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Assessing their Criticality and Projecting their Needs for Green Technologies

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Critical Minerals for India

Assessing their Criticality and Projecting their Needs for Green Technologies*

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Abstract

This paper assesses the level of criticality of 23 select minerals for India's manufacturing sector. Various indicators quantify the criticality along the dimensions of economic importance and supply risk. Lithium, strontium, and niobium have relatively high economic importance, and heavy rare earth elements, niobium, and silicon have relatively high supply risks. This paper also projects India's mineral needs for green technologies, including renewable electricity generation and electric vehicle manufacturing, in line with the country's various climate change mitigation objectives over the next two decades. While India has a large mineral geological potential, many of these minerals are not readily available domestically. Hence, there will be a need for further exploration, acquiring foreign mineral assets, and strengthening supply chains.

Backdrop

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 on account of non-availability or risks of unaffordable price spikes. These minerals lack substitutability and recycling processes. The global concentration of extraction and processing activities, the governance regimes, and environmental footprints in resource-abundant countries adversely impact availability risks. While some of these minerals 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 (Chadha, 2020).

India has been taking various steps for 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 in line 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. Critical minerals will play an important 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). However, the 21st-century's need for clean energy and high-tech equipment is proving to be a challenge due to the economic slump caused by COVID-19. 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 chain of requisite manufacturing equipment at home (Chadha, 2020).The objective of this paper is twofold: first, to assess the criticality of some of the minerals required for India's progress towards adopting green technologies, including solar power, wind turbines, and batteries for electric vehicles; and second, to project scenarios for India's minerals requirements over the next two decades.

I – Assessing the Criticality of Non-Fuel Minerals in India

Various 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 (CMAs) Whittle et al. (2020) conclude that the lack of availability of these minerals could disrupt manufacturing operations in Australia. The 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 and hence can impact global supplies.

The US National Science and Technology Council (USNSTC) defines critical minerals as “those that have a supply chain that is vulnerable to disruption, and that serve an essential function in the manufacture of a product, the absence of which would cause significant economic or security consequence”. 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).

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

Critical Minerals Assessments for India

A Planning Commission report in 2011 (Planning Commission, 2011) highlighted the need for the assured availability of minerals resources for the country’s industrial growth, with a clear focus on the well-planned exploration and management of already discovered resources. The report analysed 11 minerals under four broad categories: metallic, non-metallic, precious stones and metals, and strategic minerals. The strategic minerals were tin, cobalt, lithium, germanium, gallium, indium, niobium, beryllium, tantalum, tungsten, bismuth, and selenium. These minerals are termed strategic due to the limited availability of substitutes and their demand in high-technology products such as LCD screens, hybrid cars, wind turbine magnets, and defence equipment. The report emphasised the need to increase resource efficiency, identify substitutes, and develop end-of-life mineral recycling.

The Ministry of Mines sponsored study titled “Rare Earths and Energy Critical Minerals: A Roadmap and Strategy for India” (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. However, initiatives need to be taken in the areas of refining, metal/alloy production, and manufacturing components for end-use.

In their book on strategic minerals, Lele and Bhardwaj analysed the availability, requirements, utility, and deficiency of nine strategic minerals in India: antimony, bismuth, beryllium, cobalt, germanium, lithium, nickel, tungsten, and tin (Lele & Bhardwaj, 2014). 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. In a subsequent study, Lele (2019) has an extended discussion on India’s need for strategic minerals. The paper discussed the importance of these minerals for the green energy transition, and the various challenges faced in the sector, including its mining and processing. The study mentioned the need for research in recycling of strategic minerals and finding the right substitutes.

A study sponsored by the Department of Science and Technology and the Council on Energy, Environment and Water (DST-CEEW) highlighted the paucity of research in India related to ensuring mineral resource security for the manufacturing sector. The study made a pioneering attempt at computing a criticality index for 49 non-fuel minerals, including rare earth minerals (Gupta, Biswas, & Ganesan, 2016). A mineral used in small quantities in a high-value-add manufacturing sector is considered more critical than a mineral used in large quantities in a low-value-add manufacturing sector. The supply-side risks for a mineral are based on the domestic endowment, 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 the reference year 2011.[1] One of its recommendations was for India to institute the institutional reforms outlined in the National Mineral Exploration Policy (NMEP) 2016, which included 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 for ensuring a constant supply of critical minerals (Ministry of Mines, 2016).

This paper evaluates the criticality of 23 non-fuel minerals in India. Of these minerals, some are found in surficial deposits (such as iron ore and bauxite), while others are in deep-seated deposits (such as rare earths and copper). While the DST-CEEW (2016) study was based on the EU methodology (European Commission, 2014), this CSEP study uses the updated EU methodology (European Commission, 2017) with some modifications.

Methodology

Indicators

This study evaluates the criticality of 23 minerals by economic importance for the Indian economy and their supply risks. The supply risks have been computed using the monopoly power of the mineral-producing and sourcing countries according to their governance regimes.

[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.

Table 1: Minerals Chosen: Uses and Rationale

Mineral	Major Uses	Critical for India in:		
		CEEW 2011	IBM Inventory 2015	Planning Commission 2011
Bauxite	Aluminium			
Chromium	Alloys of steel, dyes	✓		
Cobalt	Alloys of steel, medical implements, batteries	✓	✓	✓
Copper	Electricity applications, pipes and pumps			
Graphite	Refractories, rubber, and electronics	✓		
Indium	Electronics, electrical equipment			✓
Iron	Steel			
Lead	Batteries, electrical equipment			
Limestone	Cement	✓		
Lithium	Batteries (electric vehicles)		✓	✓
Manganese	Steel production			
Molybdenum	Steel alloy	✓	✓	
Neodymium	Permanent magnet			
Nickel	Steel alloy		✓	
Niobium	Alloys of steel	✓	✓	✓
Heavy rare earths	Alloys of steel, alloys of aluminium		✓	✓
Light rare earths	Ceramics, flint	✓	✓	✓
Silicon	Electronics components, steel manufacturing	✓		
Silver	Jewellery, medicine, electronics			
Strontium	Alloys of aluminium	✓		
Titanium	Pigments		✓	
Vanadium	Steel alloy	✓	✓	
Zinc	Steel alloy			

Sources: (Gupta, Biswas, & Ganesan, 2016), (Indian Bureau of Mines, 2015) (Planning Commission, 2011)

Some minerals, such as copper ore and iron ore, were not found to be strategic or critical according to earlier reports, but this study includes these minerals for their perceived economic importance. Other additional minerals included in this study are also needed to manufacture clean energy technologies like wind turbines, solar PVs, and electric vehicles.

In this study, the criticality of three sets of rare earth elements (REEs) have been considered: (1) yttrium and scandium (collectively called heavy rare earths); (2) cerium (referred to as light rare earths); and (3) neodymium. REEs are a group of seventeen metallic elements. A variety of these minerals are imported or produced in India, not all of which have been covered in this study. There has been some production of yttrium, cerium, neodymium, praseodymium, and lanthanum, primarily through the extraction of monazite. Neodymium is also a light rare earth element, used for the manufacture of permanent magnets, including turbines and mobile phones (Hanseng(Ningbo) Magnetech, 2019).

Economic importance

The economic importance (EI) axis of this study broadly measures the impact on the manufacturing sector if a mineral is not available in the supply chain. Three indicators were used to compute the economic importance of each mineral (Equation 1). The first was the average of the GVAs of the manufacturing sectors in which the mineral is consumed, weighted by the respective mineral consumption shares in these sectors relative to the total mineral consumption. The second was the substitutability index, which measures the cost and performance of substitutes for the mineral, in case available, in each end-use application. The third was the GVA multiplier coefficient, which measures a mineral's impact on the manufacturing GVA, computed using sectoral GVA multipliers.

Economic Importance:

$$EI = \left(\sum_{s} A_s Q_s\right) \times \sigma_{EI} \times \mu \qquad (1)$$

Equation 1 shows the computation of a mineral's economic importance, 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;

and μ is the mineral's GVA multiplier coefficient.

The study used the three most recent Annual Surveys of Industries (ASI) – 2016-17, 2017-18, and 2018-19 – for computing the indicators in EI.[2] The detailed unit-level ASI data was used, and a three-year arithmetic mean was taken for the EI axis. The ASI includes industry statistics for only the organised sector (see Annex 1 for the broad classification of manufacturing sectors). While data are available for the unorganised sector, it was assumed that most mineral use takes place in the organised sector. Additionally, the ASI unit-level data reports ten of the most consumed products by each factory. Hence, the consumption data of some minerals may not be reported, and the results could be underestimated.

For this study, the domestic and imported consumption of minerals was computed at the 5-digit level of the National Industrial Classification (NIC) (Central Statistical Organisation, 2008) from the ASI data. Sectoral GVAs were also computed at the 5-digit level from the unit-level data and matched with the published results. Information on the types of mineral ores and their chemical and alloy forms was taken from the National Product Classification (NPC) (Central Statistics Office, 2011a). Ideally, only the ore form of the mineral should be analysed, but as India does not extract or process many of the minerals in this study, the processed forms of these minerals were included

[2] The 2018-19 ASI was published in September 2021. This version used a different method for computing the GVA, where rent received for buildings is included and expenses on R&D are excluded. 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.

(Annex 2 lists the NPCs of the minerals considered). Data on indium and neodymium were not included in the NPC list, so the global reference values of the industry-wise use of these minerals were taken from relevant sources.

The substitutability index, the second indicator under EI, is a measure that dampens the economic importance of a mineral if similarly priced substitutes exist which perform well. The index ranges from 0.6 to 1.0, where 0.6 represents a highly substitutable mineral and 1.0 represents a mineral that is not substitutable. The substitutability index is computed by assigning a score based on each substitute's cost and performance (Table 2) for each broad end-use case. For cases in which the use of a mineral is a secondary product (such as steel or aluminium), the final use of the secondary product was considered (e.g., infrastructure for steel and structural components for aluminium). This cost-performance score has been evaluated using published information on the existence of substitutes, and their relative costs and performance (Annex 3). The substitutability index is the average cost-performance score weighted by the shares of mineral consumption by the two-digit sectors (Equation 2).

Table 2: Cost-Performance Matrix

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

Substitutability Index:

$$\sigma_{EI} = \sum_{s} A_s \sigma_s \qquad (2)$$

Equation 2 gives the computation of 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;

and σ_s is the cost-performance score for sector s.

The third component of the economic importance of minerals is the GVA multiplier coefficient of each mineral. These are based on the GVA multipliers of 131 sectors computed using the CSEP India Input-Output Transactions Table 2015-16 (Annex 4) (Chadha, Saluja, & Sivamani, 2021). The GVA multiplier is 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. The GVA multiplier coefficient of a mineral was computed as an average of the GVA multipliers of the mineral-consuming sectors weighted by respective sectors' GVA shares in manufacturing GVA and the sectoral shares of mineral consumption to the total consumption of the mineral. The GVA multiplier coefficients for each mineral were scored as shown in Annex 4. Minerals with high GVA multiplier coefficients would increase the EI score.

GVA Multiplier Coefficient:

$$\mu = \sum_{s} A_s \mu_s Q_s \qquad (3)$$

The computation of the weighted average GVA multiplier is shown in Equation 3, where:

μ is the mineral's GVA multiplier coefficient;

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

μ_s is the GVA multiplier for sector s;

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

Supply risk

The supply risk indicator of the criticality assessment seeks to measure the vulnerability in global mineral supply chains due to the concentration of mineral extraction in some countries and the quality of governance in these jurisdictions. The Herfindahl-Hirschman Index (HHI) was used to measure the concentration of mineral extraction by country (López-Morel & Navarro-López, 2014). Two sets of producing countries are considered: the extracting countries and the countries from which India sources its raw material. A higher HHI score for a mineral indicates that fewer countries extract this mineral, thus increasing its supply risk. The supply risk also rises if supplying countries have poor governance systems and is partially offset when supplying countries have better governance regimes. The quality of governance has been measured using the World Bank's Worldwide Governance Indicators (WGI) (World Bank, 2021). Country-wise, mineral extraction data is taken from *World Mining Data* (WMD) (Reichl & Schatz, 2021) and, if the data is missing in the WMD, from the United States Geological Survey (USGS) (U.S. Geological Survey, 2021). India's sourcing of mineral data is taken from the Indian Bureau of Mines and the World Bank's WITS database (World Bank, 2019).

The governance and market concentration supply risks of a mineral are offset by three factors: India's import reliance on the mineral, the rate of end-of-life recycling in India, and the supply risk substitutability. In the case of a mineral with low import reliance, its global extraction concentration becomes less relevant; for a mineral with a high recycling rate in India, the supply risk is lowered; and for a mineral that has substitutes with lower supply risks, its supply risk is also reduced. The computation of the supply risk is given in Equation 4.

Data on end-of-life recycling was taken from various published sources, including Indian government publications (Annex 5). However, due to the lack of data on the recycling rates of many minerals in India, instead of using actual recycling rates, a score is assigned based on the level of recycling (Table 3).

Table 3: Recycling Scores

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

Supply risk:

$$SR_G = \left[(HHI_{WGI})_{GS} \times \frac{IR}{2} + (HHI_{WGI})_{India} \times \left(1 - \frac{IR}{2}\right)\right] \times (1-\rho) \times \sigma_{SR} \times \epsilon \qquad (4)$$

The computation of the supply risk is shown in Equation 4, 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;

ρ is the end-of-life recycling rate of the mineral, ranging from 0 to 1;

IR represents the import reliance of the minerals;

σ_{SR} is substitutability in the supply risk axis;

and ϵ is the degree of self-sufficiency.

$(HHI_{WGI})_{GS}$ represents the concentration of global supply of minerals, while $(HHI_{WGI})_{India}$ considers only the concentration of minerals in countries from which India sources its mineral needs.

The Herfindahl-Hirschman Index (HHI):

$$HHI_{WGI} = \sum_c S_c^2 WGI_c \qquad (5)$$

The HHI is computed by taking the sum of the squares of the shares of mineral extraction by country. The governance score of each of the countries is also accounted for in the computation of the HHI, shown in Equation 5, where:

S_c represents the share of mineral extraction in country c;

and WGI_c the world governance indicator score for country c.

The HHI equation was used twice: first, to compute the concentration of the global supply of minerals, and second to compute the concentration of Indian sourcing of mineral imports by country.

The WGI data give six dimensions of governance for each country: Voice and Accountability; Political Stability and the Absence of Violence; Government Effectiveness; Regulatory Quality; Rule of Law; and Control of Corruption. These dimensions are measured on a range of -2.5 to 2.5. For this study, the arithmetic means of the scores were normalised (using a min-max transformation) with frontier values of -2.5 and 2.5, such that all scores ranged from 0 to 100. The scores were then inverted, so that 0 represented the best-performing country and 100 the worst. This was done so that a higher score would increase the supply risk of the mineral.

Import Reliance (IR)

$$IR = \frac{import - export}{domestic\ production + import - export} \qquad (6)$$

The computation of import reliance is given in Equation 6. Import reliance is 100% for minerals not extracted in India (i.e., when domestic production = 0, IR = 1). The IBM Yearbook provides information on the degree of self-sufficiency of some of the minerals considered in this study (Annex 6) (Indian Bureau of Mines, 2019). The concept of self-sufficiency refers to the degree of domestic production of a mineral satisfying domestic needs.

The level of substitutability in the context of supply risk was computed by taking the geometric mean of two indicators: whether the mineral and its substitute are primary minerals or mined as by-products or co-products; and the level of production of the substitute (Annex 7). Information on these was taken from various published sources. Minerals were scored based on the ease of the extraction process of the substitutes, and the corresponding levels of their production (Tables 4 and 5).

An example of co-products is lead and zinc, which are typically found together, and 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, but if it is a co-product or by-product, and the substitute is a primary product, there is a reduction in its supply risk substitutability. Minerals that are co-products and by-products are likely to have some constraints in their supply chains due to difficulties in their extraction and processing.

The production level of the substitute is also considered: when a substitute has a higher production level than the mineral, the supply risk is lower. When computing this indicator, an assumption was made that the substitute would replace the mineral in equal weight, which is not always the case.

Table 4: Mineral Extraction of Substitutes Scores

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

Table 5: Production Level of Substitutes Scores

Substitute	Score
Less production	1.0
More production	0.9

Substitutability Supply Risk

$$\sigma_{SR} = \sqrt{\left(\sum_{s} A_s \sigma_P\right)\left(\sum_{s} A_s \sigma_{BC}\right)} \tag{7}$$

As with the computation of EI substitutability, the SR substitutability indicators were computed by taking the average of the scores, weighted by the mineral consumption in each sector. The computation of SR substitutability is given in Equation 7, where:

σ_{SR} is the SR substitutability indicator;

A_s is the share of mineral consumption in sector s;

σ_P represents the production substitutability;

σ_{BC} the co-/by-production score;

and σ_{SR} the overall substitutability for supply risk.

The supply risk of each mineral relating to environmental protection performance was also computed, in addition to the quality of governance indicators. Equations 4 and 5 were used to compute the environmental supply risks (SRE) which would account for the extracting and supplying countries' performance on sustainability issues. The Environmental Performance Index (EPI) was used for this indicator (Yale Center for Environmental Law & Policy, 2020). However, there was a high degree of correlation between the EPI and WGI datasets (0.78), and an even higher correlation between and (0.98). Thus, only the governance supply risk results were included in this study.

The methodology used in this study modifies the supply risk equation from the EU Methodology Guidelines 2017 by including an additional component, to measure the level of mineral self-sufficiency; takes values between 0.6 and 1.0, where 0.6 indicates a high level of domestic production compared to imports, and 1.0 indicates a high level of imports compared to domestic production. This term is in addition to the computed IR value to ensure that domestic production levels are fully captured. Mineral-wise values and scores of self-sufficiency are given in Annex 8.

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 other trade war issues. While export taxes are permitted under the multilateral WTO discipline, quantitative restrictions are not allowed, 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 is collated from different sources.

Results

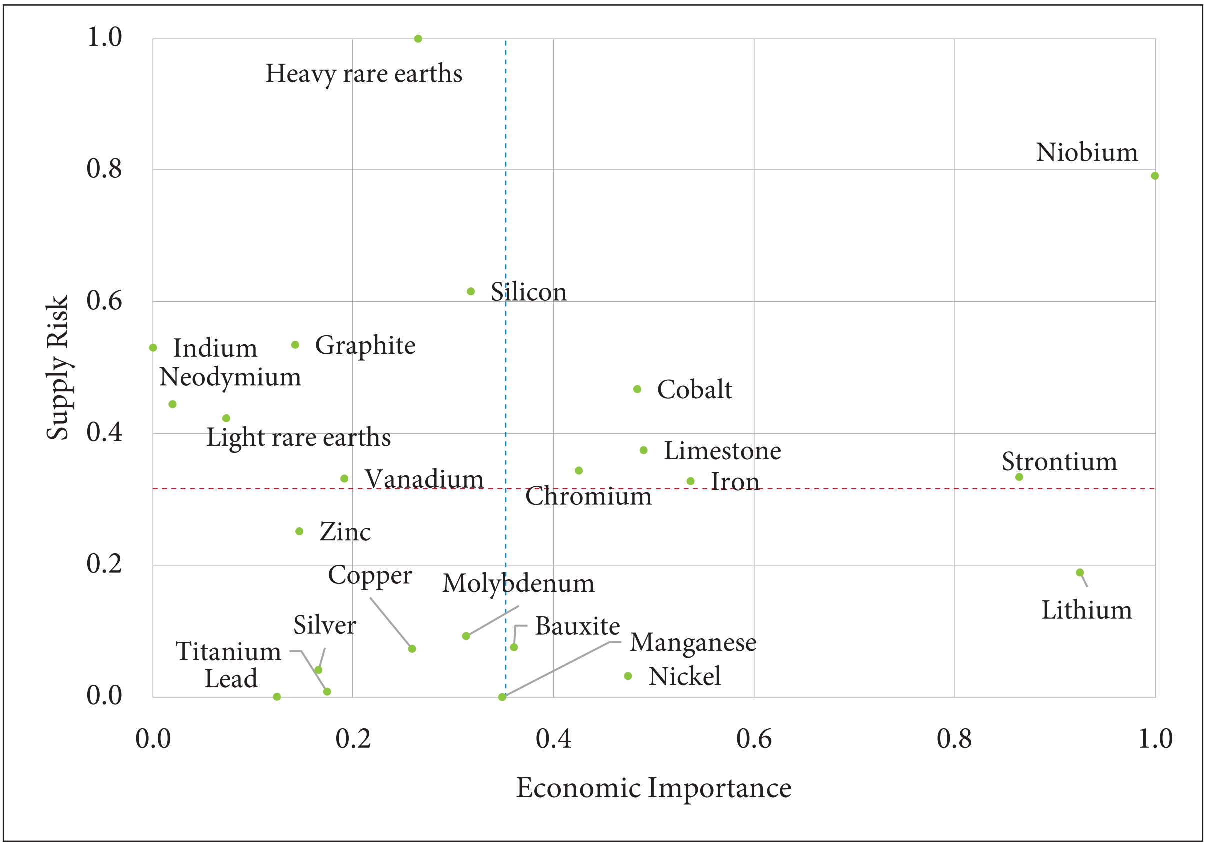
The computed criticality of 23 minerals in terms of their economic importance and supply risks is shown in Table 6. Higher values are shown in darker colours. Economic importance broadly measures the share of manufacturing value-add foregone in India in the absence of a specific mineral's availability. The supply risk indicates the global-level concentration of mineral extraction and processing.

Table 6: Results of Critical Minerals Assessment

Mineral	Economic Importance	Supply Risks
Bauxite	1.0%	5.1
Chromium	1.2%	14.2
Cobalt	1.3%	18.5
Copper	0.8%	5.0
Graphite	0.5%	20.8
Heavy rare earths	0.8%	36.6
Indium	0.1%	20.6
Iron	1.5%	13.7
Lead	0.4%	2.5
Light rare earths	0.3%	17.0
Limestone	1.3%	15.3
Lithium	2.4%	9.0
Manganese	1.0%	2.5
Molybdenum	0.9%	5.7
Neodymium	0.2%	17.7
Nickel	1.3%	3.6
Niobium	2.6%	29.5
Silicon	0.9%	23.5
Silver	0.5%	3.9
Strontium	2.3%	13.9
Titanium	0.6%	2.8
Vanadium	0.6%	13.8
Zinc	0.5%	11.1

The results from Table 6 have been normalised between 0 and 1 using the min-max transformation and depicted in graphical form in Figure 1. The horizontal and vertical lines in the graph represent the average supply risk and economic importance scores, respectively. Minerals in the upper-right quadrant are the most critical, with high risks on both axes. In contrast, minerals in the lower-left quadrant are relatively less critical on both counts.

Figure 1: Normalised Results of Critical Minerals Assessment



This study has analysed the criticality of 23 minerals for the Indian economy. For each of these, the study 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 mining potential and transformation to green technology use, including renewable energy and electric vehicles.

The analysis suggests that niobium, lithium, and strontium, have relatively high economic importance, adjusted by their substitutability possibilities and GVA multipliers. Nine minerals have relatively low economic importance: titanium, graphite, silver, vanadium, zinc, lead, light rare earths, neodymium, and indium. Most minerals have some degree of substitutability, except for niobium and silver, for which no good substitutes were found.

The supply risk is relatively high for yttrium and scandium (heavy rare earths), followed by niobium and silicon. India does not have the recycling capacity for most minerals except for copper and iron, although this is low. While there are limited technological options for recycling some minerals, for some there is scope for increased end-of-life recycling, as demonstrated by higher recycling rates globally. Titanium, lead, and manganese face relatively low level of supply risks.

Future Work

The current study on critical minerals assessment encompasses two axes, economic importance and supply risk, with multiple indicators measuring each. More indicators may be added to more precisely evaluate the criticality of these minerals. For example, on the supply risk axis, trade considerations could be included, which would bring into the computation the existing trade agreements that allow easier imports of minerals (i.e., considering tariffs and export restrictions). Additionally, this exercise computes the current scenario of mineral criticality. The second section of this paper looks at cases in which some minerals may become more critical over the next two decades due to the increased use of green technologies for climate change mitigation. However, broader changes in the manufacturing structure of the economy have not been studied. Finally, the critical minerals assessment must be performed periodically to capture the changing requirements of domestic and global economies.

II – Projecting India's Mineral Needs for Green Technologies

India's Climate Change Mitigation Commitments

Global discussions and policies are in favour of countries moving to clean energy technologies for power generation and transport. The UN Environment Programme defines climate change mitigation as the process to reduce or prevent the emission of greenhouse gases. The world needs new technologies and renewable energy, but at the same time existing equipment can be modified to be made more energy efficient, by adding internet connectivity to machinery or through carbon capture and storage (United Nations Environment Programme, 2021).

One of the earliest international treaties on climate change to which India was a signatory was the Kyoto Protocol in 1997, at the third Conference of Parties (COP-3) of the United Nations Climate Change Conference (UNFCCC).[3] The agreement sought to reduce greenhouse gas emissions based on the consensus that human-made greenhouse gas emissions predominantly cause global warming. However, India had no binding targets under this treaty. A follow-up event in Copenhagen in 2009, COP-15 (United Nations Framework Convention on Climate Change, 2009), announced the constitution of the Green Climate Fund (GCF), which was formally established at COP-16 held in Cancun in 2011 (UNFCCC, 2011). The objective of the GCF is to support developing countries in adopting climate-resilient development paths towards lower emissions.

More recently, the COP-21 was held in Paris in 2015 (UNFCCC, 2015). The Paris Agreement, a legally binding international treaty on climate change, became operational on November 4, 2016. Its goal is to limit global warming to well below 2 degrees, preferably to 1.5 degrees Celsius, compared to pre-industrial times levels[4]. The Paris Agreement works on a five-year cycle of increasingly ambitious climate action by countries. By 2020, countries were to submit their plans for climate action known as their nationally determined contributions (NDCs).

The most recent meeting on climate change issues was held in November 2021 in Glasgow to discuss accelerating action towards the goals of the Paris Agreement (UNFCCC, 2021). India committed to five broad climate change mitigation strategies in COP26, including increasing its non-fossil fuel energy capacity to 500 GW by 2030 (which is higher than the earlier 450 GW target which has been used in this study for mineral demands computations), reducing the carbon intensity of the economy by less than 45 percent in 2030 compared to 2005 levels, and achieving the target of Net Zero emissions by 2070 (Ministry of External Affairs, 2021).

India has been undertaking various actions for 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 for sustainable development in line with the country's economic and environmental objectives. The NAPCC consists of eight missions headed by various central ministries, including the National Solar Mission and the National Mission for Enhanced Energy Efficiency.

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[3] The first COP meeting (COP 1) was held in Berlin in March 1995.

[4] The IPCC Special Report on Global Warming uses the reference period 1850-1900 to refer to pre-industrial times (Intergovernmental Panel on Climate Change, 2018).

India announced its Nationally Determined Contributions (NDC) in 2015. Three of its quantifiable goals (of a total of eight NDCs) are to: reduce the emission intensity of its GDP by 33-35% by 2030 from 2005 levels (Government of India, 2015); increase the share of cumulative power generation capacity from non-fossil fuel-based energy sources to 40% by 2030, aided by technology transfers and low-cost international finance from the Green Climate Fund; and create additional carbon sinks of 2.5-3 GtCO2e.

One of the major intermediate goals for 2030 is to increase renewable energy capacity to 450 GW, from 100 GW in 2021 (excluding large hydropower generation), most of which will be from solar power (Ministry of New and Renewable Energy, 2021).

The country will need to ensure a reliable supply of either the raw minerals for manufacturing or the end-use green technologies to meet these climate change mitigation targets. This section seeks to quantify the mineral needs for these technologies, in raw form as well as embedded within imported products, and prioritise the importance of securing mineral assets, either domestically or from abroad, based on the critical mineral assessment carried out in the previous section.

Literature Review

The two reports, *India 2020 Energy Policy Review* and *India Energy Outlook 2021,* by the International Energy Agency (IEA) have various projections on energy-use changes in India until 2040 (International Energy Agency (IEA), 2020b) (International Energy Agency (IEA), 2021a). The latter makes four projections based on the country's recovery from the COVID-19 pandemic and its policies on clean energy: the Stated Policies Scenario (STEPS), India Vision Case (IVC), Delayed Recovery Scenario (DRS), and Sustainable Development Scenario (SDS). Figure 2 shows India's electricity generation projections till 2040.[5]

The World Bank report *Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition* highlights the mineral needs for various clean energy technologies and provides global mineral demand projections until 2050 (Hund, La Porta, Fabrega, Laing, & Drexhage, 2020). It states that "a low-carbon future will be very mineral intensive because clean energy technologies need more materials than fossil-fuel-based electricity generation technologies." The report delineates the relative demand risks from cross-cutting minerals and concentrated minerals. "Cross-cutting minerals, such as copper, chromium, and molybdenum, are used across a wide variety of clean energy generation and storage technologies and have stable demand conditions. This is because these minerals do not depend on the deployment of any one specific technology within the clean energy transition." On the other hand, "concentrated minerals, such as lithium, graphite, and cobalt, are needed only for one or two technologies and therefore possess higher demand uncertainty as technological disruption and deployment could significantly impact their demand."

While most of the supplies would come from new mining activities, overall demand can be partly met through adopting efficient technologies and recycling, keeping in mind human rights and environmental externalities (Dominish, Teske, & Florin, 2019).

IEA's *The Role of Critical Minerals in Clean Energy Transitions* discusses the reliability of supply chains in meeting projected demands. It highlights that "*today, the data shows a looming mismatch between the world's strengthened climate ambitions and the availability of critical minerals that are essential to realising these ambitions*" (International Energy Agency (IEA), 2021b). While there is no

[5] The Stated Policies Scenario (STEPS) provides a balanced assessment of the direction in which India's energy system is heading, based on today's policy settings and constraints and an assumption that the spread of Covid-19 will largely be brought under control in 2021.

shortage of resources worldwide, *today's supply and investment plans for many critical minerals fall well short of what is needed to support the accelerated deployment of solar panels, wind turbines, and electric vehicles.*

India's Green Technology Commitments

One facet of India's critical mineral needs will depend on the types of clean energy technologies used in the transition and the share of domestic manufacturing versus import reliance in each technology. Thus, the discussion would differ across types of energies and their projections.

Solar power will play a major role in India's clean energy transition. Some of the key minerals for manufacturing photovoltaic cells include silicon, silver, indium, arsenic, gallium, germanium, and tellurium[6] – *none of which India produces.*

The government had announced in 2015-16 a goal of 175 GW of renewable energy capacity by 2022 (United Nations, 2016), of which solar capacity would make up 100 GW. In 2021, solar capacity is around 44 GW (Central Electrical Authority, 2021). The declared goal of 450 GW renewable capacity by 2030 would include 300 GW of solar power (the breakdown of the remaining 150 GW has not yet been announced but would primarily include small hydropower, wind, and some bioenergy) (Ministry of New and Renewable Energy, 2020).

To meet the goal of enhanced solar power capacity, the Ministry of New and Renewable Energy has set up support mechanisms to help develop domestic solar PV manufacturing (Ministry of New and Renewable Energy, 2021): besides production-led incentives (PLIs), customs duties on modules and cells will be imposed from April 2022 to encourage domestic manufacturing and purchases (Bhaskar, 2020); and some solar park tenders include a clause that mandates that a certain number of panels must be domestically produced (Garg, 2021).

Until 2011, India was one of the largest exporters of solar modules manufactured by companies such as Tata Power Solar Systems, Moser Baer, and BHEL. However, domestic growth was undercut for various reasons, including lack of financial support, inconsistent government policy, and competition from low-priced Chinese exports (Das, 2021).

Wind turbines will also play a role in India's clean energy transition. Some important minerals needed for their manufacture are chromium, manganese, molybdenum, nickel, and rare earth elements. India extracts some chromium, manganese, and rare earth elements (REEs), but the bulk of the REEs are currently mined and processed in China.

India targets having 60 GW wind turbine capacity by 2022, up from 39.5 GW in August 2021 (United Nations, 2016). Of the 450 GW renewables target in 2030, wind is expected to provide for some of the remaining 150 GW renewables capacity. India has a 300 GW wind potential at a 100m hub height and can develop offshore wind projects, though the tariffs for offshore wind power are higher than their onshore counterparts (Bhatti, 2021).

Domestic manufacturing capacity in India exists for wind turbines, including that of 1.5 MW and 1.6 MW turbines. The government provides concessional custom duty certificates (CCDCs) – a reduced custom duty rate on components required for the manufacturing of wind turbines – for critical components needed for wind turbines to promoting their manufacturing (Ministry of New and Renewable Energy, 2021a), along with other schemes to promote domestic manufacturing and installation (Ministry of New and Renewable Resources, 2021b).

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[6] The criticality and mineral requirements of some of these minerals will be measured in the ongoing work at CSEP.

Electric vehicles (EVs) are seeing a push in India under the Faster Adoption and Manufacturing of Hybrid and Electric Vehicles (FAME) scheme (Mint, 2021). The transition to electric vehicles would reduce vehicular emissions and dependency on fossil fuels. Some of the key minerals needed to manufacture EV batteries include lithium, cobalt, and rare earth elements. However, India does not mine lithium or cobalt, though it has some resources and reserves of cobalt.

NITI Aayog has set a 2030 target for EV sales to make up 70% of commercial car sales, 30% of private car sales, 40% of buses, and 80% of two-wheelers and three-wheelers (Narasimhan, 2020). This is supported by production-linked incentives to battery and automobile manufacturers. Additionally, the country would need to develop its public charging infrastructure.

Various domestic companies are developing projects for the manufacture of Li-ion batteries. These include a joint venture by Toshiba, DENSO, and Suzuki (to supply EV plants in India), Exide Industries, Tata Chemicals, Amperex Technology, and Li Energy (EV Reporter, 2019). Epsilon Carbon was the first company in India to manufacture graphite anode materials for Li-ion batteries, for which the raw material is coal tar (domestically available in India) (EV Reporter, 2020). The recycling of Li-ion batteries is also being planned for by companies such as Tata Chemicals (Tata Chemicals, 2019), which has set up a manufacturing plant in Gujarat and is working to establish more such plants (Tata Chemicals, 2021).

Other sectors of importance to India's green technology transition include nuclear power and hydro turbines. The uses of the minerals mentioned in this section are given in Table 7, with details on India's geological potential and the top global extractors.

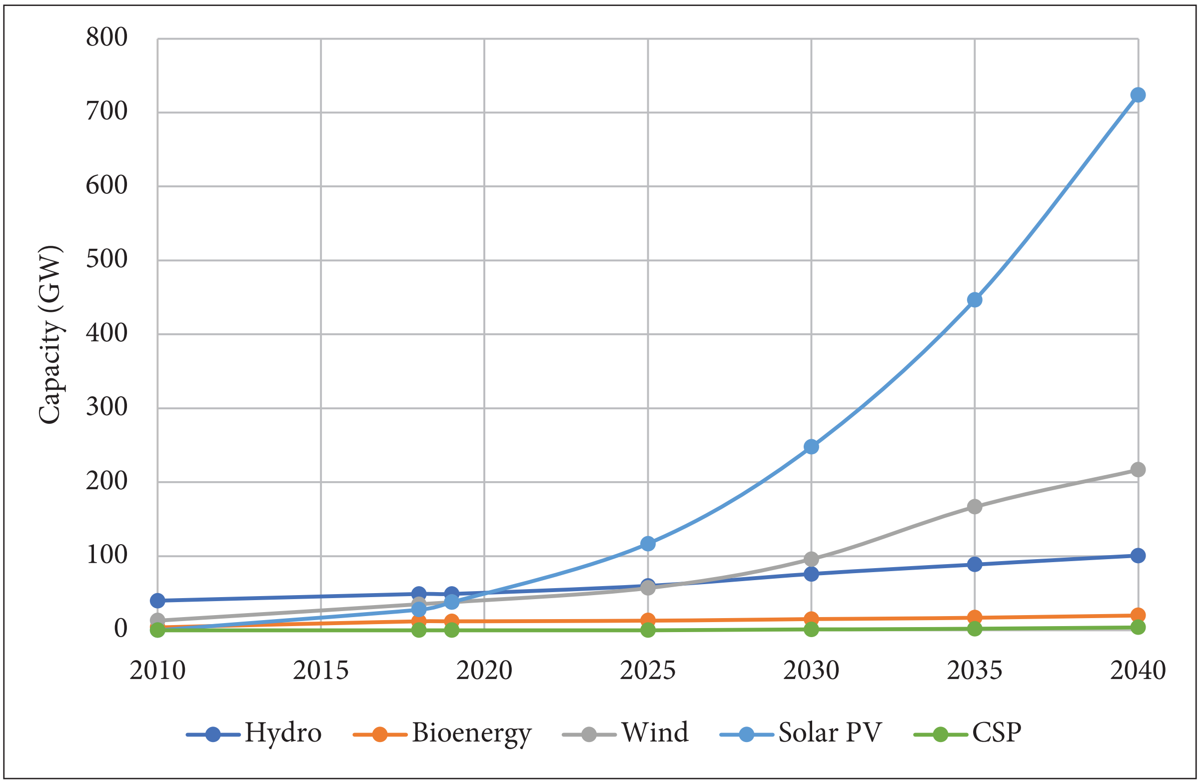
Projecting Mineral Demands

The *India Energy Outlook 2021* provides various projections of electricity generation capacity in the country up to 2040 (International Energy Agency (IEA), 2021a). This study uses the Stated Policies Scenario (STEPS) to estimate India's mineral needs for clean technologies. STEPS is based on the Indian government's stated policies and the assumption that the COVID-19 pandemic will be brought under control by the end of 2021.

Figure 2 shows the breakdown of renewable power capacity from 2010 to 2040 in the STEPS projections. The IEA estimates India's power capacity from renewable sources at 26% in 2019; the projection under STEPS is 69% in 2040. The driving force behind this change will be solar power, which will account for 68% of the renewable power capacity and 47% of total power capacity. However, this technology only includes solar PVs and not concentrated solar power (CSP)[7] which is expected to contribute only a minor share of the renewable power capacity. As a result, coal power capacity will see a moderate increase till around 2030, although the overall share of coal in total power capacity will drop from 57% in 2019, to 34% in 2030, and to 17% in 2040. However, India has not yet quantified its phasing down of coal use in power generation, though it is feasible for operational capacity to peak in 2030 (Ahluwalia & Patel, 2021).

[7] CSP uses mirrors to concentrate solar power onto a receiver, which generates electricity primarily through thermal generation.

Figure 2: Renewable Power Capacity Projection (STEPS)



Clean technologies would require critical minerals in varying proportions. The approximate material intensities have been sourced from the relevant literature (Ashby, Attwood, & Lord, 2012). This section of the study focuses on the demand for key minerals for the manufacture of various green technologies (Table 7).

Table 7: Critical Minerals Used in Green Technologies

Mineral	Clean Technology Uses	India's Geological Potential	Top Three Global Extractors
Chromium	Stainless steel alloys (wind turbines)	Yes	South Africa, Turkey, Kazakhstan
Cobalt	Steel alloys, batteries, pigment	Yes	DR Congo, China, Canada
Graphite	Electrical conductors	Yes	China, India, Brazil
Indium	Photovoltaic cells, display technology	None	China, South Korea, Japan
Lithium	Batteries	None	Australia, China, Chile
Manganese	Steel and aluminium alloys	Yes	South Africa, China, Australia
Molybdenum	Steel alloys	Yes	China, Chile, United States
Nickel	Stainless steel alloys	Yes	Indonesia, Philippines, Russia
Rare earth elements	Batteries, electronics, magnets	Some	China, United States, Myanmar
Silicon	Electronics, infrastructure	Yes	China, Russia, Norway

Sources: (Indian Bureau of Mines, 2015) and (U.S. Geological Survey, 2021)

Some assumptions were made when computing the total mineral requirements. First, it was assumed that no existing or constructed renewable energy capacity would be decommissioned during the period of the projections. Secondly, the mineral intensities for green technologies would not change. Thirdly, while these results show the total amount of critical minerals needed, not all will be manufactured domestically – some would be embedded within the country's technology imports.

The combined mineral requirements in metric kilotonnes (KT) for all India's green technology needs are shown in Table 8[8]. Barring aluminium (and steel, though it is not part of this computation), which is essential for structural components across all technologies, India's requirements for copper and silicon are the highest. Copper is essential for all electrical components, and silicon forms the main part of solar PVs.

Table 8: Critical Mineral Requirements (STEPS)

Mineral	Mineral Requirements (KT)				
	2019-25	2025-30	2030-35	2035-40	Total
Copper	388	737	1,006	1,113	3,244
Nickel	36	31	46	32	145
Manganese	21	55	77	55	208
Cobalt	7	0	0	0	7
Chromium	54	97	108	95	354
Molybdenum	8	11	13	10	42
Zinc	139	363	524	375	1,400
Rare earths	1	7	6	4	19
Silicon	312	517	786	1,094	2,709
Aluminium	1,725	2,922	4,351	5,830	14,827
Lead	3	5	4	4	16
Titanium	0	1	1	1	3
Neodymium	1	3	4	3	10
Silver	0	7	7	13	26
Indium	6	10	16	22	55

Aside from the minerals needed for clean energy technologies, India will also need minerals to manufacture EVs, particularly two-wheelers and three-wheelers. Projections of EV sales have been taken from a CEEW-CEF study on EVs in India and mineral intensities from the IEA (Singh, Chawla, & Jain, 2020) (International Energy Agency (IEA), 2021c). Consideration should also be given to charging stations required for the EVs. In the context of critical mineral requirements, EVs with battery-swapping technology would require a larger quantity of battery minerals. Additionally, some charging stations may use renewable energy to supplement the electricity needs for these vehicles (NITI Aayog, 2021).

There will also be an increase in demand for energy storage projects with the rising share of renewable energy in the power generation mix. Energy storage will be crucial in smoothening the variability in electricity generation from solar and wind. Currently, pumped hydro storage accounts for the most capacity in global energy storage. With improvements in technologies and decreasing costs, battery

[8] Given the Prime Minister's COP26 declaration of renewable energy capacity increasing to 500 GW in 2030 (compared to 450 GW), the reported numbers are underestimates.

storage systems may become more popular in the future. South Australia has installed a 150 MW battery storage for grid stabilisation, as backup for power generation losses, and to manage the large amounts of renewables tied into the grid (Tomevska, 2020). The Indian government has announced plans for similar setups, including a tender for a 1 GWh battery storage system to manage the increasing share of renewable energy (Livemint, 2021). Further work is needed to quantify the total energy storage requirements for the country, based on the renewable energy in the network and the mineral needs for these technologies.

Table 9 shows the mineral requirements for the base case estimates of EV sales between 2020 and 2030.

Table 9: Mineral Requirements for Electric Vehicles (2020-30)

Mineral	Mineral Requirements (KT)
Copper	1,569
Lithium	262
Nickel	1,177
Manganese	723
Cobalt	392
Graphite	1,955
Zinc	3
Rare earths	15

The minerals required for clean energy technologies would be met by extracting and processing the minerals in India, importing the minerals for domestic manufacturing, or importing the assembled components (with the minerals embedded). The Indian Bureau of Mines' latest National Mineral Inventory (NMI) published in 2015 contains data on the quantities of known total resources of minerals explored. The quantity of total resources is the sum of the reserves (the economically mineable segment) and the remaining resources not yet identified as reserves. India's obvious geological potential (OGP) is vast. It is estimated that only 10% of OGP has been explored (Press Trust of India, 2016).

Tables 10 and 11 show data on the resources and reserves of minerals from the NMI and contrasts this with estimates of mineral requirements for clean energy technologies and EVs in the STEPS and base case scenarios, respectively. The sixth column, the share of needs to reserves, calculates what proportion of the 2015 mineral reserves will be used to manufacture clean technologies. Some minerals, including copper, silver, and graphite, have high ratios of mineral needs-to-reserves, which indicate that reserves will fall short of the manufacturing needs. There are also minerals with no reserves but some indication of resources, such as cobalt and molybdenum. Converting these resources to reserves through more detailed exploration will help reduce the country's dependence on mineral imports. In cases where there are currently no known resources, it would be prudent to develop supply chains or, in critical cases, acquire foreign mineral assets to guarantee these minerals for domestic manufacturing.

Table 10: Mineral Inventory and Select Mineral Needs for Clean Energy Manufacturing (2020-40)

Mineral	Reserves (KT)	Total Resources (KT)	Typical Share of Metal in Ore (%)	Mineral Needs (KT)	Ratio of Needs-to-Reserves (%)
Copper#	2,735	12,158	100	3244	118.6
Nickel	0	189	1.5	145	No reserves
Manganese	93,475	495,874	35	208	0.6
Cobalt	0	44,910	0.5	7	No reserves
Chromium	102,210	344,016	40	354	0.9
Molybdenum	0	19,372	0.5	42	No reserves
Zinc#	10,000	36,363	100	1400	14.0
Rare earths	0	25	100	19	No reserves
Silicon	17,283	183,963	100	2709	15.7
Bauxite	656,422	3,896,864	20	14827	11.3
Lead#	2,482	13,004	100	16	0.6
Titanium	14,420	413,626	6	3	0.3
Neodymium	None		N/A	N/A	No resources
Silver#	7	30	100	26	371.4
Indium	None		N/A	N/A	No resources

Note: #Mineral inventory includes reserves and resources of the metal content rather than the ore.

Source: (Indian Bureau of Mines, 2015) and Authors' calculations

Table 11: Mineral Inventory and Select Mineral Needs for Electric Vehicle Manufacturing (2020-30)

Mineral	Reserves (KT)	Total Resources (KT)	Typical Share of Metal in Ore (%)	Mineral Needs (KT)	Ratio of Needs-to-Reserves (%)
Copper#	2,735	12,158	100	1,569	57.4
Lithium	None		N/A	262	No resources
Nickel	0	189	1.5	1,177	No reserves
Manganese	93,475	495,874	35	723	2.2
Cobalt	0	44,910	0.5	392	No reserves
Graphite	7,961	194,887	25	1,955	98.2
Zinc#	10,000	36,363	100	3	0.0
Rare earths	0	25	100	15	No reserves

Note: #Mineral inventory includes reserves and resources of the metal content rather than the ore.

Source: (Indian Bureau of Mines, 2015) and Authors' calculations

The move to renewable energy targets from 2021-2025 to 2025-2040 would require increasing quantities of aluminium, copper, indium, manganese, silicon and zinc. For example, increase in the quantity requirement of indium and silicon by more than 2.5 times; aluminium more than 3.3 times; copper more than 2.8 times; and manganese and zinc more than 2.6 times. Similarly, for the manufacture of electric vehicles, mineral demands will increase multiple fold.

Future Work

Further work may be done on the projections of mineral demands for green technology under different scenarios, including the IEA's Sustainable Development Scenario (SDS). More work would be required to recompute the future critical minerals demand in congruence with the COP26 declarations. Future work would also consider India's specific green technologies needs, their respective mineral intensities, and the projected changes in these intensities over time. The mineral demand will vary considerably depending on the technology demand scenario and the specific types of technology used. For example, the global demand for lithium in 2040 may increase by 13 to 51 times compared to today's levels, depending on the types of batteries manufactured and their uptake in electric vehicles. Similar wide variation scenarios have been predicted for other minerals, including cobalt, graphite, and rare earth elements (International Energy Agency (IEA), 2021c).

Summary of Key Findings

There will be an increase in the demand for several critical minerals as India transitions towards renewable power generation and electric vehicles. The move to renewable energy would require increasing quantities of various minerals, including copper, manganese, zinc, and indium. Likewise, the move to electric vehicles would require increasing quantities of various minerals, including copper, lithium, cobalt, and rare earth elements. However, India does not have reserves of nickel, cobalt, molybdenum, rare earths, neodymium and indium, and the needs for copper and silver are higher than India's current reserves.

The critical minerals assessment results suggest that niobium, lithium, and strontium have relatively high economic importance, adjusted by their substitutability possibilities and GVA multipliers. Additionally, most minerals have some degree of substitutability, except for niobium and silver, for which no good substitutes have been found. The supply risk is relatively high for yttrium and scandium (heavy rare earths), followed by niobium and silicon. However, India does not have the recycling capacity for most minerals except aluminium, copper and steel.

Policy Implications: The Way Forward

The results of this projection exercise indicate that India is not equipped to meet its green technology requirements through domestic mining alone. Imports of minerals for domestic manufacturing or imports of the final product (embedded in these minerals) will be needed to meet its policy agenda on climate change mitigation.

While India would need to rely on imports for these technologies over the next two decades, further work must be done to better utilise the available minerals within the country for its longer-term needs. Newly installed renewable capacity today will require replacement after two to three decades. India can be better prepared for the next stage of green technology utilisation by laying the groundwork for exploring and mining. Tables 10 and 11 show that the country has resources of nickel, cobalt, molybdenum, and heavy rare earth elements, but further exploration would be needed to evaluate the quantities of their reserves. Part 1 of this study shows that this is particularly important for heavy rare earths and cobalt due to their high supply risks. While nickel currently has a lower supply risk than the other minerals in this study, it has high economic importance, and an assured domestic source would help lower the supply risk.

There are some minerals where India has no known resources, such as lithium and indium, and here the country must focus on securing supply chains for these minerals and acquiring foreign mineral assets to ensure their continuous supply.

The study results point to policy recommendations for ensuring uninterrupted supplies of critical minerals through enhanced domestic mineral exploration and extraction, along with assured sources elsewhere. Particular attention should be given to deep-seated minerals (Mathai, 2019). The import risks of critical minerals may be reduced by developing resilient supply chains, signing trade agreements, and acquiring mining assets abroad. In addition, government-to-government engagement efforts through KABIL[9] need to be supplemented with the acquisition of private mines.

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

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Annex 1: Manufacturing Sectors at NIC 2-digit level

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

Annex 2: National Product Classification for Manufacturing Sector (NPCMS)[10] Codes of Selected Minerals

NPC	Mineral	Description	Type
1424001	Chromium	Chromium ore and concentrate	Ore
1429001	Chromium	Chrome lead	Ore
1429002	Chromium	Chrome ore and concentrate	Ore
3424016	Chromium	Basic chromium sulphate	Chemical
4111300	Chromium	Ferro-chromium/ Ferro-chrome	Ferro
1429011	Cobalt	Cobalt ore and concentrate	Ore
3424023	Cobalt	Cobalt chloride	Chemical
3424024	Cobalt	Cobalt phosphate	Chemical
3425011	Cobalt	Cobalt acetate	Chemical
4111503	Cobalt	Ferro cobalt	Ferro
1421000	Copper	Copper, ores and concentrates	Ore
3422002	Copper	Copper oxide	Chemical
3424025	Copper	Copper sulphate	Chemical
3466204	Copper	Copper oxychloride	Chemical
1410001	Iron	Iron ores, Hematite	Ore
1410003	Iron	Iron ore, Magnetite	Ore
1410099	Iron	Iron ores not elsewhere classified	Ore
3422004	Iron	Iron hydroxide	Chemical
3422005	Iron	Iron oxide	Chemical
1520006	Limestone	Lime stone	Ore
1520007	Limestone	Lime anbuz	Ore
1520008	Limestone	Lime powder	Ore
1520099	Limestone	manufacture of lime or cement; not elsewhere classified	Ore
3424028	Lithium	Lithium bromide	Chemical
3424029	Lithium	Lithium carbonate	Chemical
3424030	Lithium	Lithium chloride	Chemical
3424031	Lithium	Lithium compounds	Chemical
4111506	Niobium	Ferro niobium	Ferro
3429000	Rare earths	Compounds of rare earth metals, of yttrium or of scandium	Chemical
3899502	Rare earths	Ferro cerium & others pyrotechnic products	Ferro
1513007	Silicon	Silica	Ore
1540015	Silicon	Silica clay	Ore
3416017	Silicon	Ethyl silicate	Chemical
3427001	Silicon	Alkali silicate	Chemical
3427003	Silicon	Calcium silicate hydrated	Chemical
3427005	Silicon	Potassium silicate	Chemical
3427008	Silicon	Sodium silicate	Chemical
3526050	Silicon	Magnesium trisilicate	Chemical
4111513	Silicon	Ferro silicon	Ferro
3421018	Strontium	Strontium nitrate	Chemical
1423001	Bauxite	Bauxite calcined	Ore

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

1423002	Bauxite	Bauxite raw	Ore
3795000	Graphite	Artificial graphite; colloidal or semi-colloidal graphite; preparations based on graphite or other carbon in the form of semi-manufactures	Product
4295005	Graphite	Rod, Wire, Graphite	Product
4695001	Graphite	Carbon brush	Product
4695002	Graphite	Carbon rods	Product
4695003	Graphite	Carbon tracks	Product
4695099	Graphite	Carbon electrodes, carbon brushes, lamp carbons, battery carbons and other articles of graphite or other carbon of a kind used for electrical purposes; not elsewhere classified	Product
1429005	Lead	Lead ores and concentrates, Litharge	Ore
3422006	Lead	Lead monoxide	Chemical
3422007	Lead	Lead compounds	Chemical
3422008	Lead	Lead oxide	Chemical
3422009	Lead	Lead suboxide (lso)	Chemical
3424027	Lead	Lead sulphite	Chemical
1639003	Manganese	Manganese, ore	Ore
1639004	Manganese	Manganese, silica	Ore
3412004	Manganese	Manganese stearate	Chemical
3422011	Manganese	Manganese dioxide	Chemical
3424037	Manganese	Manganese carbonate	Chemical
4111200	Manganese	Ferro-manganese	Ferro
4111511	Manganese	Ferro silico manganese	Ferro
1429008	Molybdenum	Ores, molybdenum	Ore
3422012	Molybdenum	Molybdenum trioxide	Chemical
4111505	Molybdenum	Ferro molybdenum	Ferro
1422000	Nickel	Nickel ores and concentrates	Ore
1639005	Nickel	Nickel ore	Ore
3424039	Nickel	Nickel carbonate	Chemical
4111400	Nickel	Ferro-nickel	Ferro
1424006	Silver	Silver mineral	Ore
3421017	Silver	Silver nitrate	Chemical
3422019	Titanium	Titanium dioxide	Chemical
3422020	Vanadium	Vanadium pentoxide	Chemical
4111517	Vanadium	Ferro vanadium	Ferro
1429003	Zinc	Zinc concentrate	Ore
3422021	Zinc	Zinc hydroxide	Chemical
3422022	Zinc	Zinc oxide	Chemical
3424080	Zinc	Zinc carbonate	Chemical
3424081	Zinc	Zinc chloride	Chemical
3424082	Zinc	Zinc sulphate	Chemical

Source: Central Statistics Office (2011b)

Annex 3: Cost-Performance Scores for Substitutability

Mineral	Substitutability
Bauxite	0.86
Chromium	0.90
Cobalt	0.80
Copper	0.90
Graphite	0.81
Indium	0.87
Iron	0.90
Lead	0.88
Limestone	0.88
Lithium	0.95
Manganese	0.90
Molybdenum	0.73
Neodymium	0.97
Nickel	0.75
Niobium	1.00
Heavy rare earths	0.94
Light rare earths	0.97
Silicon	0.94
Silver	1.00
Strontium	0.77
Titanium	0.75
Vanadium	0.92
Zinc	0.71

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 indicate that the mineral is less substitutable in the economy, with a maximum score of 1.0 (not substitutable), and a minimum score of 0.6 (highly substitutable).

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

Note: Detailed results are provided in a supplementary document (Annex 3.i).

Annex 4: GVA Multipliers

Sectoral GVA Multipliers		
2-Digit NIC	**Sector**	**GVA Multiplier**
10	Food products	7.2
11	Beverages	2.1
12	Tobacco products	2.0
13	Textiles	2.6
14	Wearing apparel	2.6
15	Leather and leather products	2.3
16	Wood and wood products except furniture	2.1
17	Paper products	3.9
18	Printing	1.3
19	Coke and refined petroleum	4.5
20	Chemicals and chemical products	3.8
21	Pharmaceuticals, medicinal chemical and botanical products	2.0
22	Rubber and plastics products	3.8
23	Other non-metallic mineral products	2.4
24	Basic metals	4.8
25	Fabricated metal products, except machinery and equipment	2.2
26	Computer, electronic and optical products	2.5
27	Electrical equipment	1.5
28	Machinery and equipment not elsewhere classified	2.6
29	Motor vehicles, trailers and semi-trailers	3.9
30	Other transport equipment	3.1
31	Furniture	2.0
32	Other manufacturing	23.8

Mineral-Wise GVA Multipliers and Multiplier Scores			
Mineral	**Weighted Average Multiplier of the Mineral-Consuming Sectors**	**Multiplier Coefficients with GVA Weights**	**Multiplier Score**
Chromium	4.66	0.48	1.2
Cobalt	6.28	0.43	1.2
Copper	4.61	0.47	1.2
Iron	4.75	0.49	1.2
Limestone	3.27	0.26	1.1
Lithium	2.42	0.15	1.0
Niobium	4.80	0.50	1.2
Heavy rare earths	4.30	0.44	1.2
Light rare earths	4.89	0.33	1.1
Silicon	3.60	0.32	1.1
Strontium	3.49	0.31	1.1
Bauxite	4.05	0.38	1.1
Lead	3.10	0.27	1.1
Manganese	4.65	0.48	1.2
Molybdenum	4.60	0.47	1.2
Nickel	4.51	0.45	1.2
Silver	16.96	0.36	1.1
Titanium	3.79	0.34	1.1
Vanadium	4.59	0.47	1.2
Zinc	4.08	0.39	1.1
Graphite	3.50	0.18	1.0
Indium	2.27	0.08	1.0
Neodymium	4.21	0.09	1.0

Computing Multiplier Scores	
Multiplier Coefficients	**Multiplier Score**
< 0.20	1.0
> 0.20 and < 0.40	1.1
> 0.40	1.2

Annex 5: End-of-Life Recycling Rates

Mineral	Recycling Rate (%)	Score
Bauxite	25	0.33
Chromium	5	0
Cobalt	5	0
Copper	20	0.33
Graphite	0	0
Indium	1	0
Iron	35	0.33
Lead	85	0.67
Limestone	0	0
Lithium	0	0
Manganese	53	0.67
Molybdenum	25	0.33
Neodymium	0	0
Nickel	57	0.67
Niobium	0	0
Heavy Rare earths	1	0
Light Rare earths	1	0
Silicon	0	0
Silver	9	0.33
Strontium	0	0
Titanium	0	0
Vanadium	0	0
Zinc	10	0.33

Annex 6: Mineral Import Reliance in India

Mineral	Import Reliance (%)
Bauxite	0
Chromium	0
Cobalt	100
Copper	61
Graphite	67
Indium	100
Iron	0
Lead	48
Limestone	0
Lithium	100
Manganese	49
Molybdenum	100
Neodymium	100
Nickel	100
Niobium	100
Rare earths heavy	13
Rare earths light	100
Silicon	17
Silver	3
Strontium	100
Titanium	0
Vanadium	100
Zinc	11

Annex 7: Supply Risk Substitutability

Mineral	Level of Production	Co-/By-Product	Supply Risk Substitutability
Chromium	1.00	1.00	1.00
Cobalt	0.90	0.93	0.91
Copper	0.90	1.00	0.95
Iron	1.00	1.00	1.00
Limestone	1.00	1.00	1.00
Lithium	0.90	1.00	0.95
Niobium	1.00	1.00	1.00
Heavy rare earths	0.91	0.94	0.92
Light rare earths	0.90	0.93	0.91
Silicon	0.98	1.00	0.99
Strontium	0.96	1.00	0.98
Bauxite	1.00	1.00	1.00
Lead	1.00	0.80	0.89
Manganese	1.00	1.00	1.00
Molybdenum	0.99	0.90	0.95
Nickel	0.90	1.00	0.95
Silver	0.90	0.97	0.94
Titanium	0.90	1.00	0.95
Vanadium	0.90	1.00	0.95
Zinc	0.91	0.80	0.85
Graphite	0.96	1.00	0.98
Indium	0.90	0.84	0.87
Neodymium	0.91	1.00	0.95

Note: Detailed results are provided in a supplementary document (Annex 7.i).

Annex 8: Domestic Self-Sufficiency

HHI	Domestic Self-Sufficiency
Chromium	0.6
Cobalt	1.0
Copper	0.9
Iron	0.6
Limestone	0.6
Lithium	1.0
Niobium	1.0
Heavy rare earths	1.0
Light rare earths	1.0
Silicon	0.6
Strontium	1.0
Bauxite	0.6
Lead	0.8
Manganese	0.8
Molybdenum	1.0
Nickel	1.0
Silver	1.0
Titanium	0.6
Vanadium	1.0
Zinc	0.6
Graphite	0.9
Indium	1.0
Neodymium	1.0

Note: Higher values indicate lower self-sufficiency, and vice versa. The scores range from 0.6 (most self -sufficient) to 1.0 (least self -sufficient). For example, India is self-sufficient in iron ore (though it does import small quantities), hence the mineral has a score of 0.6; it does not produce indium, hence it has a score of 1.0.

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