112201	Iron	Processed
4112202	Iron	Processed
4112203	Iron	Processed
4112204	Iron	Processed
4112205	Iron	Processed
4112206	Iron	Processed
4112207	Iron	Processed
4112208	Iron	Processed
4112209	Iron	Processed
4112210	Iron	Processed
4112299	Iron	Processed
4121101	Iron	Processed
4121102	Iron	Processed
4121103	Iron	Processed
4121104	Iron	Processed
4121105	Iron	Processed
4121199	Iron	Processed
4121201	Iron	Processed
4121202	Iron	Processed
4121203	Iron	Processed
4121204	Iron	Processed
4121205	Iron	Processed
4121206	Iron	Processed
4121207	Iron	Processed
4121208	Iron	Processed
4121209	Iron	Processed
4121210	Iron	Processed
4121299	Iron	Processed
4121302	Iron	Processed
4121399	Iron	Processed
4121400	Iron	Processed
4122101	Iron	Processed
4122199	Iron	Processed

NPC	Mineral(s)	Type
4122201	Iron	Processed
4122202	Iron	Processed
4122299	Iron	Processed
4122301	Iron	Processed
4122399	Iron	Processed
4122401	Iron	Processed
4122402	Iron	Processed
4122403	Iron	Processed
4122499	Iron	Processed
4123101	Iron	Processed
4123102	Iron	Processed
4123103	Iron	Processed
4123199	Iron	Processed
4123201	Iron	Processed
4123299	Iron	Processed
4123301	Iron	Processed
4123302	Iron	Processed
4123303	Iron	Processed
4123304	Iron	Processed
4123399	Iron	Processed
4123400	Iron	Processed
4123900	Iron	Processed
4124101	Iron	Processed
4124102	Iron	Processed
4124103	Iron	Processed
4124104	Iron	Processed
4124105	Iron	Processed
4124199	Iron	Processed
4124201	Iron	Processed
4124202	Iron	Processed
4124203	Iron	Processed
4124204	Iron	Processed
4124299	Iron	Processed
4124300	Iron	Processed
4124401	Iron	Processed
4124499	Iron	Processed
4125101	Iron	Processed
4125102	Iron	Processed
4125103	Iron	Processed
4125104	Iron	Processed
4125105	Iron	Processed
4125106	Iron	Processed
4125107	Iron	Processed

NPC	Mineral(s)	Type
4125108	Iron	Processed
4125109	Iron	Processed
4125110	Iron	Processed
4125199	Iron	Processed
4125201	Iron	Processed
4125202	Iron	Processed
4125299	Iron	Processed
4125301	Iron	Processed
4125302	Iron	Processed
4125303	Iron	Processed
4125304	Iron	Processed
4125305	Iron	Processed
4125399	Iron	Processed
4126100	Iron	Processed
4126200	Iron	Processed
4126301	Iron	Processed
4126302	Iron	Processed
4126303	Iron	Processed
4126304	Iron	Processed
4126305	Iron	Processed
4126399	Iron	Processed
4126400	Iron	Processed
4126599	Iron	Processed
4126600	Iron	Processed
4126701	Iron	Processed
4126702	Iron	Processed
4126799	Iron	Processed
4127101	Iron	Processed
4127102	Iron	Processed
4127103	Iron	Processed
4127104	Iron	Processed
4127105	Iron	Processed
4127106	Iron	Processed
4127199	Iron	Processed
4127301	Iron	Processed
4127302	Iron	Processed
4127399	Iron	Processed
4128101	Iron	Processed
4128102	Iron	Processed
4128103	Iron	Processed
4128104	Iron	Processed
4128199	Iron	Processed
4128201	Iron	Processed

NPC	Mineral(s)	Type
4128202	Iron	Processed
4128299	Iron	Processed
4128300	Iron	Processed
4128400	Iron	Processed
4128501	Iron	Processed
4128502	Iron	Processed
4128503	Iron	Processed
4128599	Iron	Processed
4128601	Iron	Processed
4128602	Iron	Processed
4128699	Iron	Processed
4128700	Iron	Processed
4128800	Iron	Processed
4128900	Iron	Processed
4129100	Iron	Processed
4129300	Iron	Processed
1429005	Lead	Ore
3422006	Lead	Chemical
3422007	Lead	Chemical
3422008	Lead	Chemical
3422009	Lead	Chemical
3424027	Lead	Chemical
3936401	Lead	Scrap
3936499	Lead	Scrap
4144101	Lead	Processed
4144102	Lead	Processed
4144103	Lead	Processed
4144104	Lead	Processed
4144199	Lead	Processed
4154201	Lead	Processed
4154202	Lead	Processed
4154203	Lead	Processed
4154204	Lead	Processed
4154205	Lead	Processed
4154206	Lead	Processed
4154299	Lead	Processed
3899502	Light rare earths	Ferro
1520006	Limestone	Ore
1520007	Limestone	Ore
1520008	Limestone	Ore
1520099	Limestone	Ore
3742001	Limestone	Processed
3742002	Limestone	Processed

NPC	Mineral(s)	Type
3742003	Limestone	Processed
3742099	Limestone	Processed
3424028	Lithium	Chemical
3424029	Lithium	Chemical
3424030	Lithium	Chemical
3424031	Lithium	Chemical
1639002	Magnesium	Ore
3416005	Magnesium	Chemical
3422010	Magnesium	Chemical
3424032	Magnesium	Chemical
3424033	Magnesium	Chemical
3424034	Magnesium	Chemical
3424035	Magnesium	Chemical
3424036	Magnesium	Chemical
3936704	Magnesium	Scrap
4160109	Magnesium	Processed
4160110	Magnesium	Processed
4160111	Magnesium	Processed
4160207	Magnesium	Processed
4111510	Magnesium; Iron	Ferro
1639003	Manganese	Ore
1639004	Manganese	Ore
3412004	Manganese	Chemical
3422011	Manganese	Chemical
3424037	Manganese	Chemical
4160308	Manganese	Processed
4160309	Manganese	Scrap
4160310	Manganese	Processed
4111200	Manganese; Iron	Ferro
4111511	Manganese; Iron	Ferro
4127200	Manganese; Iron	Processed
3424053	Manganese; Potassium	Chemical
1429008	Molybdenum	Ore
3422012	Molybdenum	Chemical
3424010	Molybdenum	Chemical
3936705	Molybdenum	Scrap
4160112	Molybdenum	Processed
4160113	Molybdenum	Processed
4160208	Molybdenum	Processed
4160209	Molybdenum	Processed
4160210	Molybdenum	Processed
4160211	Molybdenum	Processed
4111505	Molybdenum; Iron	Ferro

NPC	Mineral(s)	Type
3421001	Molybdenum; Phosphorus	Chemical
1422000	Nickel	Ore
1639005	Nickel	Ore
3424039	Nickel	Chemical
3424040	Nickel	Chemical
3936201	Nickel	Scrap
3936299	Nickel	Scrap
4142101	Nickel	Processed
4142102	Nickel	Processed
4142103	Nickel	Processed
4142199	Nickel	Processed
4142201	Nickel	Processed
4142202	Nickel	Processed
4142203	Nickel	Processed
4142299	Nickel	Processed
4152101	Nickel	Processed
4152102	Nickel	Processed
4152199	Nickel	Processed
4152201	Nickel	Processed
4152202	Nickel	Processed
4152203	Nickel	Processed
4152204	Nickel	Processed
4152299	Nickel	Processed
4152301	Nickel	Processed
4152302	Nickel	Processed
4152399	Nickel	Processed
4152401	Nickel	Processed
4152402	Nickel	Processed
4152403	Nickel	Processed
4152499	Nickel	Processed
4111400	Nickel; Iron	Ferro
4151405	Nickel; Silver	Processed
4151607	Nickel; Silver	Processed
4111506	Niobium; Iron	Ferro
1611002	Phosphorus	Ore
1611003	Phosphorus	Ore
1639006	Phosphorus	Ore
3416007	Phosphorus	Chemical
3416013	Phosphorus	Chemical
3416015	Phosphorus	Chemical
3416018	Phosphorus	Chemical
3416040	Phosphorus	Chemical
3418001	Phosphorus	Chemical

NPC	Mineral(s)	Type
3418002	Phosphorus	Chemical
3418003	Phosphorus	Chemical
3418005	Phosphorus	Chemical
3418006	Phosphorus	Chemical
3418007	Phosphorus	Chemical
3418008	Phosphorus	Chemical
3418099	Phosphorus	Chemical
3421002	Phosphorus	Chemical
3421014	Phosphorus	Chemical
3421015	Phosphorus	Chemical
3422013	Phosphorus	Chemical
3422014	Phosphorus	Chemical
3423130	Phosphorus	Chemical
3423131	Phosphorus	Chemical
3423132	Phosphorus	Chemical
3423133	Phosphorus	Chemical
3423144	Phosphorus	Chemical
3423200	Phosphorus	Chemical
3424022	Phosphorus	Chemical
3424062	Phosphorus	Chemical
3424071	Phosphorus	Chemical
3424078	Phosphorus	Chemical
3424079	Phosphorus	Chemical
3424099	Phosphorus	Chemical
3428099	Phosphorus	Chemical
4111507	Phosphorus; Iron	Ferro
3424054	Phosphorus; Potassium	Chemical
4133001	Platinum	Processed
4133004	Platinum	Processed
4133099	Platinum	Processed
3421016	Potassium	Chemical
3422015	Potassium	Chemical
3422016	Potassium	Chemical
3424042	Potassium	Chemical
3424043	Potassium	Chemical
3424044	Potassium	Chemical
3424045	Potassium	Chemical
3424046	Potassium	Chemical
3424047	Potassium	Chemical
3424048	Potassium	Chemical
3424050	Potassium	Chemical
3424051	Potassium	Chemical
3424052	Potassium	Chemical

NPC	Mineral(s)	Type
3424055	Potassium	Chemical
3427004	Potassium	Chemical
3427005	Potassium; Silicon	Chemical
4111508	Selenium; Iron	Ferro
1513005	Silicon	Ore
1513006	Silicon	Ore
1513007	Silicon	Ore
1540015	Silicon	Ore
3416017	Silicon	Chemical
3427001	Silicon	Chemical
3427003	Silicon	Chemical
3427008	Silicon	Chemical
4111513	Silicon; Iron	Ferro
1424006	Silver	Ore
3421017	Silver	Chemical
4131003	Silver	Processed
3421018	Strontium	Chemical
3936706	Tantalum	Scrap
4160114	Tantalum	Processed
4160212	Tantalum	Processed
4160213	Tantalum	Processed
4160214	Tantalum	Processed
4111514	Tantalum; Iron	Ferro
1429012	Tin	Ore
3936601	Tin	Scrap
3936699	Tin	Scrap
4144301	Tin	Processed
4144302	Tin	Processed
4144303	Tin	Processed
4144399	Tin	Processed
4154701	Tin	Processed
4154702	Tin	Processed
4154703	Tin	Processed
4154704	Tin	Processed
4154799	Tin	Processed
3422001	Titanium	Chemical
3422019	Titanium	Chemical
3936708	Titanium	Scrap
4160115	Titanium	Processed
4160116	Titanium	Processed
4160215	Titanium	Processed
3936709	Tungsten	Scrap
4160117	Tungsten	Processed

NPC	Mineral(s)	Type
4160118	Tungsten	Processed
4160216	Tungsten	Processed
4160217	Tungsten	Processed
4160218	Tungsten	Processed
4111516	Tungsten; Iron	Ferro
3422020	Vanadium	Chemical
4111517	Vanadium; Iron	Ferro
1429003	Zinc	Ore
3422021	Zinc	Chemical
3422022	Zinc	Chemical
3424080	Zinc	Chemical
3424081	Zinc	Chemical
3424082	Zinc	Chemical
3936500	Zinc	Scrap
4144201	Zinc	Processed
4144202	Zinc	Processed
4144299	Zinc	Processed
4154400	Zinc	Processed
4154501	Zinc	Processed
4154502	Zinc	Processed
4154503	Zinc	Processed
4154504	Zinc	Processed
4154505	Zinc	Processed
4154506	Zinc	Processed
4154507	Zinc	Processed
4154508	Zinc	Processed
4154509	Zinc	Processed
4154599	Zinc	Processed
4123104	Zinc; Iron	Processed
4126306	Zinc; Iron	Processed
1424007	Zirconium	Ore
1631010	Zirconium	Ore
3936710	Zirconium	Scrap
4160120	Zirconium	Processed
4160121	Zirconium	Processed
4160219	Zirconium	Processed
4111512	Zirconium; Iron	Ferro
4111518	Zirconium; Iron	Ferro

Source: Central Statistics Office (2011b)

Annex 3: Cost-Performance Scores for Substitutability

Mineral	Substitutability
Antimony	0.950
Barium	0.924
Bauxite	0.731
Beryllium	0.973
Bismuth	0.874
Boron	1.000
Chromium	0.714
Cobalt	0.853
Copper	0.854
Fluorine	0.891
Gallium	0.995
Germanium	0.925
Graphite	0.783
Hafnium	0.796
Heavy Rare Earths	1.000
Indium	0.867
Iron	0.917
Lead	0.806
Light Rare Earths	1.000
Limestone	0.881
Lithium	0.893
Magnesium	0.957
Manganese	0.983
Molybdenum	0.840
Neodymium	0.971
Nickel	0.940
Niobium	1.000
Phosphorus	1.000
Platinum	0.875
Potassium	0.999
Rhenium	0.941
Scandium	0.759
Selenium	0.727
Silicon	0.863
Silver	0.750
Strontium	0.877
Tantalum	0.866
Tin	0.779
Titanium	0.820
Tungsten	0.823
Vanadium	0.909
Zinc	0.929
Zirconium	0.956

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

Note: Detailed results can be provided upon request.

Source: Authors' computations

Annex 4: Sectoral GVA Multipliers

2-Digit NIC	Sector	GVA Multiplier
10	Food products	5.81
11	Beverages	5.81
12	Tobacco products	5.81
13	Textiles	3.25
14	Wearing apparel	3.25
15	Leather and leather products	3.25
16	Wood and wood products except furniture	2.60
17	Paper products	3.13
18	Printing	3.13
19	Coke and refined petroleum	8.80
20	Chemicals and chemical products	2.95
21	Pharmaceuticals, medicinal chemical and botanical products	2.71
22	Rubber and plastics products	3.72
23	Other non-metallic mineral products	2.58
24	Basic metals	4.49
25	Fabricated metal products, except machinery and equipment	4.49
26	Computer, electronic and optical products	3.14
27	Electrical equipment	3.14
28	Machinery and equipment not elsewhere classified	3.14
29	Motor vehicles, trailers and semi-trailers	2.96
30	Other transport equipment	2.96
31	Furniture	4.20
32	Other manufacturing	4.20

Source: Authors' computations

Annex 5: Mineral-Wise GVA Multipliers and Multiplier Scores

Mineral	Multiplier Coefficients with GVA Weights	Multiplier Score
Antimony	0.193	1.0
Barium	0.250	1.1
Bauxite	0.294	1.1
Beryllium	0.213	1.1
Bismuth	0.157	1.0
Boron	0.281	1.1
Chromium	0.447	1.2
Cobalt	0.259	1.1
Copper	0.302	1.1
Fluorine	0.386	1.1
Gallium	0.239	1.1
Germanium	0.334	1.1
Graphite	0.183	1.0
Hafnium	0.369	1.1
Heavy Rare Earths	0.465	1.2
Indium	0.240	1.1
Iron	0.368	1.1
Lead	0.301	1.1
Light Rare Earths	0.461	1.2
Limestone	0.263	1.1
Lithium	0.196	1.0
Magnesium	0.295	1.1
Manganese	0.448	1.2
Molybdenum	0.380	1.1
Neodymium	0.465	1.2
Nickel	0.320	1.1
Niobium	0.390	1.1
Phosphorus	0.329	1.1
Platinum	0.248	1.1
Potassium	0.290	1.1
Rhenium	0.240	1.1
Scandium	0.465	1.2
Selenium	0.305	1.1
Silicon	0.291	1.1
Silver	0.148	1.0
Strontium	0.378	1.1
Tantalum	0.278	1.1
Tin	0.335	1.1
Titanium	0.271	1.1
Tungsten	0.257	1.1
Vanadium	0.258	1.1
Zinc	0.334	1.1
Zirconium	0.178	1.0

Note: the following table has been used to assign the multiplier score for each mineral, based on the multiplier coefficient.

Multiplier Coefficients	Multiplier Score
< 0.20	1.0
> 0.20 and < 0.40	1.1
> 0.40	1.2

Source: Authors' computations

Annex 6: Cross-Cutting Index

Mineral	Cross-Cutting Index
Antimony	1.0
Barium	1.0
Bauxite	1.1
Beryllium	1.1
Bismuth	1.0
Boron	1.0
Chromium	1.0
Cobalt	1.2
Copper	1.0
Fluorine	1.0
Gallium	1.0
Germanium	1.0
Graphite	1.2
Hafnium	1.0
Heavy Rare Earths	1.0
Indium	1.0
Iron	1.0
Lead	1.0
Light Rare Earths	1.0
Limestone	1.0
Lithium	1.0
Magnesium	1.0
Manganese	1.0
Molybdenum	1.0
Neodymium	1.0
Nickel	1.0
Niobium	1.0
Phosphorus	1.0
Platinum	1.0
Potassium	1.0
Rhenium	1.0
Scandium	1.0
Selenium	1.0
Silicon	1.0
Silver	1.0
Strontium	1.0
Tantalum	1.0
Tin	1.0
Titanium	1.0
Tungsten	1.1
Vanadium	1.0
Zinc	1.0
Zirconium	1.0

Source: Authors' computations

Annex 7: Comparison of Supply Risks Using EPI vs WGI

Mineral	WGI Supply Risk	EPI Supply Risk
Antimony	33.0	33.6
Barium	12.6	16.6
Bauxite	7.6	8.6
Beryllium	17.9	27.4
Bismuth	35.4	46.1
Boron	12.9	19.8
Chromium	15.6	20.0
Cobalt	29.1	24.4
Copper	6.0	8.6
Fluorine	10.1	12.7
Gallium	33.2	43.3
Germanium	26.9	35.1
Graphite	13.8	16.7
Hafnium	13.4	18.6
Heavy Rare Earths	11.5	15.1
Indium	15.1	20.0
Iron	11.0	12.3
Lead	8.9	11.3
Light Rare Earths	11.5	15.1
Limestone	14.7	19.0
Lithium	10.2	14.4
Magnesium	26.4	34.4
Manganese	17.4	22.8
Molybdenum	9.6	13.3
Neodymium	11.0	14.4
Nickel	12.9	18.4
Niobium	29.8	36.0
Phosphorus	12.5	16.2
Platinum	16.6	22.4
Potassium	3.5	4.9
Rhenium	13.5	18.7
Scandium	25.6	34.0
Selenium	3.6	5.0
Silicon	6.3	8.6
Silver	4.9	7.3
Strontium	11.0	13.4
Tantalum	12.8	17.4
Tin	19.2	29.2
Titanium	4.8	5.2
Tungsten	25.8	39.7
Vanadium	12.0	19.8
Zinc	3.6	5.5
Zirconium	7.2	11.1

Source: Authors' computations

Annex 8: End-of-Life Recycling Rates

Mineral	Recycling Score
Antimony	0.00
Barium	0.00
Bauxite	0.02
Beryllium	0.00
Bismuth	0.00
Boron	0.00
Chromium	0.00
Cobalt	0.00
Copper	0.02
Fluorine	0.00
Gallium	0.00
Germanium	0.00
Graphite	0.00
Hafnium	0.00
Heavy Rare Earths	0.00
Indium	0.00
Iron	0.02
Lead	0.04
Light Rare Earths	0.00
Limestone	0.00
Lithium	0.00
Magnesium	0.00
Manganese	0.00
Molybdenum	0.00
Neodymium	0.00
Nickel	0.00
Niobium	0.00
Phosphorus	0.00
Platinum	0.02
Potassium	0.00
Rhenium	0.00
Scandium	0.00
Selenium	0.00
Silicon	0.00
Silver	0.02
Strontium	0.00
Tantalum	0.00
Tin	0.02
Titanium	0.00
Tungsten	0.00
Vanadium	0.00
Zinc	0.02
Zirconium	0.00

Source: Authors' computations

Annex 9: Mineral Import Reliance in India

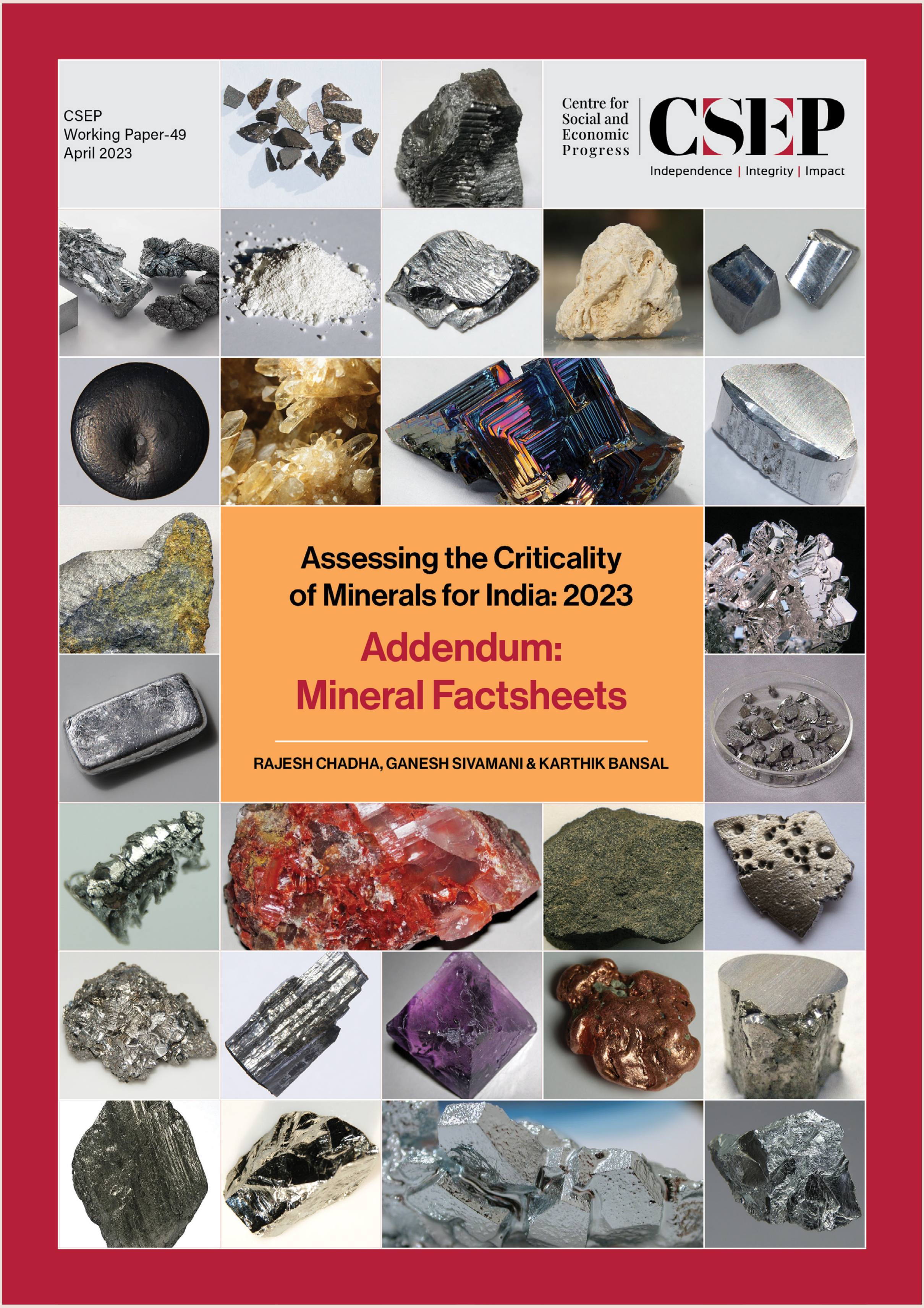
Mineral	Import Reliance (%)	Self-Sufficiency Index
Antimony	100	1.0
Barium	5	0.6
Bauxite	9	0.6
Beryllium	100	1.0
Bismuth	100	1.0
Boron	100	1.0
Chromium	0	0.6
Cobalt	100	1.0
Copper	57	0.8
Fluorine	100	1.0
Gallium	100	1.0
Germanium	100	1.0
Graphite	28	0.7
Hafnium	100	1.0
Heavy Rare Earths	100	1.0
Indium	100	1.0
Iron	0	0.6
Lead	57	0.8
Light Rare Earths	100	1.0
Limestone	0	0.6
Lithium	100	1.0
Magnesium	46	0.8
Manganese	58	0.8
Molybdenum	100	1.0
Neodymium	100	1.0
Nickel	100	1.0
Niobium	100	1.0
Phosphorus	85	0.9
Platinum	100	1.0
Potassium	100	1.0
Rhenium	100	1.0
Scandium	100	1.0
Selenium	100	1.0
Silicon	10	0.6
Silver	93	1.0
Strontium	100	1.0
Tantalum	100	1.0
Tin	100	1.0
Titanium	0	0.6
Tungsten	100	1.0
Vanadium	46	0.8
Zinc	7	0.6
Zirconium	78	0.9

Source: IBM, ASI, Authors' Computations

Annex 10: Supply Risk Substitutability

Mineral	Level of Production	Co-/By-Product	Supply Risk Substitutability
Antimony	0.98	0.98	0.98
Barium	1.00	0.96	0.98
Bauxite	1.00	0.95	0.97
Beryllium	1.00	0.99	0.99
Bismuth	0.97	0.90	0.94
Boron	1.00	1.00	1.00
Chromium	1.00	0.99	1.00
Cobalt	0.93	0.97	0.95
Copper	1.00	0.95	0.98
Fluorine	1.00	0.95	0.97
Gallium	1.00	1.00	1.00
Germanium	0.96	0.98	0.97
Graphite	1.00	0.90	0.95
Hafnium	0.87	0.93	0.90
Heavy Rare Earths	1.00	1.00	1.00
Indium	0.81	0.90	0.85
Iron	1.00	0.99	0.99
Lead	0.81	0.95	0.88
Light Rare Earths	1.00	1.00	1.00
Limestone	1.00	1.00	1.00
Lithium	1.00	0.95	0.97
Magnesium	1.00	0.98	0.99
Manganese	1.00	1.00	1.00
Molybdenum	0.92	0.93	0.92
Neodymium	1.00	0.91	0.95
Nickel	1.00	0.94	0.97
Niobium	1.00	1.00	1.00
Phosphorus	1.00	1.00	1.00
Platinum	1.00	0.96	0.98
Potassium	1.00	1.00	1.00
Rhenium	0.98	0.99	0.98
Scandium	0.92	0.92	0.92
Selenium	0.86	0.95	0.90
Silicon	1.00	1.00	1.00
Silver	0.83	1.00	0.91
Strontium	1.00	0.99	1.00
Tantalum	0.95	0.95	0.95
Tin	1.00	0.94	0.97
Titanium	1.00	0.92	0.96
Tungsten	1.00	0.96	0.98
Vanadium	0.94	0.98	0.96
Zinc	0.96	0.99	0.98
Zirconium	1.00	0.99	0.99

Note: Detailed results can be provided upon request.
Source: Authors' computations



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Assessing the Criticality of Minerals for India: 2023

Addendum: Mineral Factsheets

RAJESH CHADHA, GANESH SIVAMANI & KARTHIK BANSAL

The Addendum provides a summary of each mineral that has been assessed in this study. The mentioned details include the main use cases, the origin of extraction, India's mineral inventory, economic importance and supply risk for India, and the criticality comparison with the cut-off values.

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