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Projecting Critical Mineral Needs for India's Clean Energy Transition

How Much of Which Minerals Are Needed for the Transition?

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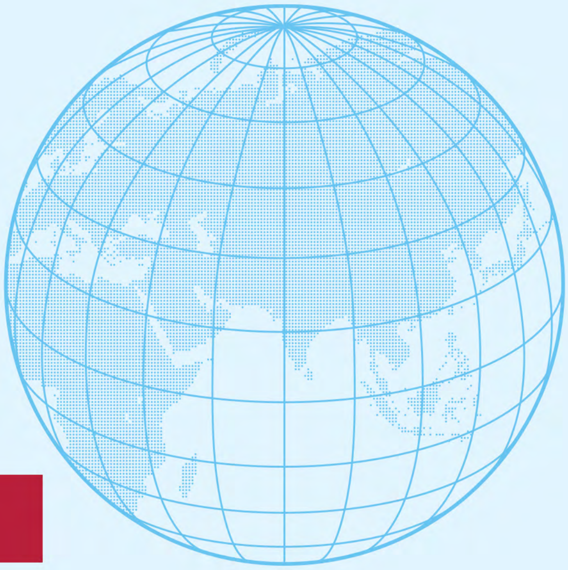

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Projecting Critical Mineral Needs for India's Clean Energy Transition

How Much of Which Minerals Are Needed for the Transition?

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Abbreviations

Abbreviation	Definition
BESS	Battery energy storage system(s)
CAGR	Compounded annual growth rate
CEA	Central Electricity Authority (of India)
CMA	Critical minerals assessment
ESG	Environment, social, and governance
EV	Electric vehicle
IEA	International Energy Agency
IESS	India Energy Security Scenarios 2047 (Version 3.0)
KABIL	Khanij Bidesh India Ltd
LFP	Lithium iron phosphate (batteries)
LIB	Lithium-ion battery
MoM	Ministry of Mines
MSP	Minerals Security Partnership
NCA	Nickel cobalt aluminium (batteries)
NCMA	Nickel cobalt manganese aluminium (batteries)
NMC	Lithium nickel manganese cobalt oxide (batteries)
NZE	Net zero emissions
PLI	Production-Linked Incentive (scheme)
PV	Photovoltaic
REE	Rare earth element
RES	Renewable energy sources
RIR	Recycling input rate
VRF	Vanadium redox flow (battery)
Year/FY	Fiscal year, April-March (FY 2025 refers to April 2024-March 2025)

Note on Units

Unit	Symbol(s)	Description
Tonnes	t	Measure of weight, 1,000 kg
Watt-hour	Wh	One watt of energy consumed for one hour of time
Watts	W	A unit of power equivalent to the electricity flowing at a rate of one joule per second
Metric Prefixes	k, M, G, T	Kilo (x1000), mega (x1,000,000), giga (x1,000,000,000), tera (x1,000,000,000,000); prefix to other units

Abstract

The Paris Agreement, adopted by 196 countries at the 21st Conference of Parties (COP21) in 2015, provided a significant boost to the clean energy transition process, including solar and wind energy and battery storage, resulting in unprecedented global growth in the demand for critical minerals required as inputs to manufacture the requisite equipment. At COP26 held in 2021, India presented its climate action strategy, including a commitment to achieving the target of net zero emissions by 2070. However, there are several challenges in achieving these targets, including mobilising adequate investments, solving technical and operational challenges, and creating a just transition framework. Another imminent concern is ensuring resilient access to the requisite green technologies and the raw materials needed for their manufacturing, referred to as "critical minerals." This paper estimates the mineral requirements to manufacture the clean energy technologies needed for India to meet its climate action commitments. It highlights the cases in which India has access to these materials domestically and the reliance on imported minerals—in either their raw, processed, or component-embedded forms—to meet the needs of the growing domestic clean energy equipment manufacturing sector. Though the mineral requirements for EV manufacturing have not been considered in this paper, a large demand is expected from this sector as well. Other sectors being electrified in India include cooking and heating, but their mineral requirements are not computed either. The demand for critical minerals in the clean energy transition will rise manifold over the coming decades. Most of these have been identified as critical by the CSEP and Ministry of Mines reports. For these minerals, especially those with no known domestic resources, mineral-wise strategies are required to ensure robust access for India's manufacturing needs and climate change mitigation ambitions. The study also shows that promoting recycling and the use of recycled materials in supply chains can help mitigate additional requirements for mines, as would improvements in mineral intensities and technology efficiencies.

Executive Summary

Critical minerals, in both primary and processed forms, are essential inputs to the production processes of an economy. Their supplies are likely to be affected due to the risks of non-availability or unaffordable price spikes (Chadha, Sivamani, & Bansal, 2023a). Without access to these essential minerals, India's and the rest of the world's clean energy transition plans may face multiple setbacks. Compared with traditional energy generation equipment, renewable energy devices, including solar, wind, and nuclear, require considerably large amounts of critical minerals. The same holds for electric vehicles (EVs) when compared with conventional internal combustion engine vehicles. Battery energy storage systems (BESS) and EV batteries also need considerable quantities of critical minerals (IEA, 2021). Hence, the global demand for critical minerals is set to rise rapidly as the world transitions to clean energy technologies to reduce emissions and meet the net zero emissions target. However, the risks of future availability are elevated due to the significant concentration of extraction and processing of critical minerals across very few countries.

India has undertaken a clean energy transition programme for climate change mitigation, energy security, and environmental preservation. At COP26 held in Glasgow in 2021, India presented its climate action strategy, including a commitment to achieving the target of net zero emissions by 2070 (PIB, 2022a). However, there are several challenges in achieving these targets, including mobilising adequate investments, solving technical and operational challenges, and creating a just transition framework. Another imminent concern is ensuring resilient access to the requisite green technologies and the raw materials needed for their manufacturing, referred to as "critical minerals." A World Bank report highlights the mineral needs for various clean energy technologies and provides global mineral demand projections until 2050 (Hund, La Porta, Fabregas, 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." A 2021 report from the International Energy Agency (IEA) highlights that "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" (IEA, 2021). The report adds that "while there is no 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 has a significant slack in the domestic availability of critical minerals and manufacturing of clean technology equipment. Hence, India must evaluate its critical mineral needs and their availabilities to meet its emissions reduction commitments. While India may consider exploring and mining critical minerals, the process may take years since the extant resources have not been converted into reserves and the known reserves have not been adequately exploited. India must consider all its options, including extracting and processing in the country, joining global supply chains at various processing stages, and owning mines and processing facilities abroad. The mining sector must gear up to meet the growing demand for critical minerals. Alternative technologies requiring fewer or different critical minerals must be found.

The *Make in India* initiative of the Government of India seeks to create domestic integrated manufacturing value chains, which are further being incentivised through various production-linked incentive (PLI) schemes. Most PLIs require domestic value addition throughout the supply chain. Hence, it is important to project the magnitude of the raw materials required for manufacturing the requisite clean energy equipment. Without resilient access to these minerals, India would have to rely on imported mineral-embedded components to feed into its manufacturing sector. Policymakers should design mineral-wise strategies to ensure domestic manufacturing of green technologies equipment has access to its requisite raw material inputs. The issue becomes particularly pertinent for the minerals for which India has no known domestic geological potential, as any strategies would necessarily involve some form of critical minerals cooperation with one or more countries.

This paper projects the mineral requirements to manufacture the clean energy technologies needed for India to meet its climate action commitments. It highlights the cases in which India has access to these materials domestically and the reliance on imported minerals (in either their raw, processed, or component-embedded forms) to meet the needs of the growing domestic clean energy equipment manufacturing sector. Though the mineral requirements for EV manufacturing have not been considered in this paper, a substantial demand is expected from this sector as well. Considering the significant amount of minerals needed to manufacture EVs, especially lithium for batteries, a follow-up study should examine the projected increase in EV sales to estimate the corresponding mineral requirements. Other sectors being electrified in India include cooking and heating, but their mineral requirements are not computed in this study. This study considers both the existing and more advanced technology options, which may be promising alternatives. These options are available for procurement to determine the mineral requirements for clean energy devices. However, given the current pace of technological progress and the potential for disruptive, more efficient technologies to emerge, it would be prudent to revise and update this analysis every two to three years to account for any new technologies, as well as updated policy prescriptions.

In continuation of an earlier piece on projecting mineral requirements (Sivamani, 2023), this study focuses on renewable electricity capacity and the required BESS to facilitate its operation. We compute the annual addition in power capacity based on various scenarios, accounting for replacing older decommissioned plants. We then examine the various technology options for each source and devise scenarios on technology trends based on available literature. Finally, the mineral intensities for each technology option for each electricity source are used to compute the mineral requirements. We also show how recycling reduces the need for virgin ores and metals, which may decrease the impending supply gap and reduce greenhouse gas emissions. Various scenarios have been considered to project India's critical mineral needs for the clean electricity transition, such as for electricity capacity, lifespans of power stations, recycling rates, and future technology changes.

The annual mineral requirements to manufacture the three technologies (solar, wind, and battery storage) have been computed for each of the scenarios highlighted above. While mineral intensities data are available for all the minerals required to manufacture each device, this study focuses on the needs of non-bulk critical minerals. India is well-endowed with supplies of bulk minerals like iron ore, limestone (for cement), and bauxite (for aluminium). Hence, the requirements of bulk materials are not discussed in these results but are available in the Excel addendum. The study presents results for fiscal years (FY) 2025, 2026, 2027, and then every fifth year after that until 2047, which is the last year for which the IESS (India Energy Security Scenarios) projects electricity capacities. Results for 2030 are also provided as it is a milestone year for India's climate targets and also the year in which the electricity capacity scenarios switch from the Central Electricity Authority (CEA) of India to IESS projections.

Policymakers can use the results of the projections exercise to devise strategies for secure supply chains of the minerals required for the clean technology transition. These strategies may be devised by considering the current status of mineral development in the country and the projected growth in their demand. For cases where India produces the mineral, strategies should focus on bolstering the domestic mining and processing regimes. India may also wish to share its expertise and invest in countries seeking to expand their domestic capabilities. In cases where India has reserves of a mineral, but a relatively high share of demand is being met through imports (i.e., low self-sufficiency), efforts may be made to allocate more mining blocks to boost production levels.

While this study projects the critical mineral requirements of clean energy technologies, other green technologies key to the net zero transition also need attention. A subsequent study must consider various scenarios on the rise in demand for EVs, amongst other green technologies, and the technology options available to compute the critical mineral needs to manufacture EVs. These projection studies should also be updated regularly to account for changes in available technologies, including both reducing mineral intensities and technological disruptions. They should also be updated to account for any new policies which redirect efforts towards different green devices.

1. Introduction

The Paris Agreement, adopted by 196 countries at the 21st Conference of Parties (COP21) in 2015, provided a significant boost to the clean energy transition, including solar and wind energy and battery storage, resulting in unprecedented global growth in the demand for critical minerals required as inputs to manufacture this equipment. Critical minerals, in both primary and processed forms, are identified as essential inputs to the production processes of an economy and whose supplies are likely to be affected due to the risks of non-availability or unaffordable price spikes (Chadha, Sivamani, & Bansal, 2023a). Without access to these essential minerals, the clean energy transition plans of India and the rest of the world may face multiple setbacks.

Compared with traditional energy generation equipment, renewable energy devices, including solar, wind, and nuclear, require considerably large amounts of critical minerals. The same holds for electric vehicles (EVs) compared with conventional internal combustion engine vehicles. Battery energy storage systems (BESS) and EV batteries also need considerable quantities of critical minerals (IEA, 2021). Hence, the global demand for critical minerals is set to rise rapidly as the world transitions to clean energy technologies to reduce emissions and meet the net zero emissions (NZE) target. However, the risks of future availability get elevated due to the significant concentration of extraction and processing of critical minerals across very few countries.

India has undertaken a clean energy transition programme for climate change mitigation, energy security, and environmental preservation. At COP26 (held in Glasgow in 2021), India presented its climate action strategy, including a commitment to achieving the target of NZE by 2070 (PIB, 2022a). However, there are several challenges in achieving these targets, including mobilising adequate investments, solving technical and operational challenges, and creating a just transition framework. Another imminent concern is ensuring resilient access to the requisite green technologies and the raw materials needed for their manufacturing, referred to as critical minerals.

A World Bank report highlights the mineral needs for various clean energy technologies and provides global mineral demand projections until 2050 (Hund, La Porta, Fabregas, Laing, & Drexhage, 2020). The report 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." This report delineates the relative demand risks of cross-cutting minerals and concentrated minerals. Copper, chromium, and molybdenum are cross-cutting minerals used across various clean energy generation and storage technologies and face stable demand conditions. On the other hand, the report highlights that minerals like lithium, silicon, cobalt, and manganese are concentrated only on one or two specific technologies. Therefore, they face higher demand uncertainty arising from future technological disruptions.

A 2021 report from the International Energy Agency (IEA) highlights that "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" (IEA, 2021). The report adds that "while there is no 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."

The demand for many metals is expected to exceed their current global supplies (Valckx, Stuermer, Seneviratne, & Ananthakrishnan, 2021). The consequent rising metal prices may delay the energy transition (Boer, 2021). With high commodity prices, green technologies might become unaffordable, leading to continued reliance on fossil fuel-based energy and transport, as the increased costs of raw materials would drive up the prices of clean energy equipment and infrastructure. Mining companies may be impacted by more stringent environment, social, and governance (ESG) norms for raising funding, which in turn could delay expansion or new operation plans, adding further pressure to a tight supply chain.

While studies have reported signs of the supply-demand mismatch in critical minerals, which may delay the net zero transition, some believe that market forces and research and development would keep the progress on track. In order to meet their growing demand, either the mining industries would be able to increase their supplies to match the projected demand increase, or technological alternatives that do not require the same type or quantities of critical minerals will be found.

India has a significant slack in the domestic availability of critical minerals and manufacturing of clean technology equipment. Hence, India must evaluate its critical mineral needs to meet its emissions reduction commitments, such as the target of achieving NZE by 2070. While India may consider exploring and mining critical minerals, the process may take years since the extant resources have not been converted into reserves and the known reserves have not been exploited adequately. India must consider all its options, including extracting and processing in the country, joining global supply chains at various processing stages, and owning mines and processing facilities abroad. Adopting a "not-in-my-backyard" approach to safeguard India's communities and environment may have adverse impacts elsewhere and compromise the country's self-resilience. The "not-in-my-backyard" concept refers to residents' opposition to proposed developments in their local area despite not objecting to similar developments elsewhere. India may not be able to sustain its march to NZE by assuming all its needs for critical minerals shall be perennially met by imports, assuming an unspoken, tacit insurance from the supplying countries.

Given that it would take more than two and a half decades for the world to reach NZE, the transition needs to be done sustainably, adopting the best practices on the ESG norms confronting the industry. Ignoring social and environmental externalities could delay the green transition. The environmental impacts of mining, the social dimensions of artisanal and small-scale mining (ASM),[1] the future of native and indigenous communities, and the welfare of the mining workforce all need careful attention and resolution. The governance aspect must ensure an efficient permitting process, ensuring the mining companies meet their commitments until and after the stage of mine closure.

The rising demand for critical minerals could lead to increased mining activities in some of the least developed countries, potentially fuelling irresponsible mining practices that utilise child labour and cause environmental damage by not adhering to ESG norms. Moreover, there are options for improving the economic well-being of many impoverished communities residing in mineral-rich land in India. It should also be noted that while the goal is to manufacture green technologies to achieve net zero emissions, both mineral extraction and processing are carbon-intensive processes and can cause adverse impacts on the environment and neighbouring communities (McKinsey & Company, 2023).

It is pertinent to study various stages of the critical minerals and clean energy technologies value chains and the interplay of these segments in driving a thriving minerals and metals industry. The states, private sector, and financial institutions will be essential actors, along with the policy push and incentives provided by the government. The *Make in India* initiative of the Government of India seeks to create domestic integrated manufacturing value chains, which are further being incentivised through various production-linked incentive (PLI) schemes. Most PLIs require domestic value addition throughout the supply chain. Hence, it is important to project the raw material requirements for manufacturing the necessary clean energy equipment. Without resilient access to these minerals, India would have to rely on imported components that have the required minerals already embedded in them to feed into its manufacturing sector. These results, along with the criticality assessment of minerals, would help policymakers design mineral-wise strategies to ensure domestic manufacturing of green technologies equipment has access to its requisite raw material inputs. The issues become particularly pertinent in the case of minerals for which India has no known domestic geological potential, as any strategies would necessarily involve some form of critical minerals cooperation with another country.

This paper estimates the mineral requirements to manufacture the clean energy technologies needed for India to meet its climate action commitments. It highlights the cases in which India has access to these materials domestically. It also emphasises the reliance on imported minerals in their raw, processed, or component-embedded forms to meet the needs of the growing domestic clean energy equipment manufacturing sector. Though the mineral requirements for EV manufacturing have not been considered in this paper, a substantial demand is expected from this sector as well. Given the considerable scale of minerals required for manufacturing EVs (particularly lithium for batteries), it would be pertinent for a subsequent study to consider their rising sales to compute mineral projections. Other sectors which are being

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[1] Artisanal and small-scale mining (ASM) refers to mining activities carried out using low technology or with minimal machinery, often in the informal sector.

electrified in India include cooking and heating, but their mineral requirements are not computed in this study.

This study considers both the existing and more advanced technology options that are available for procurement while computing the mineral requirements for clean energy devices. However, with the current pace of technological progress and the potential for disruptive and more efficient technologies, it would be prudent to revise this exercise every two to three years to account for the availability of any new technologies, as well as updated policy prescriptions.

The paper is an extension of the earlier CSEP work on projecting India's mineral needs for green technologies (Chadha & Sivamani, 2022). A new edition of Assessing the Criticality of Minerals for India, a precursor to this revised work on projections, was published in April 2023 (Chadha, Sivamani, & Bansal, 2023a). It extended the earlier assessment of 23 minerals for India to 43 based on their economic importance and supply risks. It highlighted the minerals found to be the most critical for India's economy. A blog piece with preliminary findings from this study was also published (Sivamani, 2023).

Section 2 of this paper reviews the extant literature on the subject of projecting critical mineral requirements for green transition. India's commitments made at COP26 and the current status of climate action are outlined in Section 3. Section 4 provides an overview of the technologies and manufacturing supply chains for solar and wind energy and battery storage. The methodology for projecting mineral requirements is discussed in Section 5. Section 6 outlines the projection scenarios of energy capacity pathways computed by CEA (till 2030) and NITI Aayog (till 2047), requisite mineral intensities, lifespans of technologies and recycling input rates (RIRs). The technology-wise mineral requirements till 2047 are projected in Section 7, along with some strategies for India to secure access to critical mineral supply chains. Concluding remarks and policy recommendations are highlighted in Section 8.

2. Literature Review

Numerous studies have projected critical mineral requirements for the net zero transition. However, limited research focuses on India-specific mineral projections, especially those incorporating the government's recent climate action plan announcements. One earlier attempt at a comprehensive computation was made by Chadha & Sivamani (2022), though they only considered limited scenarios up to 2040. Unlike existing literature on this subject, as highlighted in this section, this study provides a detailed, India-specific analysis of future mineral requirements.

The IEA report on *The Role of Critical Minerals in Clean Energy Transitions* (IEA, 2021) provides scenario-based global critical mineral projections for various clean energy technologies. The two scenarios considered were the Stated Policies Scenario (STEPS) and the Sustainable Development Scenario (SDS), which incorporate clean energy deployment targets, technology shares, and mineral intensity improvements. Mineral requirements were computed for solar PVs, wind turbines, other renewable generation, nuclear power, electricity networks, battery energy storage, EVs, and hydrogen supply chains. The report provides data on annual mineral requirements in 2020, 2030, and 2040 under each scenario for all technologies. However, country-specific data were not published in the study.

The IEA has also developed a risk assessment framework in its Securing Clean Energy Technology Supply Chains (2022) publication, providing guidelines that governments and businesses can use to capture the risks and vulnerabilities of supply chains (IEA, 2022a). Transitioning to NZE necessitates the rapid expansion of innovative and cost-effective clean energy technologies, which will provide energy security and ensure economic development and environmental sustainability. The IEA Energy Technology Perspectives 2023 (IEA, 2023a) discusses how governments and other stakeholders must learn to facilitate this transition by creating secure, resilient, and sustainable supply chains.

The evolving dynamics of the technology types influence the demand and prices of the required critical minerals. The rising demand for batteries has increased the cost share of battery minerals (lithium, nickel, cobalt and manganese) in the lithium-ion battery (LIB) pack from about 5% in 2015 to 20% in 2022. While the prices of these battery minerals increased till 2022, the prices started to decline after that (Trading Economics, 2024). The report finds that the currently announced pledges scenario (APS) by governments and companies may be insufficient for the world to achieve the net-zero goal by 2050. Energy-related emissions would still hover around 11 Gt CO2 in 2050. While the APS projects an emissions reduction of 15% between 2021 and 2030, the required emissions reduction is a 40% reduction under the NZE scenario.

According to the IEA Critical Minerals Market Review 2023 (IEA, 2023b), global demand (all uses) increased threefold for lithium, doubled for neodymium, and rose 70% for cobalt and 40% for nickel from 2017 to 2022. The market size of the critical minerals doubled to $320 billion. The future green transition shall be subject to the availability and affordability of critical minerals. The world demand for critical minerals for green transition will increase sharply by 2050.

Table 1: Share of Demand in Green Technologies (%)

Mineral	2017	2022
Nickel	6	16
Cobalt	17	40
Lithium	30	56
Neodymium	7	10

Source: IEA (2023c).

The IEA has alluded to three layers of the critical minerals supply-side challenges: sufficiency, diversity and ESG standards of the sources. While signs point to increased supply, future adequacy remains uncertain. Contrary to showing signs of diversification, critical mineral supplies have become even more concentrated. Progress towards achieving sustainable and responsible mining practices including respecting the rights of and working with affected communities and protecting ecosystems, has been limited. While some major mining companies have moved ahead with commitments to the welfare of the communities, the safety of workers, and increasing workforce gender balance, not much has happened in adhering to environmental standards.

In March 2023, the European Commission adopted a proposal for implementing the EU's access to a secure and sustainable supply of critical raw materials through a Critical Raw Materials (CRM) Act (European Commission, 2023). These minerals are required to develop technologies for strategic sectors such as renewable energy, digital, space, and defence. The major focus technologies include renewables, electric mobility (e-mobility), industry, information and communications technology (ICT), and aerospace and defence. The EU has set ambitious targets for requisite critical raw materials for 2030 and 2050.

A foresight study by the EU on the "Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU" (Joint Research Centre (European Commission), 2023) forecasts material demand until 2050 for the energy and digital transition and the requirements for the defence and space sectors. It also identifies the bottlenecks in supply chains, with a focus on geographic concentrations of supply chain stages in certain jurisdictions.

Clean energy technologies need much higher quantities of minerals than fossil fuel-based energy generation (Hund, La Porta, Fabregas, Laing, & Drexhage, 2020). The minerals face varying demand risks during the run-up to NZE. Minerals like copper, chromium, and molybdenum are cross-cutting across most energy-generation technologies and, hence, are likely to face stable demand in the future. Other minerals, including lithium, graphite, and cobalt, have technology-specific concentrated demand scenarios and may face future demand risks due to adopting alternative technologies. Substitution possibilities shall also play an essential role in the demand scenarios. While each of these minerals would help transform the energy sector to low emissions, it also carries its footprint of emissions during its extraction and processing. Understanding and analysing the supply chain of low-carbon technologies, from extraction to the end of life of the minerals-embedded components, is essential. Greenhouse gas emissions should be minimised at all stages of energy technology supply chains, thus offering more significant wins. The resource-rich developing economies would reap the benefits of low emissions and economic growth. While recycling and reuse shall be essential to *mine the gap*, the primary extraction of minerals would still be required.

Projecting the future needs of different critical minerals is a complex exercise. Various models have been used based on multiple assumptions and parameters regarding likely changes in population and income growth and types of evolving energy technologies. The mineral demand projections constitute vital inputs for governments, miners, processors, developers of renewable technologies and civil society. The projections, however, are subject to wide variations due to complexities and uncertainties of assumptions made (The Payne Institute for Public Policy, 2023).

3. Taking Stock of India's Clean Energy Targets

During the 26th meeting of the Conference of Parties (COP26) held in November 2021, India presented five elements (*panchamrit*) of its climate action (PIB, 2022a). Table 2 summarises the progress that India has made since then in reaching its commitments.

Following these announcements at COP26, the Government of India submitted its revised Nationally Determined Contributions (NDCs) to the UNFCCC in August 2022 (Government of India, 2022), which included the commitment to reaching NZE by 2070. Of these announcements, three were quantifiable goals (#3–#5) (Table 3).

Table 2: Status of India's Climate Action (Panchamrit)

Element	Climate Action Target		Status	
	Goal	Year	Current	Year
Reach 500 GW of non-fossil energy capacity by 2030	500 GW	2030	198.8 GW	March 2024
50% of electricity requirements will be from renewable electricity by 2030	50%	2030	24.9%	2021-22
Reduction of total projected carbon emissions by one billion tonnes from 2021 to 2030	1 billion tonnes reduction	2030	N/A	N/A
Reduction of the carbon intensity of the economy by 45% by 2030 over 2005 levels	45%	2030	33%	2019
Achieving the target of net zero emissions by 2070	Net zero	2070	26,46,556 Gg of CO_{2e}	2019

Source: (Central Electricity Authority, 2023c), (Central Electricity Authority, 2023a), (PIB, 2023c), (Ministry of Environment, Forest and Climate Change, 2023).

Table 3: Status of India's Climate Action (Updated NDCs)

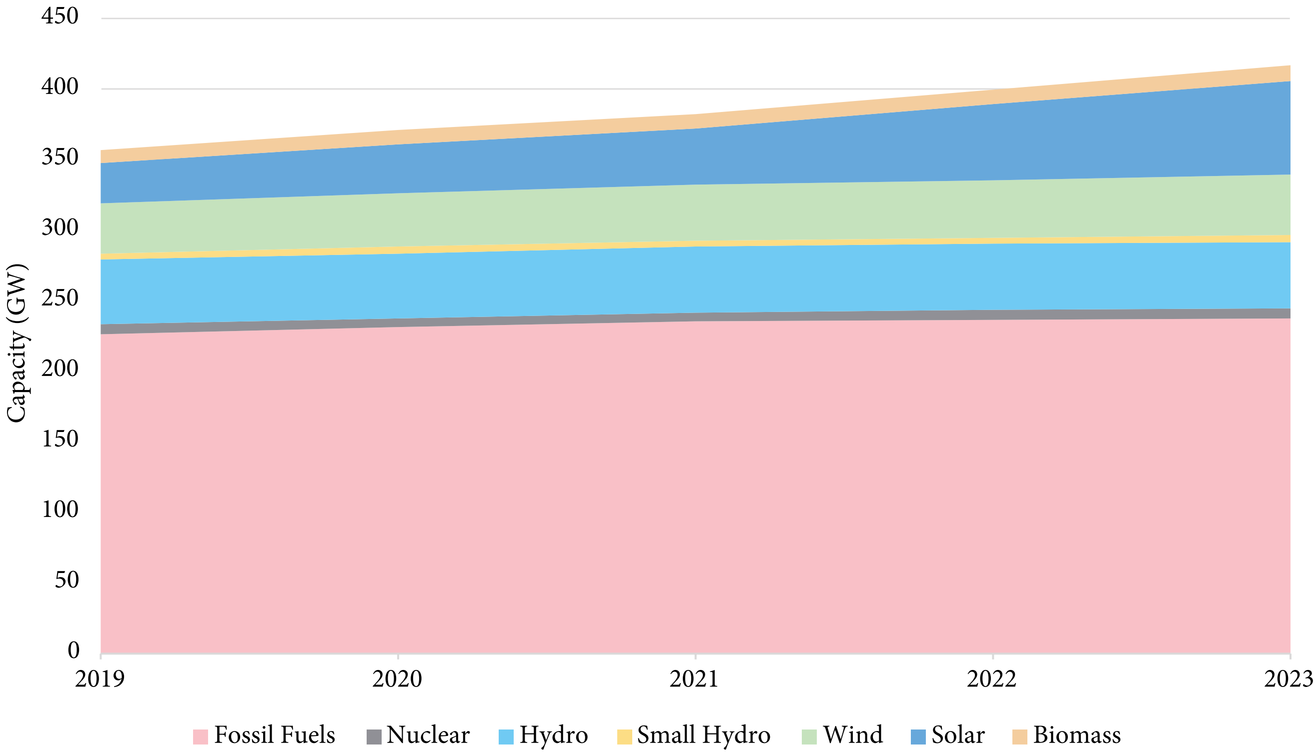
Element	Climate Action Target		Status	
	Goal	Year	Current	Year
To reduce the Emissions Intensity of its GDP by 45% by 2030, from the 2005 level	45%	2030	33%	2019
To achieve about 50% cumulative electric power installed capacity from non-fossil fuel-based energy resources by 2030, with the help of the transfer of technology and low-cost international finance, including from the Green Climate Fund (GCF)	50%	2030	45.0%	March 2024
To create an additional carbon sink of 2.5 to 3 billion tonnes of CO2 equivalent through additional forest and tree cover by 2030	2.5–3 billion tonnes reduction	2030	N/A	N/A
Achieving the target of net zero emissions by 2070	Net zero	2070	26,46,556 Gg of CO_{2e}	2019

Source: (Central Electricity Authority, 2023c), (Ministry of Environment, Forest and Climate Change, 2023).

India's non-fossil power capacity (i.e., nuclear, large hydro, small hydro, wind, solar, and biomass) stands at 188.3 GW as of December 2023. To meet the 500 GW target by 2030, an average of 44.5 GW of non-fossil capacity would need to be added over the subsequent seven years. To meet this goal, the government has committed to adding 50 GW of renewables capacity every year (PIB, 2023d). In contrast, an average of 12.4 GW was added yearly in the five preceding years. However, the Ministry of Power recently announced in February 2024 that the non-fossil fuel capacity is likely to reach 500 GW only by 2031-32 (Ministry of Power, 2024).

India's electricity capacity and generation mix have steadily shifted from fossil fuels to renewable sources (Figure 1). Between 2019 and 2023, the capacity share of renewable energy sources (RES) increased from 22% to 30%, while the renewable electricity generation share climbed from 9% to 13% (Figure 2).[2] However, while the shares of fossil fuels[3] in both capacity and generation have dropped to 57% and 73%, respectively, there has been an increase in absolute terms for both. A reliance on fossil fuels would be required for India's energy needs, with continued growth expected in coal power capacity until a likely peak sometime between 2030-2035 (PIB, 2022b). The remaining installed capacity comprises nuclear and large hydro sources, with respective shares of 2% and 11% in 2023.

Figure 1: Installed Capacity by Source (GW)



Source: Central Electricity Authority (2023a).

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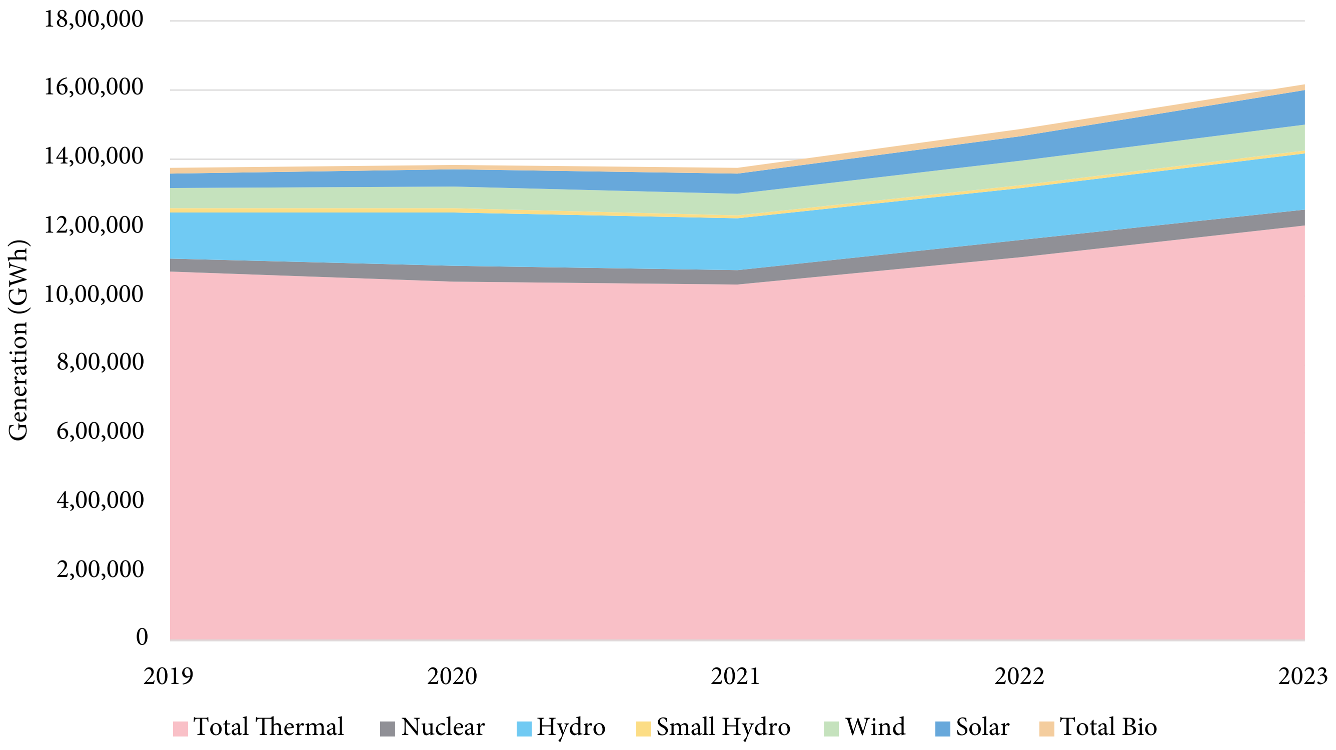
[2] RES includes electricity generation from small hydro, solar, wind, and biomass.

[3] Fossil fuel sources include coal, lignite, gas, and oil products.

Figure 2: Electricity Generation by Source (GWh)



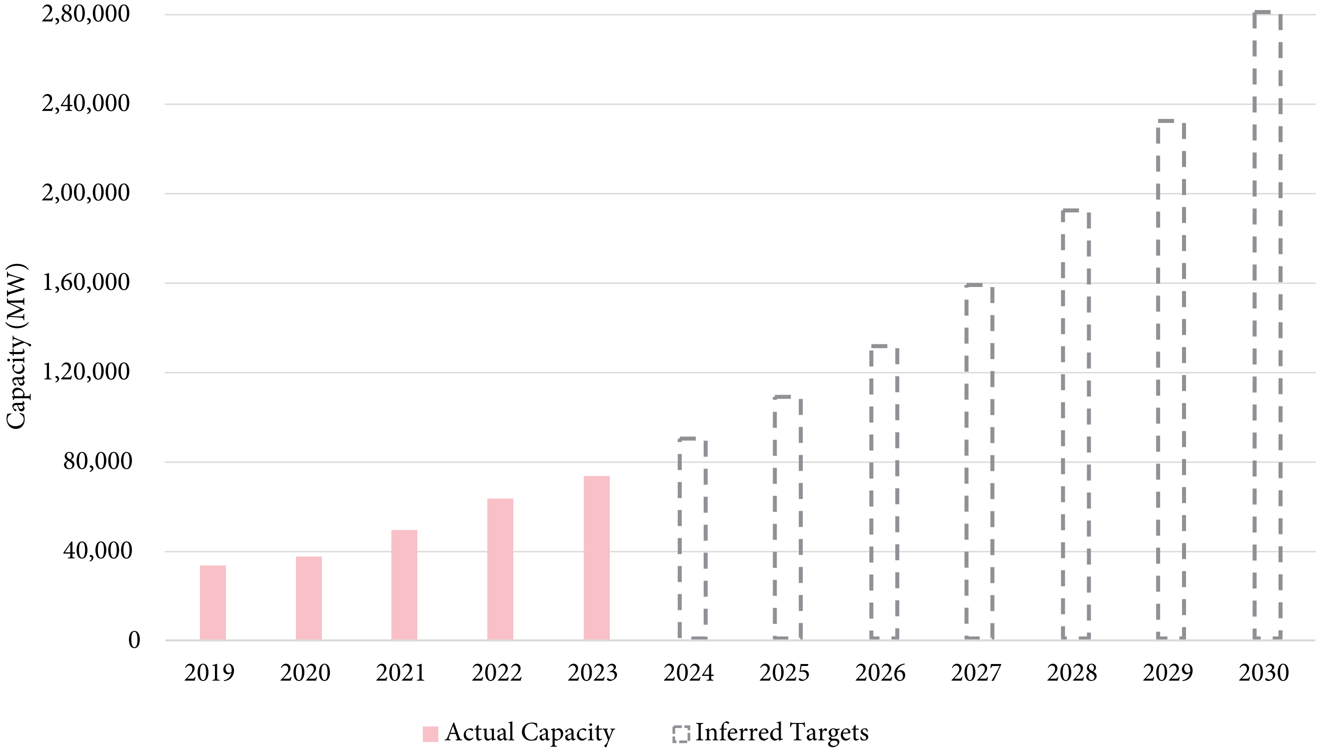
Source: Central Electricity Authority (2023a).

While there has been limited formal confirmation on the breakdown of the 500 GW by renewable sources, some government sources have suggested that 280 GW would come from solar (PIB, 2023a) and 140 GW would come from wind (PIB, 2023b). The remaining 80 GW would be made up of nuclear (currently 7.5 GW), large hydro (currently 46.9 GW), and bio-power (currently 10.8 GW), though the precise disaggregation has not been announced.

The annual rate of solar capacity addition over the past four years (21.4%) has been in line with the expected requirement for the 2030 target over the next seven years (21.1%), with an average of 29.5 GW/annum required during this period. Wind capacity, however, has increased at a much slower rate of 4.5% per annum over the past four years, compared to the 17.7% per annum required over the next seven years. An average addition of 13.6 GW per annum would be required till 2030 to meet the targets for wind capacity installation.

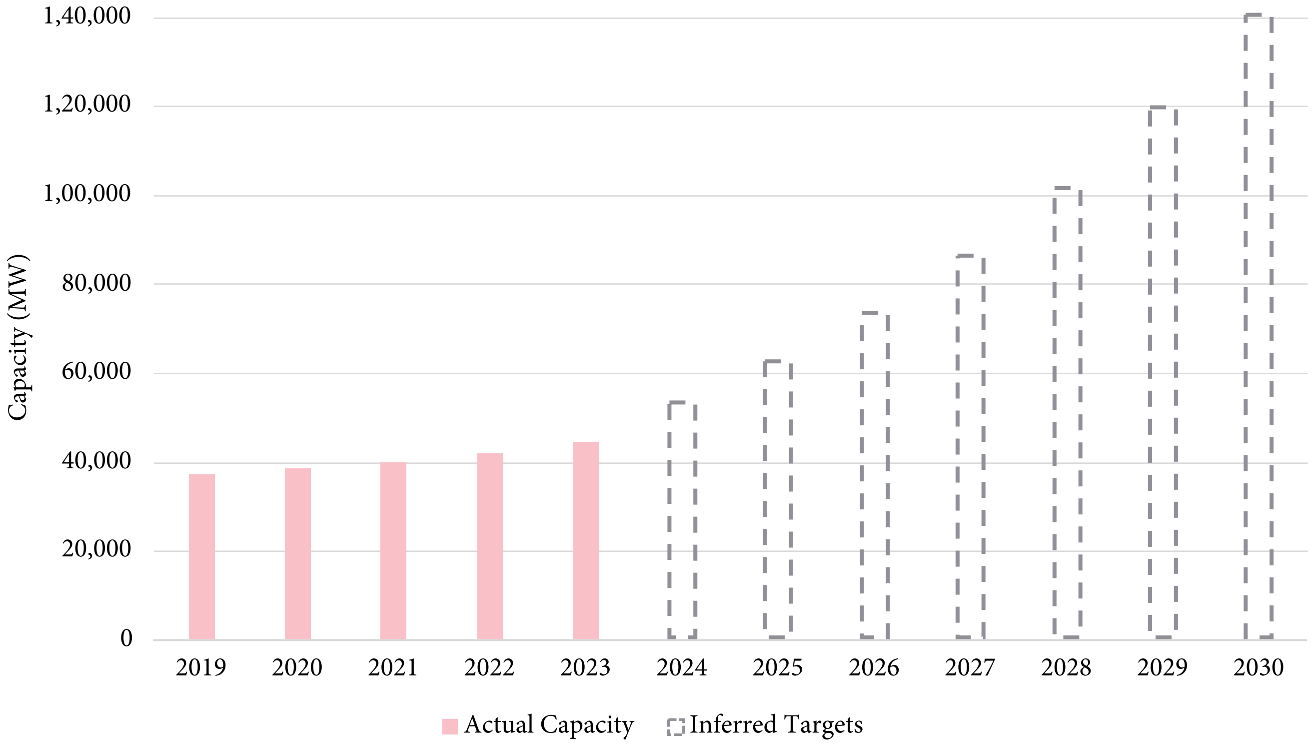
Figures 3 and 4 show the capacities of solar and wind in India from December 2019 to 2023 and a potential pathway to reach the 2030 target with a constant annual compounding capacity addition.

Figure 3: Solar Capacity (Historic and Inferred Targets)



Source: Central Electricity Authority (2023a; 2023b), Authors' computations.

Figure 4: Wind Capacity (Historic and Inferred Targets)



Source: Central Electricity Authority (2023a; 2023b), Authors' computations.

4. Overview of Clean Energy Technology Supply Chains

4.1 Solar Photovoltaics

Material Requirements

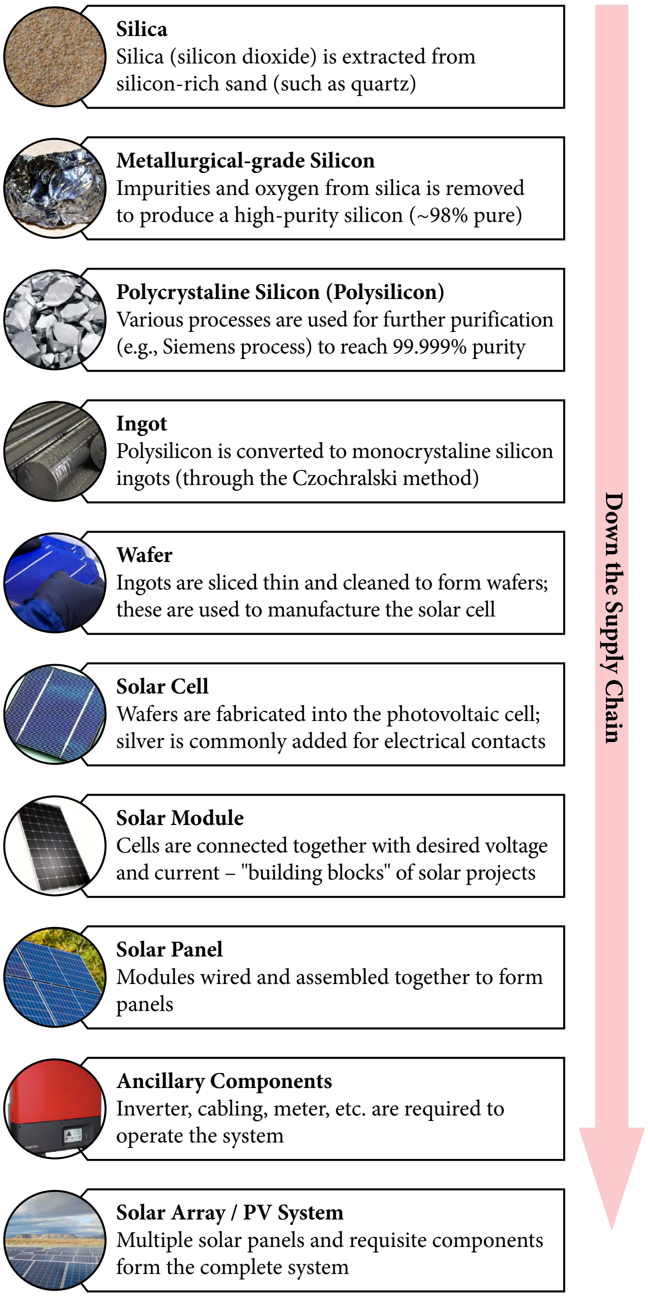
Solar panels use photovoltaic (PV) cells to convert sunlight into electricity through the PV process. Solar cells are connected to form solar modules and panels, which can then be arranged in large groups along with a *balance of system (BOS)* components to make up a solar array (or PV system). BOS components are the supporting equipment needed to run a solar array. For example, in grid-connected projects, an inverter is required to convert the generated direct current (DC) to alternating current (AC).

Various solar cell technologies are available. Wafer-based crystalline silicon (c-Si) is the most dominant, accounting for around 95% of global PV production. The remaining 5% consists of various thin-film solar cells (TFSC). c-Si solar cells are typically considered first-generation solar technology, while TFSC options are classified as second-generation. The structure of the silicon crystals further distinguishes c-Si cells as either monocrystalline or polycrystalline. Monocrystalline cells are more expensive to manufacture but more efficient, making up around 84% of total c-Si production (and hence around 80% of total solar cell manufacturing) (Fraunhofer Institute for Solar Energy Systems, 2023). Solar efficiency is measured as the percentage of the solar energy incident on the panel that is converted to electricity.

Several TFSC solutions exist, including cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and amorphous silicon (a-Si), with CdTe and CIGS being more popular currently. TFSC have the advantage of being cheaper to manufacture, slimmer, and more flexible compared to c-Si cells. However, the average efficiency of the CdTe cell is around 18%, lower than the typical efficiency of c-Si cells of around 22% (National Renewable Energy Laboratory, 2024). Third-generation solar cell technologies are also emerging (though not yet on a commercial scale), such as the copper zinc tin sulphide (CZTS) solar cell, which has the potential to reach higher efficiency than the theoretical maximum of first- or second-generation cells.

While all solar panels require similar basic construction and wiring materials (such as steel, concrete, glass, plastic, aluminium, and copper), some mineral requirements for manufacturing vary based on solar cell technology. For example, the c-Si cell requires silicon and silver, and the CdTe cell requires cadmium and tellurium. Figure 5 shows the stages of the c-Si PV manufacturing value chain, starting from the mining of silicon-rich sand to assembling a PV system.

Figure 5: Manufacturing Monocrystalline c-Si PV System



Silica
Silica (silicon dioxide) is extracted from silicon-rich sand (such as quartz)

Metallurgical-grade Silicon
Impurities and oxygen from silica is removed to produce a high-purity silicon (~98% pure)

Polycrystaline Silicon (Polysilicon)
Various processes are used for further purification (e.g., Siemens process) to reach 99.999% purity

Ingot
Polysilicon is converted to monocrystaline silicon ingots (through the Czochralski method)

Wafer
Ingots are sliced thin and cleaned to form wafers; these are used to manufacture the solar cell

Solar Cell
Wafers are fabricated into the photovoltaic cell; silver is commonly added for electrical contacts

Solar Module
Cells are connected together with desired voltage and current – "building blocks" of solar projects

Solar Panel
Modules wired and assembled together to form panels

Ancillary Components
Inverter, cabling, meter, etc. are required to operate the system

Solar Array / PV System
Multiple solar panels and requisite components form the complete system

Source: Florida Solar Energy Center (2017), Solar Energy Technologies Office (n.d.).

Image sources: (Hi-Res Images of Chemical Elements, 2009), (Enricoros at English Wikipedia, 2007), (pv magazine, 2024), (Crystal Scientific, 2014), (Oregon Department of Transportation, 2009), (Davis & Shirtliff, 2024), (SMA, 2024), (BlackRockSolar, 2013).

Table 4: Material Intensities of Solar PVs (t/GW)

Mineral	c-Si	Thin Film Solar Cells		
		CdTe	CIGS	a-Si
Concrete	60,700	60,700	60,700	60,700
Steel	67,900	67,900	67,900	67,900
Plastic	8,600	8,600	8,600	8,600
Glass	46,400	46,400	46,400	46,400
Aluminium (Al)	7,500	7,500	7,500	7,500
Copper (Cu)	4,600	4,600	4,622	4,600
Silicon (Si)	4,000	0	0	150
Silver (Ag)	20	0	0	0
Cadmium (Cd)	0	50	0	0
Tellurium (Te)	0	52	0	0
Indium (In)	0	0	15	0
Gallium (Ga)	0	0	4	0
Selenium (Se)	0	0	35	0
Germanium (Ge)	0	0	0	48

Source: Carrara, Alves Dias, Plazzotta, & Pavel (2020).

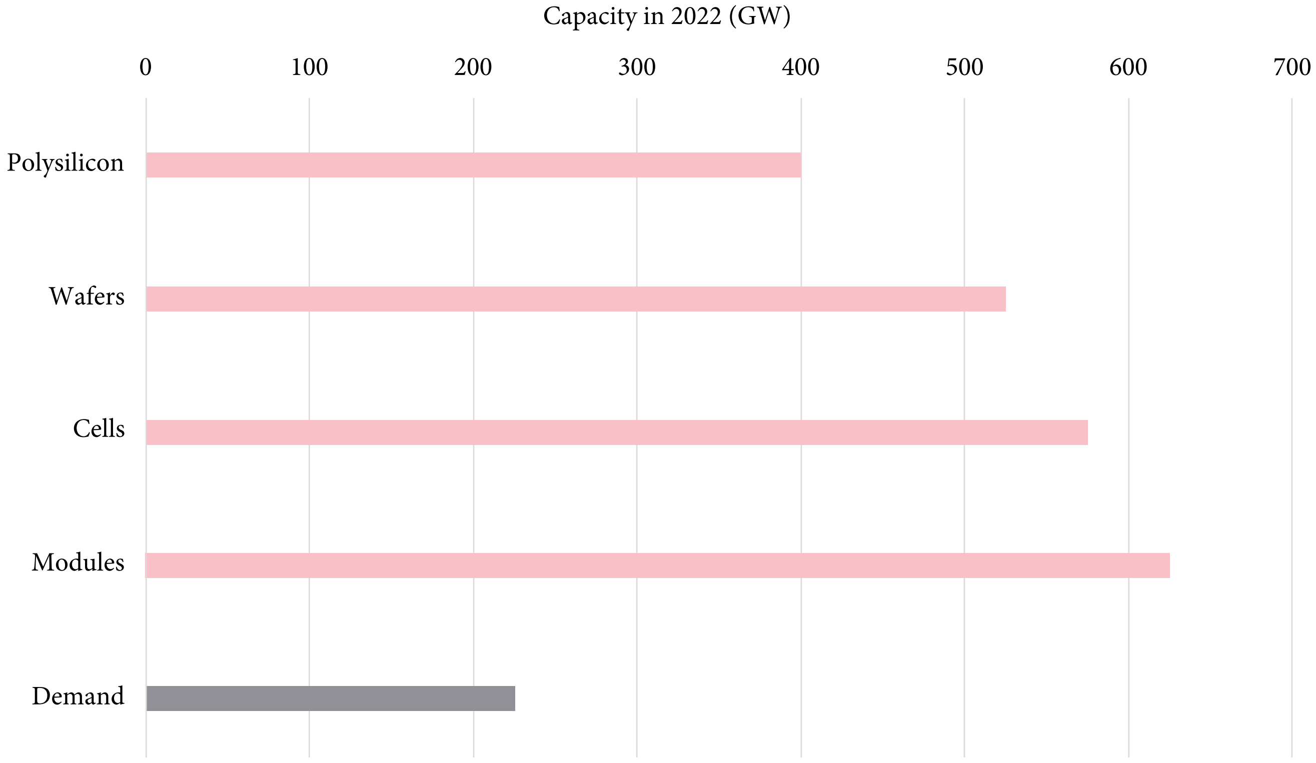
The projections for raw material requirements to manufacture solar PVs are based on the estimated materials needs per GW of installed capacity, known as mineral/material intensity. Table 4 shows the material intensities, measured in tonnes per gigawatt of installed capacity, for the following solar PV technologies: crystalline silicon (c-Si), cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and amorphous silicon (a-Si) solar PVs. While the table provides the requirements for structural materials like concrete, steel, plastic, and glass for each clean energy technology, these materials are not considered in the projections study.

Supply Chains

China currently dominates all stages of the solar PV value chain. The country produces 79% of global polysilicon, 97% of wafers, 85% of cells, and 75% of modules (IEA, 2022b). This concentration in manufacturing is prevalent with a handful of Chinese companies. India does not participate in the upstream stages of solar manufacturing and has a 1% share in cell production and a 3% share in module production. Other players in cell and module manufacturing are in Southeast Asia. Germany is a key supplier of polysilicon, while the United States and Japan manufacture higher-purity semiconductor-grade silicon. The current demand for solar panels is much lower than the manufacturing capacity, though there was a bottleneck in polysilicon manufacturing to some extent (Figure 6), which has somewhat eased in 2023. The large excess in supply has led to a surplus of solar panels and a price drop (Bernreuter Research, 2024).

While India expects to meet its short-term solar capacity demand through imports of modules and panels, the longer-term requirements are expected to be high, and the supplies are considered risky. To boost domestic solar PV module manufacturing capacity, the Government of India has initiated two PLI schemes (Ministry of New and Renewable Energy, 2024). The National Programme on High-Efficiency Solar PV Modules was launched in April 2021 with an initial outlay of ₹4,500 crore. Three successful bidders committed to installing a manufacturing capacity of 8,737 MW per annum, of which 4,368 MW is eligible for PLI benefits. This capacity will cover the entire value chain, from polysilicon manufacturing to module production.

Figure 6: Global Solar PV Supply Chain Capacity in 2022 (GW)



Source: IEA (2022b).

A second tranche of the PLI scheme was announced in September 2022, with an outlay of ₹19,500 crore. Out of 11 successful bidders, three will begin from the polysilicon manufacturing stage (15,400 MW per annum, of which 7,700 MW is eligible for PLI), five from the wafer manufacturing stage (16,800 MW per annum, with 8,400 MW eligible for PLI), and three from the cell manufacturing stage (7400 MW per annum, with 3,700 MW eligible for PLI). In total, 39,600 MW of solar manufacturing capacity will be added under the second tranche, of which 19,800 MW is eligible for PLI benefits.

Both tranches are technology-agnostic, meaning either first- or second-generation cells can be manufactured, and incentives would be provided for higher-efficiency panels. While the PLI documentation requires a minimum value of domestic value addition, it also indicates that polysilicon can be manufactured from either domestic or imported metallurgical-grade silicon (Ministry of New & Renewable Energy, 2021). The stipulated timeline for commissioning the integrated plant (i.e., polysilicon and downstream) is three years from when the Letter of Award is granted, which would be around 2025 to 2026.

While India does not currently have metallurgical-grade silicon manufacturing capacity, some companies, including Reliance New Energy Solar and Adani Solar, have committed to producing the material from quartz (Gupta, 2022).

4.2 Wind Turbines

Material Requirements

Wind turbines convert the kinetic energy of wind into mechanical energy through the rotation of blades, which then turns a generator to generate electrical energy. The blades are attached to a rotor and shaft, which either connects to the generator through a gearbox, which increases the rotational speed (in gearbox turbines) or directly (direct-drive turbines). While the gearbox design is most commonly used currently due to its technology maturity and cost-effectiveness, direct-drive turbines benefit from requiring less maintenance and higher efficiency. Direct-drive turbines are better suited for offshore wind farms, where accessing the turbines is more challenging. Table 5 highlights some of the characteristics of gearbox and direct-drive turbine designs.

Table 5: Characteristics of Gearbox and Direct Drive Turbines

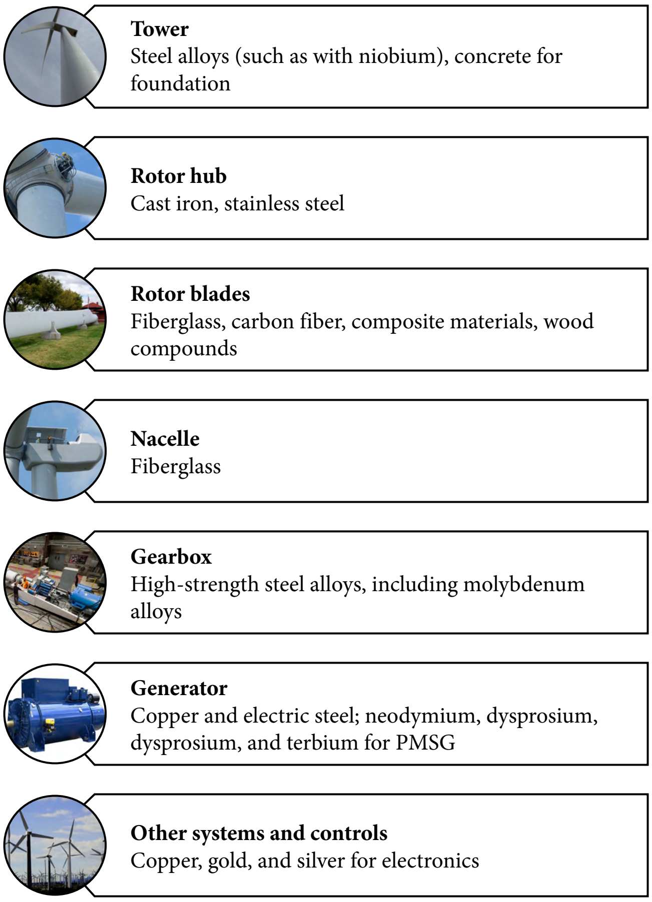
Characteristic	Gearbox	Direct Drive
Rotor	The turbine blades spin at around 10-30 revolutions per minute and are connected to a rotor and shaft inside the nacelle.	
Principle	The shaft is connected to the gearbox, which increases the rotational speed of the rotor to the optimal speed required for the generator.	The rotor connects directly to a heavier and larger generator, which can operate at lower speeds.
Gearbox	The rotational speed of the blades must be converted to match the requisite speed of the generator with minimal energy losses.	The rotor connects to the generator directly through the shaft, so a gearbox is not required.
Generator	The most common design is the doubly fed induction generator (DFIG); some have permanent magnet synchronous generators (PMSG).	The most common technology is the permanent magnet synchronous generator (PMSG); some turbines have electrically excited synchronous generators (EESG).
Efficiency	High efficiency within optimal wind speed range, but drops if the wind is too fast or slow. There are some energy losses in the gearbox.	It is more efficient at lower wind speeds and for a larger range of wind speeds than gearbox designs.
Size	The generator is smaller than the direct-drive counterpart, but space is required for the gearbox.	While there is no gearbox, the generator is larger than the gearbox counterpart.
Maintenance	The gearbox is susceptible to wear and tear, requiring more frequent maintenance.	There are fewer moving parts without the gearbox, leading to potentially lower maintenance requirements.
Uses	Most operational wind turbines, and those being manufactured, are gearbox designs.	First developed in 1991, direct drive turbines are more popularly used in offshore turbines due to their lower maintenance requirements. The use of direct-drive turbines is expected to rise as efficiencies increase.

Source: (Osmanbasic, 2020).

Over the years, wind turbines have been increasing in height and blade diameter (Office of Energy Efficiency & Renewable Energy, 2023). Offshore wind turbines typically have a much larger nameplate capacity compared to onshore turbines due to higher wind speeds and the lack of obstacles that could cause turbulence in the wind flow. The nameplate capacity refers to the maximum power output of the turbine (or plant), while the actual power output may be lower due to various factors. Hub heights (the distance from the surface to the turbine hub) of modern onshore and offshore exceed 100 m, with rotor diameters of over 150 m (GE Renewable Energy, n.d.). The average nameplate capacity of new wind turbines globally is around 3 MW, with the largest offshore turbines exceeding 10 MW (Office of Energy Efficiency & Renewable Energy, 2023). While offshore turbines tend to be larger, they share similar components to their onshore counterparts (Figure 7).

The structural elements (i.e., the wind turbine tower and foundation) require concrete and steel, with fibreglass being used for the nacelle, which houses the drivetrain, gearbox, generator, and other control equipment. Generators of both gearbox and direct-drive turbines require some permanent magnets made of rare earth elements (REEs), with direct-drive requiring more, as the generator needs to operate at lower wind speeds. REEs refer to seventeen metallic elements needed for manufacturing various high-tech products (American Geosciences Institute, 2018). They are especially important for producing magnets used in applications like laptops and wind turbine generators. Some next-generation generator technologies incorporate superconductor materials, which would result in a reduced requirement of REEs and a smaller generator weight and size (Office of Energy Efficiency & Renewable Energy, 2021).

Figure 7: Wind Turbine Components and Requisite Minerals & Metals



Tower
Steel alloys (such as with niobium), concrete for foundation

Rotor hub
Cast iron, stainless steel

Rotor blades
Fiberglass, carbon fiber, composite materials, wood compounds

Nacelle
Fiberglass

Gearbox
High-strength steel alloys, including molybdenum alloys

Generator
Copper and electric steel; neodymium, dysprosium, dysprosium, and terbium for PMSG

Other systems and controls
Copper, gold, and silver for electronics

Source: (Global Wind Energy Council, 2023).

Image sources: (brewbooks, 2007), (Anderson, Working on the Hub of Turbine No 2 at Scout Moor, 2007), (Tuck, 2014), (Anderson, 2008), (McDade, 2020), (Leroy Somer, 2022).

Estimates of mineral intensities have been taken to calculate the mineral requirements for manufacturing wind turbines. Table 6 shows the material intensities (measured in tonnes per gigawatt of installed capacity) for direct drive electrically excited synchronous generator (DD-ESG), direct drive permanent magnet synchronous generator (DD-PMSG), gearbox permanent magnet synchronous generator (GB-PMSG), and gearbox doubly-fed induction generator (GB-DFIG).

Supply Chains

The wind turbine supply chains require many critical minerals, with permanent magnets attracting the most attention and hence constituting a key bottleneck (Joint Research Centre (European Commission), 2023). China has a dominant position in the permanent magnet value chain, from extracting the required mineral neodymium to manufacturing the magnets. China accounts for 69% of global neodymium extraction and 85% of neodymium processing. While the country has an 87% global market share in manufacturing neodymium magnets (also known as NdFeB or NIB magnets due to their neodymium, ferrous and boron contents), it only has an approximate 50% share in the high-performance magnets required for wind turbines (and EVs), with Japan and Germany accounting for the remaining shares. Due to the rising demand for high-performance NIB magnets for wind turbines and EVs, a study estimates that by 2030, the demand for these magnets will exceed the supply by 2.5 times (Ma & Henderson, 2021).

The Global Wind Report 2023 highlights trends in the wind turbine manufacturing supply chains (Global Wind Energy Council, 2023). India has a strong domestic onshore wind turbine manufacturing capacity, with 13 operational onshore nacelle assembly facilities and two more facilities announced. The country's manufacturing capacity of onshore nacelle stands at 11.5 GW (representing 7% of global capacity), blades at 14.3 GW (11%), generators at 8.7 GW (7%), and gearbox at 19.2 GW (12%). However, while India's domestic onshore manufacturing capacity is expected to meet its demand by 2030, domestic offshore nacelle manufacturing has not yet taken off. In a strategy paper for establishing offshore wind energy projects, the Government of India plans to auction 37 GW of offshore wind capacity by 2029-30 (Ministry of New and Renewable Energy, 2023). Some of this demand would need to be met through imports.

Table 6: Material Intensities of Wind Turbines (t/GW)

Material	DD-EESG	DD-PMSG	GB-PMSG	GB-DFIG
Concrete	3,69,000	2,43,000	4,13,000	3,55,000
Steel	1,32,000	1,19,500	1,07,000	1,13,000
Polymers	4,600	4,600	4,600	4,600
Glass/carbon composites	8,100	8,100	8,400	7,700
Aluminium (Al)	700	500	1,600	1,400
Iron (cast) (Fe)	20,100	20,100	20,800	18,000
Boron (B)	0	6	1	0
Chromium (Cr)	525	525	580	470
Copper (Cu)	5,000	3,000	950	1,400
Dysprosium (Dy)	6	17	6	2
Manganese (Mn)	790	790	800	780
Molybdenum (Mo)	109	109	119	99
Neodymium (Nd)	28	180	51	12
Nickel (Ni)	340	240	440	430
Praseodymium (Pr)	9	35	4	0
Terbium (Tb)	1	7	1	0
Zinc (Zn)	5,500	5,500	5,500	5,500

Source: Carrara, Alves Dias, Plazzotta, & Pavel (2020).

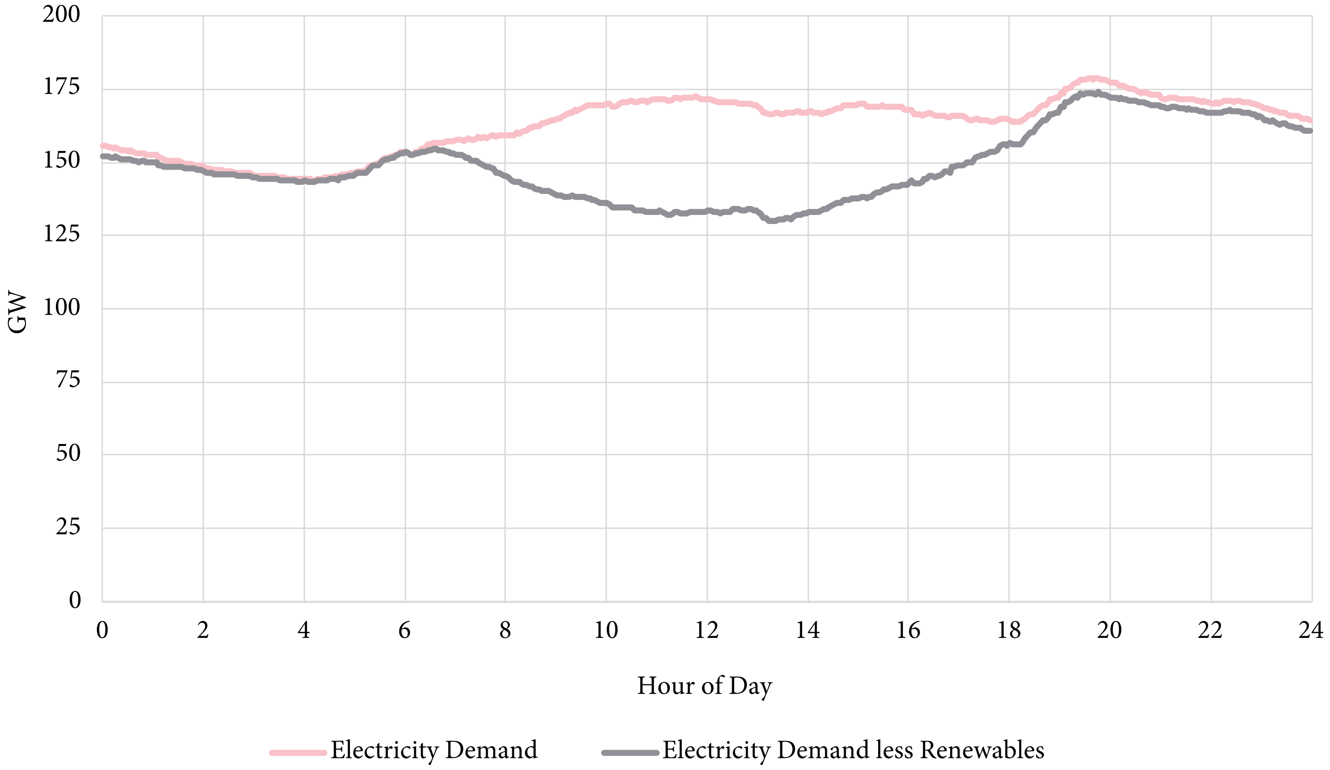
China remains dominant in the manufacture of all wind turbine components (both onshore and off-shore), with over 60% concentration in manufacturing the major components. It has enough capacity to meet both its large domestic demand as well as the demand from other countries.

4.3 Battery Energy Storage Systems

Material Requirements

Battery energy storage systems are required to tackle the intermittency of renewable energy supply and to make the power grid more reliable and efficient. The energy generation from RES is intermittent. Solar power generation depends on the geographical location, time of the day and the intensity of the sun's rays. Solar electricity generation peaks around mid-day and is absent after sunset. Wind energy also exhibits varying patterns depending on the geography, seasons and off and onshore location of the wind turbine. Such intermittency produces electricity asynchronous to typical consumption patterns. BESS can mitigate this intermittency by storing excess energy generated when the demand is low and sending it back to the grid when there is increased demand. Energy storage is vital for maintaining grid stability and ensuring a consistent electricity supply, and it reduces the need for fossil fuel-based power plants to provide a base load. Figure 8 shows the total electricity demand in India on May 4, 2023, along with the demand met through non-renewables. There is an imbalance between the generation peak of renewables (at around 11.30 am) and the electricity demand peak (at around 7.30 pm), which BESS can help smoothen.

Figure 8: India Electricity Demand vs Demand Less Renewables (May 4, 2023)



Source: CSEP Electricity & Carbon Tracker (Parray, Dalal, & Tongia, 2023), Authors' visualisation.

The global energy storage capacity reached 26 GW at the end of 2021 and is expected to increase 15-fold to 411 GW by 2030 (BloombergNEF, 2022). According to the CEA, the country is likely to have 41.65 GW of BESS capacity by 2029-30 (Central Electricity Authority, 2023b). If this capacity is achieved, it would represent around 10% of the estimated global installed capacity for energy storage. Recently, in February 2024, a 0.04 GW BESS system was inaugurated in Chhattisgarh, built alongside a solar farm (PIB, 2024a).

The choice of battery chemistry plays an important role when designing a new BESS. Various technology solutions exist, each with trade-offs between cost, energy density, lifespan, and efficiency (EVESCO, 2023). Energy storage developers must consider the grid requirements and local conditions to select the appropriate battery chemistry for a project. Currently, the most commonly used grid BESS is the lithium iron phosphate (LFP) battery, a subclass of LIBs.

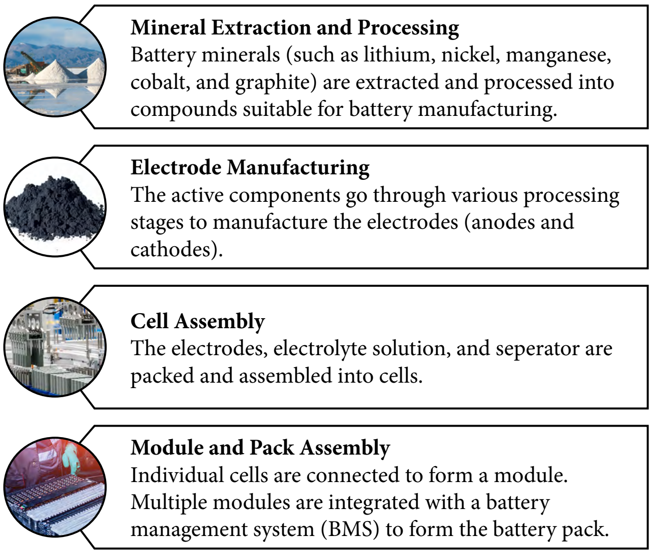
Several existing and emerging battery technologies are used for energy storage, including:

- *Lithium-ion (Li-ion)* batteries are currently the most prevalent due to their high energy density, charge and discharge efficiency, and longevity. Li-ion batteries represent a class of batteries with lithium in the positive electrode (cathode) and typically graphite in the negative electrode (anode), along with other elements in the cathode, such as:
    - *Lithium iron phosphate (LFP)* is currently the most commonly used battery chemistry for BESS.
    - *Lithium nickel manganese cobalt oxide (NMC)* is used for smaller-scale energy storage.
    - *Lithium nickel cobalt aluminium oxide (NCA)* is used for smaller-scale energy storage.
    - *Lithium nickel cobalt manganese aluminium oxide (NCMA).*
- *Lead-acid* batteries are more mature and cost-effective but have a lower energy density (and hence would require more physical space for the same energy capacity) and a shorter lifespan when charged and discharged frequently.

- Flow batteries, with the *vanadium redox flow (VRF)* battery being the most common. These batteries have long lifespans and can withstand temperature variations well. However, they are more complex and expensive to install and maintain than Li-ion batteries, and they have a lower energy density. There are also concerns regarding the availability and price volatility of vanadium. China recently connected the world's largest VRF storage system (100 MW capacity) to the grid (Santos, 2022).
- *Molten-salt/liquid-metal* batteries, such as the *sodium-sulphur (NaS)* and *sodium-nickel chloride (ZEBRA)* batteries, require high operating temperatures and are known for their high energy density and efficiency. While there are some safety concerns with this technology, it is suitable for and has been deployed at grid-scale in various countries.
- *Sodium-ion (Na-ion)* batteries are emerging as a cheaper alternative to Li-ion batteries, requiring far fewer critical minerals and no lithium. However, it has a lower power density, and the technology is primarily being used only in China (IEA, 2023c).

Among the various technologies, Li-ion remains the most prevalent option for BESS today. The broad stages of Li-ion battery manufacturing are shown in Figure 9.

Figure 9: Lithium-ion Battery Supply Chains



Mineral Extraction and Processing
Battery minerals (such as lithium, nickel, manganese, cobalt, and graphite) are extracted and processed into compounds suitable for battery manufacturing.

Electrode Manufacturing
The active components go through various processing stages to manufacture the electrodes (anodes and cathodes).

Cell Assembly
The electrodes, electrolyte solution, and seperator are packed and assembled into cells.

Module and Pack Assembly
Individual cells are connected to form a module. Multiple modules are integrated with a battery management system (BMS) to form the battery pack.

Source: (VDMA, 2019).

Image sources: (Earthworks, 2019), (Sumitomo Metal Mining, 2022), (Flexlink, 2022), (Unico, 2022).

Estimates of mineral intensities have been used to evaluate the mineral requirements for manufacturing batteries for energy storage systems. Table 7 shows the material intensities measured in tonnes per gigawatt hour (GWh) of installed capacity for different battery types:

1. Three types of lithium nickel manganese cobalt (NMC) batteries
2. Lithium nickel aluminium oxide (NCA) batteries
3. Lithium iron phosphate (LFP) batteries
4. Vanadium redox flow batteries (VRF).

NMC batteries come in various types, each with differing ratios of nickel, manganese, and cobalt. For example, NMC811 contains 80% nickel, 10% manganese, and 10% cobalt in the cathode.

Non-battery energy storage solutions, such as pumped-storage hydropower (PSH) for electricity load balancing, are also commonly used. PSH is based on the gravitational potential energy of water and uses excess electricity supply in the grid (such as when solar PVs generate the most electricity) to pump water from a low-elevation reservoir to a high-elevation reservoir. When there is excess electricity demand, the water is let out through hydroelectric turbines back to the lower-elevation reservoir.

Other forms of energy storage include *compressed air energy systems (CAES)*, where the air is compressed when electricity is cheap and then depressurised and released to drive a turbine when electricity demand rises. *Hydrogen* also has the potential to be used for storage (FCHEA, n.d.).

Supply Chains

Li-ion battery supply chains are concentrated heavily in China (IEA, 2022c). China produces 75% of all Li-ion batteries, along with 70% of cathodes and 85% of anodes. More than half of lithium, cobalt, and graphite processing is also located in China, though the battery minerals are typically mined in other countries. For instance, Australia accounts for the majority of global lithium production, the Democratic Republic of Congo is a major source of cobalt mining, and Indonesia is a leading producer of nickel. However, a significant portion of these minerals are shipped to China for processing and battery manufacturing. While some companies in India have begun some value addition in battery

Table 7: Material Intensities of Batteries (t/GWh)

Mineral	NMC811	NMC523	NMC622	NCA	LFP	VRF
Lithium (Li)	83	117	100	100	100	0
Cobalt (Co)	83	183	183	33	0	0
Nickel (Ni)	650	467	533	717	0	0
Manganese (Mn)	83	267	167	0	0	0
Graphite (C)	750	883	833	733	1,100	0
Aluminium (Al)	500	583	550	500	733	145
Copper (Cu)	333	333	317	283	433	21
Steel	333	333	317	283	433	28
Iron (Fe)	0	0	0	0	683	0
Vanadium (V)	0	0	0	0	0	3,400

Source: Transport & Environment (2021).

chains, supply chains, the global shares are currently negligible, and almost all demand for battery components is met through imports (Ministry of Heavy Industry, 2021).

To increase indigenous battery manufacturing, the Government of India formulated the National Programme on Advanced Chemistry Cell (ACC) Battery Storage, a Production Linked Incentive (PLI) scheme, with the goal of setting up giga-scale integrated manufacturing facilities. The goal is to achieve an annual manufacturing capacity of 50 GWh for ACCs and 5 GWh for niche ACCs, with a criterion for domestic value addition (Ministry of Heavy Industry, 2024). The government has estimated battery demand for EVs and energy storage to reach 120 GWh by 2030. With an expected manufacturing capacity of 145 GWh by 2030, India should be able to meet its domestic requirements (Marjolin, 2023). However, as battery mineral extraction and processing does not take place in India yet, there would still be a reliance on global supply chains to meet manufacturing needs.

4.4 Transmission Lines

Integrating new installations of clean energy power generation to the grid will require upgrades to existing transmission infrastructure. This is especially important since these RE facilities are typically distributed across different geographic locations within the country. Power grids will also need to be expanded to accommodate the growing population and increasing demand from industry.

Connecting RES to the grid will bring in a different set of considerations due to their intermittency and concentration in certain regions. For instance, offshore wind turbines would require a series of high-voltage transmission lines buried in the seafloor to connect to the mainland grid.

While this study does not project the requirements for the grid, critical minerals will also be required to manufacture the requisite components needed for the grid expansion. These include copper, zinc, tin, and silver (Kuczera & Heyck-Williams, 2022).

4.5 Electric Vehicles

This study does not project the mineral requirements for manufacturing India's green transport vehicles. However, many EV minerals overlap with those required for wind turbine generators and BESS. While a generator converts mechanical energy (from the turning blades) into electrical energy, a motor converts electrical energy (from the battery) into mechanical energy (to drive the drivetrain) (Manney, 2017).

Although EVs typically use Li-ion batteries, similar to BESS, the battery chemistry may differ to maximise energy density (for a lighter vehicle) and withstand frequent charge/discharge cycles. As the demand for EVs is set to rise considerably in India, it can be expected that the mineral requirements for their manufacturing, particularly lithium, nickel, manganese, cobalt, and graphite, will increase sharply in the coming years. On average, EVs require around six times the mass of critical minerals as compared to a conventional car (IEA, 2021).

5. Methodology

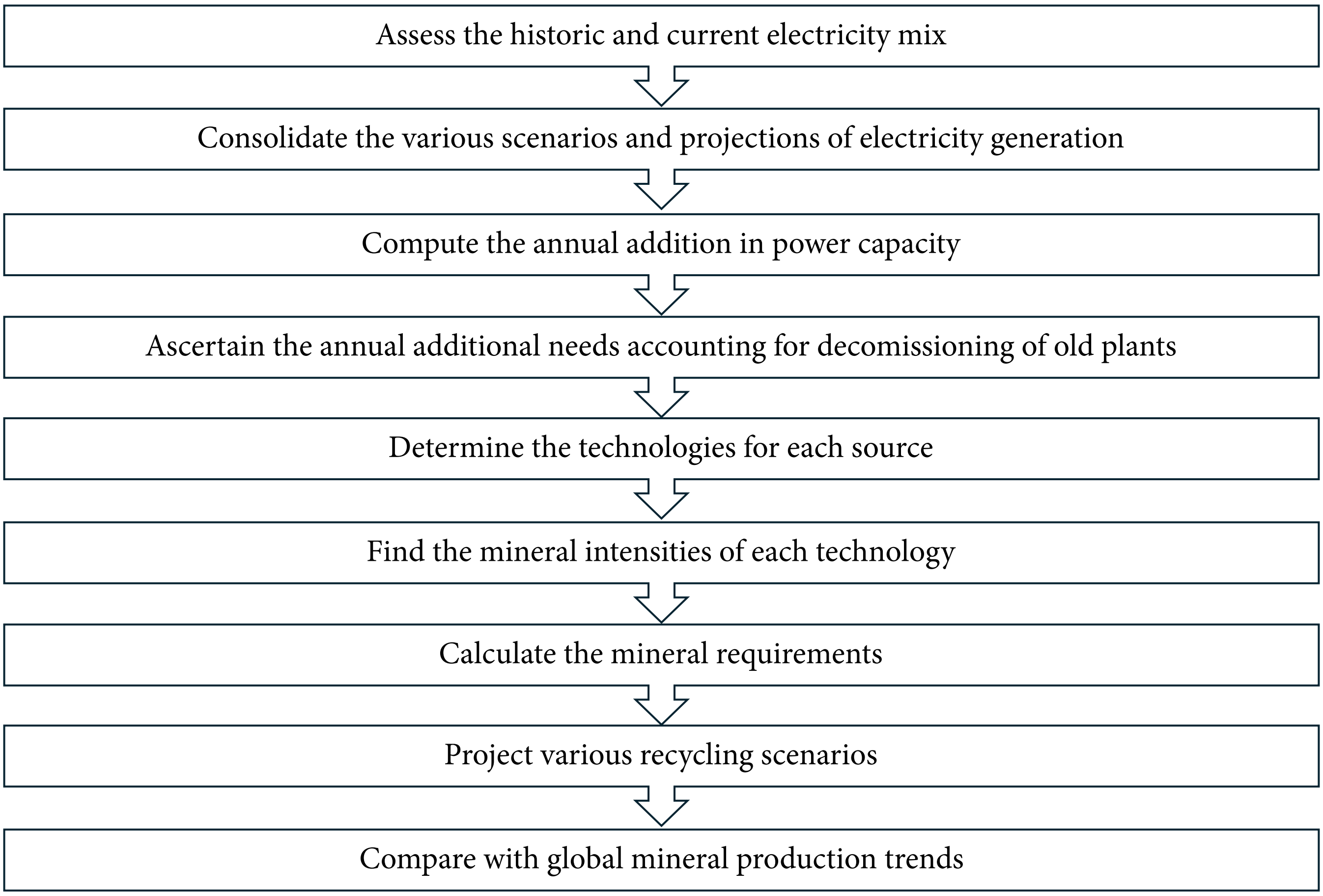
We follow the steps listed in Figure 10 to compute the critical mineral requirements for India's transition to green electricity.

This study focuses on renewable electricity capacity and the required BESS to facilitate its operation. We compute the annual addition in power capacity based on various scenarios, accounting for replacing older decommissioned plants. We then examine the different technology options for each source and devise scenarios on technology trends based on available literature. Finally, we use the mineral intensities for each technology option for each electricity source to compute the mineral requirements. We also show how recycling reduces the need for virgin ores and metals, which may decrease the impending supply gap and reduce greenhouse gas emissions.

We provide two or more alternate scenarios for each step in our methodology, each impacting the critical mineral requirements. We use an Excel-based model to compute the mineral requirements under each scenario. The various scenarios considered in this study are based on existing literature and the authors' judgement on which pathways India can attain for its low-carbon transition. However, with changing policies and evolving technologies, these results may require frequent revision. Potential technological disruptions cannot be accounted for in this model. Still, it has been developed such that users may adapt it to reflect any major changes in the types of green technologies being used.

The results indicate the total *embedded* mineral requirements in the respective sources, which may be produced or imported in India for processing or embedded within the components for domestic assembly. Section 4 of this study provides an overview of the supply chains of each technology, along with the current and expected status of domestic value addition. Based on indigenisation plans for these supply chains, which are set to occur over the next two decades, it is possible to estimate the quantities of raw materials needed, allowing for the determination of how much of these raw materials would be in the form of embedded requirements.

Figure 10: Methodology for Projecting Critical Mineral Needs



Source: Authors' elaboration.

5.1 Projection Scenarios

Various scenarios have been considered to project India's critical mineral needs for the clean electricity transition, such as for electricity capacity, lifespans of power stations, recycling rates, and future technology changes. The following sections elaborate on the chosen scenarios and the rationale for their selection.

Table 8: Mineral Projection Scenarios

Scenario	Details	Source
Electricity Capacity		
Business as Usual	CEA 2030 & NITI India Energy Security Scenarios (IESS) Level 1	Central Electricity Authority (2023b) & NITI Aayog (2023)
Determined Effort	CEA 2030 & NITI IESS Level 2	
Net Zero Pathway	CEA 2030 & NITI IESS NZE pathway	
Decommissioning		
Base Case	The average lifespan of technologies taken is 25 years for solar and wind and 10 years for battery storage	Literature review
Increased Life	Innovation of tech and repairs leads to an increased lifespan of 5 years for each—solar and wind technologies	Authors' elaboration
Recycling Input Rate		
Constant	The current recycling input rates of minerals are maintained	European Commission (2020)
Long-Term Improvements	The recycling input rates of minerals gradually increase in the long-term by 4% points every 10 years	Authors' elaboration
Solar Technologies		
Base Case	The share of c-Si versus thin-film remains 95% to 5% as it is today	Carrara, Alves Dias, Plazzotta, & Pavel (2020)
Increased Thin-Film	The share of PVs with thin-film technologies increases to 10% in 2047	
Wind Technologies		
Base Case	The share of permanent magnet-based wind turbines will go up to 50% in 2050	Carrara, Alves Dias, Plazzotta, & Pavel (2020)
Higher Permanent Magnet Use	The share of permanent magnet-based wind turbines will go up to 70% in 2050	
BESS Technologies		
Base Case	Constant share of various battery chemistries	Warrior, Tyagi, & Jain (2023)
Disruptive	Larger share of VRF batteries	
Mineral Intensities		
Base Case	Existing mineral intensities prevail throughout	Carrara, Alves Dias, Plazzotta, & Pavel (2020)
Long-Term Improvements	Investments in research and development will lead to reduced mineral intensities	Authors' elaboration

5.2 Electricity Capacity Scenarios

For the electricity capacity scenarios in this exercise, we use two sources for projected capacities:

1. 2023-2030: The CEA's *Report on Optimal Generation Mix 2030 Version 2.0* considers recent policy commitments for renewable energy and the associated technical and financial constraints for operationalisation (Central Electricity Authority, 2023b).
2. 2031-2047: NITI Aayog's *India Energy Security Scenarios, 2047* (IESS) (NITI Aayog, 2023), an open-source Excel-based tool that provides several energy policy scenarios and assesses the supply and demand of energy in the country until 2047.

The CEA report provides a roadmap for decarbonising the electricity sector until 2030,[4] aligning with the government's various renewable energy targets. The study undertook generation planning with several scenarios, considering future electricity demand and minimising costs. Table 9 summarises the CEA report's findings, contrasts the likely installed capacity in 2030 with the installed capacity in 2023, and computes the required compounded annual growth rate (CAGR) to meet the targets.

BESS is expected to see the largest growth, from the current negligible capacity to over 41 GW in 2030. The total renewable energy capacity is expected to reach 482 GW in 2030, just shy of the 500 GW target. Some of this differential can be attributed to the slower-than-required growth of wind turbine capacities.

The NITI IESS, 2047 (Version 3.0) is a "scenario-based accounting tool […] to model supply and demand sectors for India leading up to 2047," providing "implications on water, land, cost besides emissions and energy transition." The IESS provides four predefined scenarios, defined as "levels" in the model, as well as a fifth scenario for the net zero transition. While the IESS tool simulates electricity capacity mixes (amongst other factors) from 2022 to 2047 in 5-year intervals, we only consider the model results starting from 2030. The CEA study provides a more realistic estimate of the short-term electricity mix based on various technical and cost factors, which the IESS does not capture. For electricity capacity scenarios after 2030, we incorporate three of the IESS scenarios—Level 1, Level 2, and NZE—with CEA results for 2030 to create three scenarios for this study:

1. Business as usual: Electricity capacity in 2030 as per CEA and the IESS Level 1 scenario (described in the NITI Aayog report as "least effort")
2. Determined effort: Electricity capacity in 2030 as per CEA and the IESS Level 2 scenario
3. Net zero pathway: Electricity capacity in 2030 as per CEA and the IESS NZE pathway, a combination of the four given levels in such a way that India is on the net zero transition

Table 9: CEA Likely Installed Capacity (MW) in 2029-30

Source (MW)	2023	2030	CAGR
Large Hydro	42,104	53,860	4%
Pumped Storage Power	4,746	18,986	22%
Small Hydro	4,944	5,350	1%
Coal & Lignite	2,11,855	2,51,683	2%
Gas	24,824	24,824	0%
Nuclear	6,780	15,480	13%
Solar	66,780	2,92,566	23%
Wind	42,633	99,895	13%
Biomass	10,802	14,500	4%
Battery Energy	20	41,650	198%
Battery Energy (MWh)	100	2,08,248	198%

Source: Central Electricity Authority (2023b).

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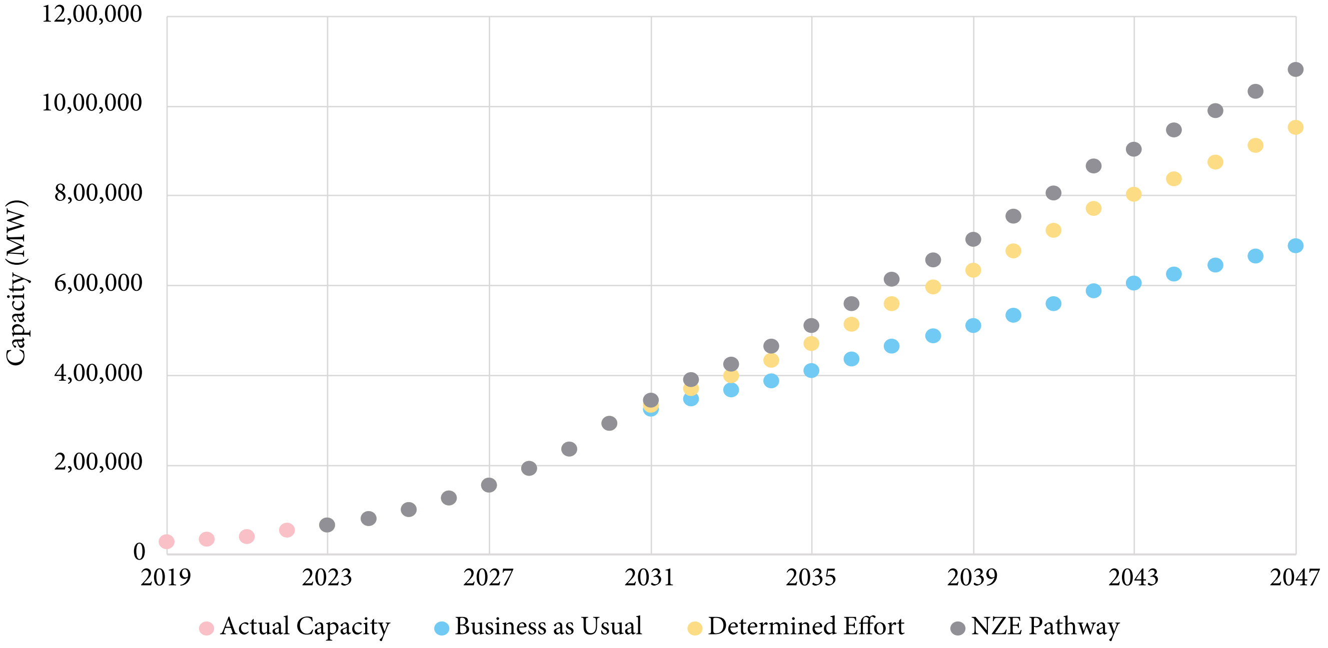
[4] 2030 refers to the financial year 2029-30, which starts in April 2029 and ends in March 2030.

Mineral projections using only the three stated NITI Aayog IESS information have also been computed (i.e., without incorporating CEA projections until 2030). These results are provided in Appendix A.

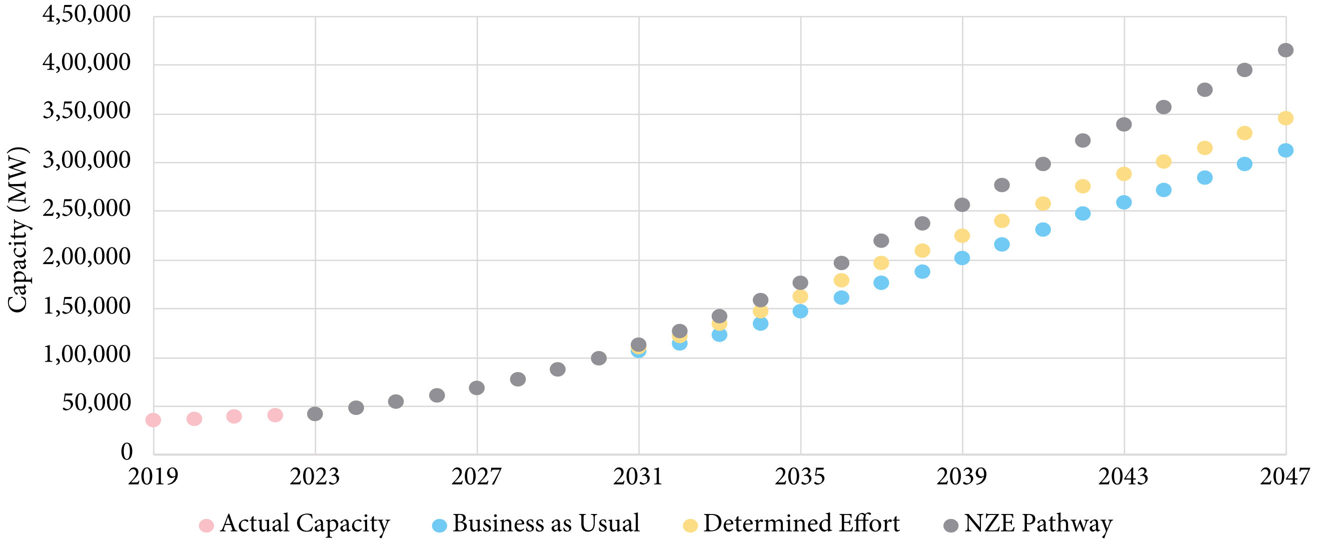
Figures 11, 12, and 13 show the capacity scenarios for solar PVs, wind turbines, and BESS, respectively. While the figures show the combined capacities of onshore and offshore, these are considered separately in the analysis due to the differing technology requirements. For the case of BESS, the second and third scenarios were both taken from IESS Level 2 to achieve a smoother transition from the CEA 2030 estimates. From each of these scenarios, we have computed the annual capacity additions required for each technology. It should be noted that while this data accounts for the domestic requirements, India may also export some of the devices. This methodology does not account for the mineral requirements for the export sector but rather only for meeting domestic clean energy targets.

Figure 11: Solar PV Capacity Scenarios (MW)



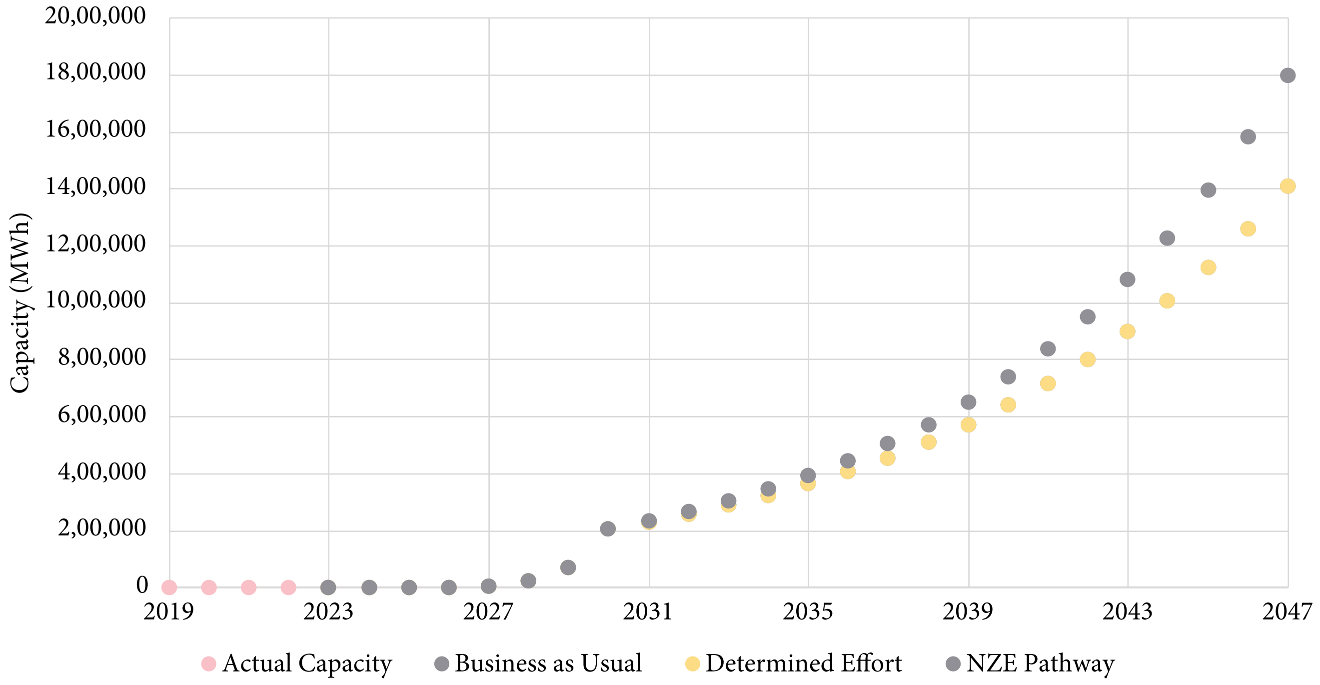
Source: CEA (2023b), NITI Aayog (2023), Authors' elaboration.

Figure 12: Wind Capacity Scenarios (MW)



Source: CEA (2023b), NITI Aayog (2023), Authors' elaboration.

Figure 13: BESS Capacity Scenarios (MWh)



Source: CEA (2023b), NITI Aayog (2023), Authors' elaboration.

Note: The Business as Usual and Determined Effort cases have the same BESS installed capacity projections.

5.3 Decommissioning Rates

Aside from building the requisite capacity annually, India would also need to consider decommissioning older renewable energy plants. The typical lifespan of wind turbines and solar panels is 20-25 years each, after which the device would degrade and operate at lower efficiencies. In many cases, if the site has good wind resources, the wind farm is repowered by replacing older turbines with modern and more efficient technologies (NEER, 2020). The same may not necessarily hold for solar farms. However, unlike wind turbines, solar panel efficiencies have not experienced similar efficiency gains to incentivise replacing modules (Penrod, 2023). Batteries have a lower lifespan than wind and solar, typically lasting only eight years (and in some cases can be extended to 10 years) (Choi, Jo, & Han, 2019).

In either case—repowering or decommissioning—older and less efficient capacity would need to be replaced with newer devices, resulting in a greater mineral demand. In our study, we consider two decommissioning scenarios for these technologies:

1. Base case: The lifespans of solar panels and wind turbines are considered to be 20 years, while BESS last for 8 years.
2. Increased life: Due to improvements in technologies and maintenance, the lifespans of solar panels and wind turbines increase to 25 years and BESS to 10 years.

While wind and solar farms have been in India since the 20th century, there is limited data on exact annual capacities. Data from CEA first reports wind power generation in 2007 and solar power generation in 2010. These installed capacities would need to be repowered or decommissioned by 2030. In the increased life scenario, demand for minerals gets pushed back a few years, relieving any supply chain pressures in the short term and allowing manufacturers more time to determine their mineral sourcing. It also gives more time for newer and more efficient technology to be developed and utilised.

5.4 Recycling Input Rates (RIRs)

The RIR refers to the share of materials consumed that come from recycled sources. It differs from *recycling rates,* which measure what share of material gets recycled but does not reveal to what extent recycled materials are being consumed in manufacturing supply chains. For minerals with higher RIRs, there would be a lower requirement for newly mined ores. Due to a lack of data on Indian RIRs for most critical minerals, data were taken from the EU. The data are likely to overstate the use of recycled materials in India. However, these data may be considered an upper bound (and an international good practice) of how much new mining can be avoided. Other limitations of using the RIRs data include: (a) supply chains of the considered technologies may not be suited to consume recycled materials, and (b) India may still need to import scrap; although this reduces global mining activities, India would rely on imports to meet its recycled material needs. Three scenarios were considered to determine the potential new mining savings through the use of recycled materials:

1. No recycled inputs: All the requisite minerals have to be mined.
2. Constant rates: The current RIRs will remain uniform until 2047.
3. Long-term improvements: Over time, the RIR increases for each mineral; we have chosen an increase in the RIR of 0.4 percentage points annually.

5.5 Solar PV Technologies

Section 4.1 provides an overview of the various solar PV technologies currently manufactured, as well as some of the emerging trends in new technologies. In this study, we consider two scenarios for the change in solar PV technologies with respect to the share of c-Si and thin-film (CdTe, CIGS, and a-Si) panels (Carrara, Alves Dias, Plazzotta, & Pavel, 2020):

1. Base case: The installed capacity share of c-Si and thin-film panels remain constant at 95%:5% as it is today.
2. Increased thin film: The share of thin film panels in installed capacity will increase gradually to 10% in 2047, while the share of c-Si will drop to 90%.

5.6 Wind Turbine Technologies

An overview of the available wind turbine technologies has been provided in Section 4.2. To compute the mineral requirements for manufacturing wind turbines, we consider onshore and offshore variants separately, for which the IESS 2047 provides the disaggregation. We consider two scenarios for wind turbine technologies (Carrara, Alves Dias, Plazzotta, & Pavel, 2020), treating onshore and offshore turbines differently and highlighting the increasing use of permanent-magnet generators, which would entail a greater quantity of REEs:

1. Base case: The share of permanent magnet-based onshore wind turbines increases from 20% to 50% (direct drive from 5% to 25% and gearbox from 15% to 25%), and the share of permanent magnet-based offshore wind turbines increases from 70% to 75% (all direct drive).
2. Higher proliferation of permanent magnets: The share of permanent magnet-based turbines increases more than the base case; for onshore turbines, the share increases from 20% to 70% (direct drive from 5% to 30% and gearbox from 15% to 30%); and for offshore turbines, the share increases from 70% to 80% (all direct drive).

5.7 BESS Technologies

We examine two scenarios for changes in battery chemistry, highlighting the potential for a greater proliferation of NMC and VRF batteries compared to the more commonly used LFP batteries today (Warrior, Tyagi, & Jain, 2023). Alternative battery technologies include those with higher energy densities, potentially reducing mineral requirements for the same capacity, or new battery chemistries, which have been discussed in Section 4.3. A rapid shift towards Na-ion batteries, for example, would result in a decline in the demand for critical minerals, especially lithium. However, based on the prevailing trends for battery chemistries in India, we have considered the following two scenarios:

1. Base case: The current shares of battery chemistries remain constant.
2. Disruptive case: The share of NMC (8%) and VRF (2%) batteries increased to 20% and 10%, respectively, while the share of LFP batteries declined from 81% to 67%.

5.8 Mineral Intensities

Data on mineral intensities for solar panels, wind turbines, and batteries have been sourced from literature (Carrara, Alves Dias, Plazzotta, & Pavel, 2020; Transport & Environment, 2021). These represent the minerals required to produce a unit of green technology currently. While the mineral intensities are typically provided as a range of values, we have taken the average value for our computations.

With advancements in material sciences and evolutions in the efficiency and design of the technologies, it can be expected that mineral intensities for the considered devices may reduce over time, leading to dampened requirements of critical minerals per unit of capacity. For example, wafer thickness in solar cells has been reduced as a cost-cutting measure, which leads to lower requirements of materials per cell; one study estimates a 40% reduction in silver over the next decade (VDMA, 2023), though this level of decline may not last for the subsequent decade due to intrinsic physical limits.

In this study, we consider two scenarios for changes in mineral intensities:

1. Base case: The prevailing mineral intensities remain constant throughout the period. While improvements are expected, there are limited estimates of its magnitude. Hence, this forms an upper-bound estimate for mineral requirements.
2. Long-term improvements: Literature shows varying ranges of mineral intensity changes, which depend on the device and mineral considered. For our study, we have chosen a 0.60% annual reduction in mineral intensities.

While declining mineral intensities account for improvements in material sciences and efficiencies, it does not consider the possibility of mineral substitutions. Aside from a complete change in the chemistries of the technology, it may also be possible to retain the existing chemistry while substituting one mineral with another of similar properties. For example, in certain use cases, aluminium may be a substitute for copper in wires. Though its performance may not be at the same level as copper, it benefits from being more cost-effective. Similarly, the use of dysprosium in permanent magnet generators for wind turbines can be reduced and, if required, replaced with neodymium, a less costly mineral (Pavel, et al., 2017).

6. Results

This study computes the annual mineral requirements to manufacture three technologies: solar, wind and battery storage. It does this for each scenario highlighted in Section 5.1. While data on mineral intensities is available for all minerals required to manufacture each device, the focus is on the needs of non-bulk critical minerals. India has abundant supplies of bulk minerals like iron ore, limestone (used for cement), and bauxite (used for aluminium). Therefore, the requirements for bulk materials are not discussed in these results but are available in the Excel addendum.

The study shows results for fiscal years (FY) 2025, 2026, 2027, and every five years after that until 2047 (the year up to which IESS projects electricity capacities). Results for 2030 are also provided, as it is a milestone year for India's climate targets and the year when the electricity capacity scenarios switch from CEA to IESS projections.

The first set of results in each subsection provides an overall base case scenario for electricity capacities, decommissioning, each technology type, and mineral intensities. Subsequent results explore the impacts of changing some of these scenarios, contrasted against the base case requirements. The study also presents the impacts of recycling on reducing mining requirements.

Finally, the technology-wise mineral requirements are contextualised with the current mining status in India (Table 10), including India's self-sufficiency. Self-sufficiency is measured as the ratio of domestic mineral consumption to total consumption (domestic and imported). This information is presented alongside results from:

1. The CSEP critical minerals assessment (CMA) (Chadha, Sivamani, & Bansal, 2023a) which measures a mineral's criticality by computing its economic importance and supply risks. Minerals ranked only high in economic importance are marked with EI, only high in supply risk with SR, and high in both axes are marked as critical.
2. The Ministry of Mines (MoM) 2023 report (Ministry of Mines, 2023) which lists 30 critical minerals for India, the country's first official list of critical minerals.

Table 10: Classification of Mineral Inventory

Classification	Description
Geological Potential	There is an increased possibility of finding these minerals
Resources	An indication of mineral occurrence
Reserves	The mineralised area has been explored and identified as economically mineable
Production	Mining activities take place to extract minerals

Source: United Nations (2020).

6.1 Solar PV Mineral Requirements

Table 11 shows the annual mineral requirements for solar PVs in the base case for all parameters, along with the projected capacity addition in GW. In this base case scenario, the demand for various minerals used in solar PVs would increase by over 2.5 times over the next two decades compared to the requirements in 2025.

Due to a discontinuity in the electricity capacity projections from the CEA and the IESS study, there is an intermediate peak in mineral demand in 2030. This peak is to meet the 2030 electricity capacity targets. After 2030, the mineral requirements drop until 2032 and then increase again.

The technology base case for solar PVs assumes a constant share of c-Si panels. Compared to this base case, an increased share of thin-film solar panels (up to 10% in 2047) would result in an over 200% increase in demand for thin-film minerals by 2047. These thin-film minerals include cadmium, tellurium, indium, gallium, selenium, germanium, etc. At the same time, the demand for silicon and silver would decrease.

In absolute terms (Table 12), the annual demand for these thin-film minerals will increase by 7.7 times in 2047 compared to 2025. However, the demand for other solar PV minerals, like in the base case, will increase by around 2.5 times. Comparing these results with global projections from the IEA shows that India would demand just under half of the world's mineral requirements for solar PVs, which aligns with the country's ambitious solar capacity targets.

Table 11: Solar PV Annual Mineral Requirements (t) – Base Case

Minerals (t)	2025	2026	2027	2030	2032	2037	2042	2047
Copper	89,145	1,10,091	1,35,958	2,56,815	1,10,411	1,55,898	1,90,953	2,37,560
Silicon	73,954	91,330	1,12,789	2,13,051	91,596	1,29,331	1,58,413	1,97,077
Silver	370	457	564	1,065	458	647	792	985
Cadmium	23	29	35	67	29	41	50	62
Tellurium	24	30	37	70	30	42	52	64
Indium	6	7	8	16	7	10	12	15
Gallium	1	2	2	4	2	3	3	4
Selenium	13	16	20	37	16	23	28	34
Germanium	3	3	4	8	3	5	6	7
GW Addition	19	24	30	56	24	34	42	52

Source: Authors' computations.

Table 12: Solar PV Annual Mineral Requirements (t) – Thin-Film Case

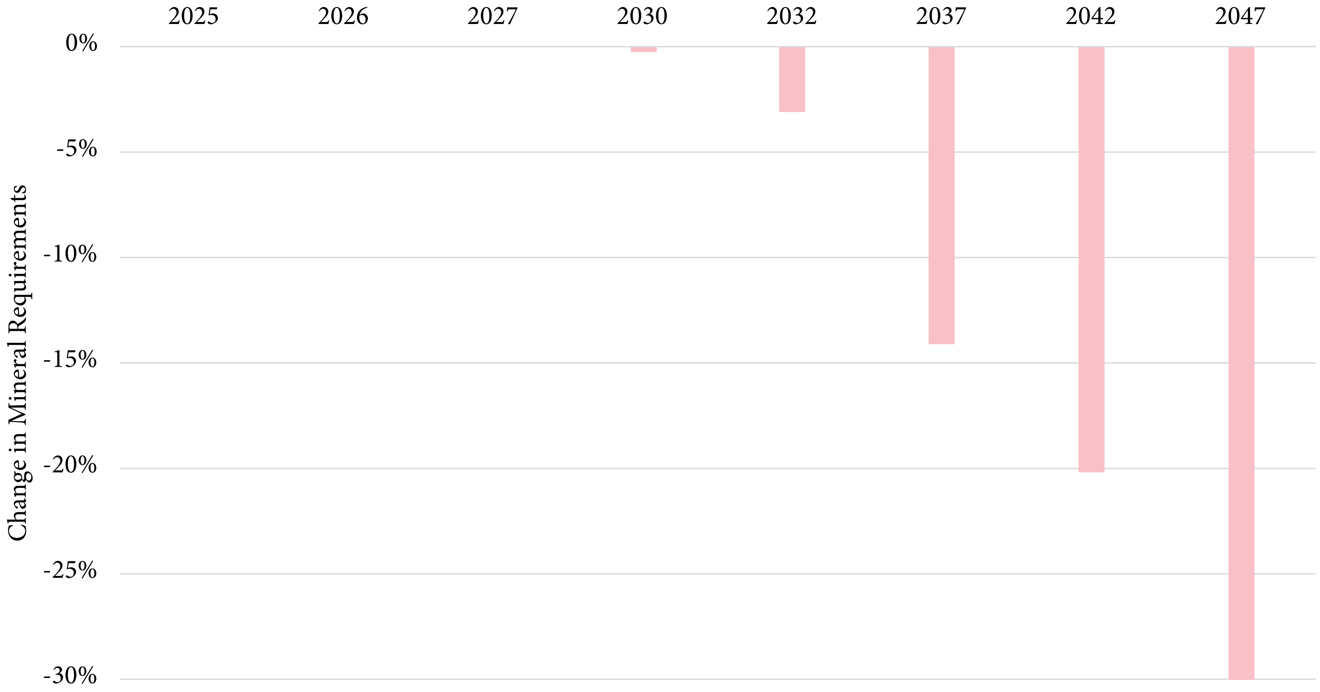
Minerals (t)	2025	2026	2027	2030	2032	2037	2042	2047
Copper	89,148	1,10,094	1,35,963	2,56,828	1,10,421	1,55,915	1,90,979	2,37,621
Silicon	72,804	89,717	1,10,558	2,07,498	87,029	1,21,732	1,47,322	1,70,373
Silver	364	449	553	1,037	435	608	736	851
Cadmium	31	39	50	103	59	90	122	237
Tellurium	32	41	52	107	61	94	127	246
Indium	7	9	12	25	14	21	29	56
Gallium	2	2	3	7	4	6	8	15
Selenium	17	22	28	57	33	50	68	131
Germanium	4	5	6	12	7	11	15	28

Source: Authors' computations.

If the lifespan of solar projects is extended from 20 to 25 years, the demand for minerals used in solar panels will begin to decrease in 2030, which is around the time when some of India's early solar capacity in India would need to be decommissioned or replaced. By 2047, there could be up to a 30% reduction in mineral demand compared to the base case scenario.

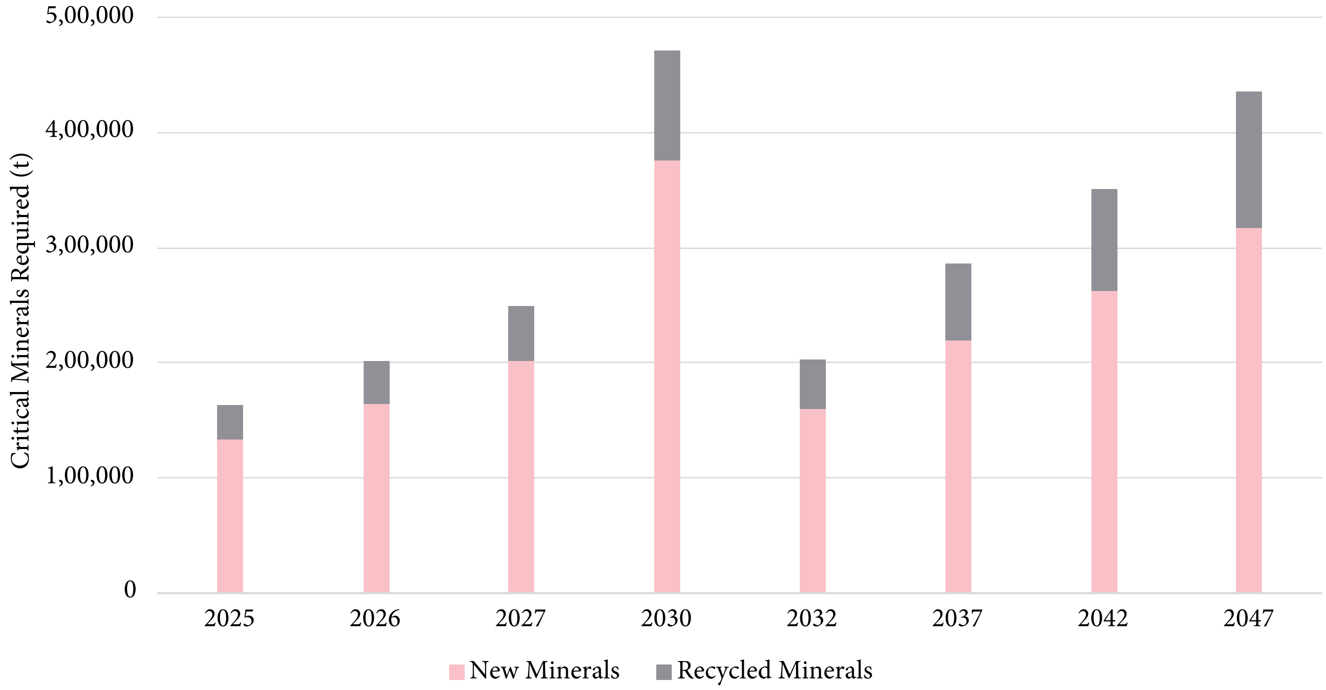
Solar panels contain various minerals that can be recycled and reused to manufacture new panels. While structural materials like glass, aluminium, and steel are recyclable, so are the critical minerals, including silver, copper, and (crystalline) silicon (Hurdle, 2023). Based on the existing RIRs, around 17.5% of the total mineral requirements can be met through recycled inputs (Figure 15). With long-term improvements in the collection and use of recycled materials, this could reach 27.1% by 2047. This increased recycling could save a cumulative 1500 kt of these critical metals over the next two decades.

Figure 14: Solar PV Annual Change in Mineral Requirements (t) – Increased Life Case



Source: Authors' computations.

Figure 15: Solar PV Annual Mineral Requirements (t) – Increasing Recycling Case



Source: Authors' computations.

Table 13: Solar PV Mineral Requirements Summary

Mineral	Ratio of Requirements to 2025 Base		Status in India	Self-Sufficiency (%)	CSEP	MoM
	2047 Base Case	2047 Net Zero				
Copper	3.3	4.9	Production	43	EI	✓
Silicon			Production	90	EI	✓
Silver			Production	7	EI	–
Cadmium			–	0	N/A	✓
Tellurium			–	0	N/A	✓
Indium			–	0	SR	✓
Gallium			–	0	Critical	✓
Selenium			–	0	EI	✓
Germanium			–	0	SR	✓

Source: Authors' computations, Chadha, Sivamani, & Bansal (2023a),[5] *Ministry of Mines (2023).*

In the base case for electricity generation (and all other parameters), the demand for minerals used in solar PV panels increases by 3.3 times between 2024 and 2047 (Table 13). When following the net zero pathway, the demand for these solar PV minerals increases by 4.9 times.

India produces copper, silicon, and silver but has low self-sufficiency for copper and silver. There are currently no known resources for the other critical minerals needed for solar PV manufacturing. Considering India's ambitions for domestic solar manufacturing, companies need to find foreign sources for these minerals, of which indium, gallium,

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[5] N/A indicates that the mineral was not assessed in the study

and germanium have high supply risks due to their concentrated extraction and processing in China.

6.2 Wind Turbine Mineral Requirements

The annual mineral requirements for wind turbines are shown in Table 14, along with the projected capacity addition in GW. There would be an initial peak in mineral demand around 2027 as older wind farms require decommissioning or repowering. Similar to the requirements for solar PVs, there is also an intermediate peak in mineral demand just before 2030 to meet the pledged climate targets. The demand for minerals is projected to continue rising gradually from 2033 onwards.

In the base case, the demand for boron, praseodymium, and terbium will increase by between 14 and 15 times in 2047 compared to 2025 requirements. Neodymium, a key permanent magnet material, sees a demand increase of 9.9 times during the same period. All minerals experience a substantial rise in demand compared to the requirements in 2025.

When considering the case of a higher share of permanent magnet wind turbines, the increase in mineral demand becomes starker (Table 15). The mineral demand is higher for all minerals, barring nickel and zinc than in the base case (Figure 16). The demand for boron, praseodymium, and terbium will increase by over 15 times in 2047 compared to 2025 and by 11.2 times for neodymium. Comparing these results to the IEA projections for 2030 (under their base case scenario) shows that India would require approximately 15% of the global mineral demand for wind turbines.

Table 14: Wind Turbines Annual Mineral Requirements (t) – Base Case

Mineral	2025	2026	2027	2030	2032	2037	2042	2047
Boron	5	6	22	21	23	38	44	67
Chromium	3,096	3,502	7,877	6,826	4,980	10,626	9,261	11,549
Copper	9,115	10,355	26,146	22,688	18,639	36,067	33,565	44,804
Dysprosium	26	31	90	82	80	144	153	220
Manganese	4,888	5,522	12,401	10,673	7,690	16,429	14,096	17,434
Molybdenum	647	732	1,646	1,425	1,038	2,215	1,926	2,399
Neodymium	223	261	830	766	788	1,368	1,503	2,201
Nickel	2,577	2,902	6,202	5,294	3,535	7,961	6,473	7,604
Praseodymium	26	31	123	115	133	214	250	381
Terbium	5	6	25	24	27	44	51	77
Zinc	34,253	38,684	86,863	74,692	53,725	1,14,797	98,288	1,21,433
GW Addition	6	7	16	14	10	21	18	22

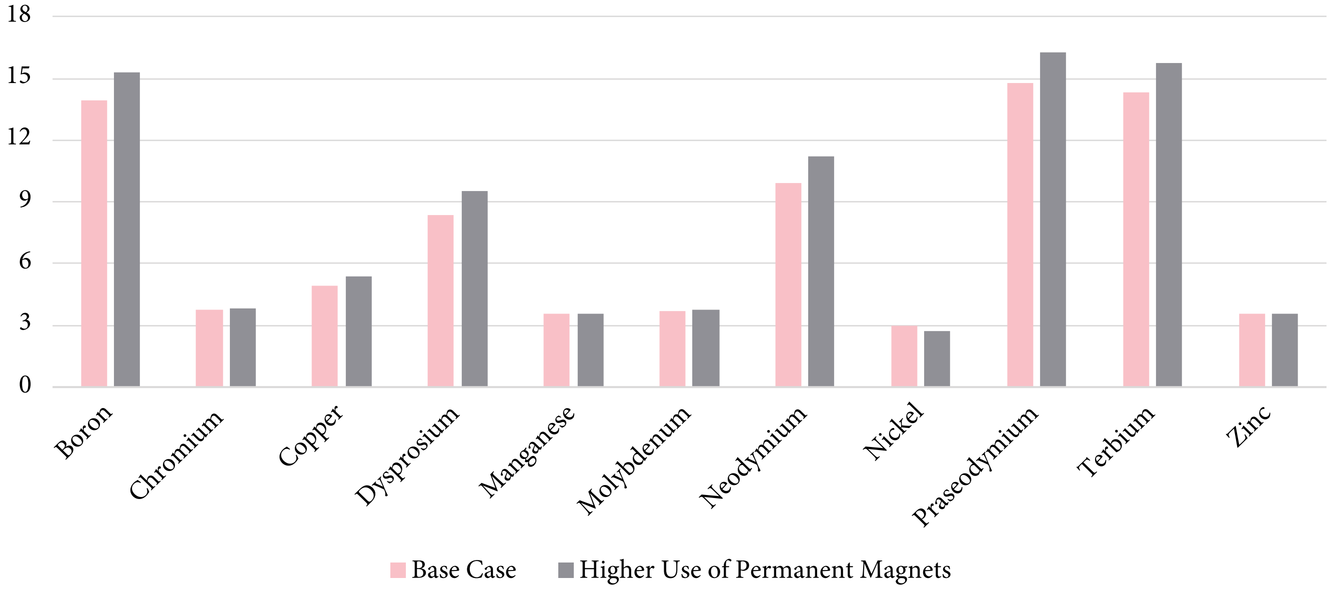
Source: Authors' computations.

Table 15: Wind Turbines Annual Mineral Requirements (t) – Higher Permanent Magnet Use

Mineral	2025	2026	2027	2030	2032	2037	2042	2047
Boron	6	7	24	25	28	50	61	89
Chromium	3,136	3,554	7,960	6,952	5,107	10,946	9,626	11,964
Copper	9,174	10,447	26,349	23,118	19,237	37,875	36,536	49,318
Dysprosium	29	35	97	94	93	178	198	279
Manganese	4,896	5,531	12,416	10,696	7,713	16,487	14,162	17,510
Molybdenum	655	741	1,661	1,448	1,061	2,273	1,992	2,474
Neodymium	255	304	904	889	925	1,736	1,995	2,854
Nickel	2,557	2,874	6,152	5,204	3,427	7,657	6,029	6,978
Praseodymium	31	38	136	137	158	282	344	508
Terbium	7	8	28	28	32	58	70	103
Zinc	34,253	38,684	86,863	74,692	53,725	1,14,797	98,288	1,21,433

Source: Authors' computations.

Figure 16: Ratio of Mineral Demand in 2025 vs 2047 – Base Case and Permanent Magnet Case



Source: Authors' computations.

Unlike solar PVs, increasing the lifespan of wind turbines does not seem to have as much of an effect on mineral demand in the short term since wind turbines have been in operation in India for a longer time (according to CEA data). The demand for minerals will be lower in most years, leading up to 2047 in the increased-life scenario. In this scenario, there would be cumulative savings in critical minerals demand between 2025 and 2047 of around 261 kt, or 9%, compared to the base case.

The requirements for all minerals increase in the net zero pathway scenario for electricity capacities (Table 16). India is endowed with all of these minerals but only produces chromium, copper, manganese, and zinc. There is some production of REEs (indicated with a* in the table) in India. However, this primarily consists of lanthanum and cerium, with some quantities of neodymium and praseodymium (Indian Bureau of Mines, 2022a). While India does have boron resources (which are needed for the fibreglass blades of wind turbines), no extraction takes place currently. However, domestic processing capacity already exists, which relies on imports of crude borates (Indian Bureau of Mines, 2022b).

Table 16: Wind Turbines Mineral Requirements Summary

Mineral	Ratio of Requirements to 2025 Base		Status in India	Self-Sufficiency (%)	CSEP	MoM
	2047 Base Case	2047 Net Zero				
Boron	14.0	18.7	Resources	0	Critical	–
Chromium	3.7	4.8	Production	100	Critical	–
Copper	4.9	6.4	Production	43	EI	✓
Dysprosium	8.4	11.0	*	*	SR	✓
Manganese	3.6	4.6	Production	42	Critical	–
Molybdenum	3.7	4.7	Resources	0	EI	✓
Neodymium	9.9	13.1	*	*	SR	✓
Nickel	3.0	3.7	Resources	0	Critical	✓
Praseodymium	14.8	19.8	*	*	SR	✓
Terbium	14.3	19.2	*	*	SR	✓
Zinc	3.5	4.5	Production	93	EI	–

Source: Authors' computations, Chadha, Sivamani, & Bansal (2023a), Ministry of Mines (2023).

6.3 BESS Mineral Requirements

The annual requirements for manufacturing BESS for India's grid under the base case scenarios are provided in Table 17, along with the projected capacity addition in GWh. The demand for battery minerals for India's battery storage is expected to rise significantly in both the base and disruptive cases, reflecting the short-term requirements for energy storage in the grid. As with solar and wind, there would need to be a sharp increase in mineral demand around 2030 to meet intermediate climate targets. In the disruptive case (Table 18), the demand for vanadium increases much more than that for the other battery minerals, as VRF batteries are expected to rise in popularity in this scenario.

Table 17: BESS Annual Mineral Requirements (t) – Base Case

Mineral	2025	2026	2027	2030	2032	2037	2042	2047
Lithium	58	174	517	13,671	2,771	9,401	11,878	20,845
Cobalt	17	49	147	3,878	786	2,667	3,370	5,914
Nickel	52	155	461	12,198	2,473	8,388	10,598	18,599
Manganese	20	61	181	4,797	972	3,298	4,167	7,314
Graphite	609	1,814	5,405	1,42,892	28,966	98,259	1,24,153	2,17,884
Copper	240	714	2,128	95,588	11,404	38,684	48,878	85,779
Vanadium	43	129	384	56,255	2,060	6,988	8,830	15,496
GWh Addition	1	2	5	138	28	95	120	211

Source: Authors' computations.

Table 18: BESS Annual Mineral Requirements (t) – Disruptive Case

Mineral	2025	2026	2027	2030	2032	2037	2042	2047
Lithium	58	172	510	13,344	2,608	8,751	10,579	17,730
Cobalt	16	47	137	3,528	661	2,285	2,888	5,173
Nickel	52	155	462	12,393	2,692	9,524	13,451	26,129
Manganese	19	56	165	4,159	732	2,527	3,079	5,396
Graphite	605	1,799	5,345	1,40,143	27,481	92,064	1,11,103	1,85,596
Copper	405	1,205	3,584	94,107	18,568	62,341	75,878	1,27,968
Vanadium	239	709	2,109	55,358	10,908	36,591	44,406	74,609

Source: Authors' computations.

Long-term improvements in mineral intensities would help reduce mineral demand. For example, in the long-term improvements scenario for mineral intensities, the cumulative demand for lithium would be 19 kt less than the base case, representing a saving of almost 10% between 2025 and 2047. Similarly, recycling can play a role in reducing the fresh demand from mines. For example, the cumulative nickel requirement can be reduced by 16% over the projection period through the use of recycled inputs for wind turbine manufacturing.

Compared to the 358-times increase in mineral demand in 2047 vis-à-vis 2025 in the base case, the demand is estimated to rise 495 times in the net zero pathway case (Table 19). These requirements can be reduced through improvements in technologies, reducing mineral intensities, and increased rates of recycled material inputs. Many battery minerals are geologically present in India. However, some of these are still at the resources stage, requiring further exploration before they can be mined. While lithium resources were discovered in the country in 2023, it is expected to take some more years for mining activities to begin (Chadha & Sivamani, 2023a). Processing facilities would also need to be established; otherwise, many of these minerals would have to be sent to other countries for value addition.

7. Strategies to Secure Supply Chains

Policymakers can use the results of the projections exercise (Table 20) to devise strategies for securing supply chains of the minerals required for the clean technology transition. These strategies may be developed by considering the current status of mineral development in the country and the projected growth in their demand. For cases where India produces the mineral, strategies should focus on bolstering the domestic mining and processing regimes. India may also wish to share its expertise and invest in countries seeking to expand their domestic capabilities. In cases

Table 19: BESS Mineral Requirements Summary

Mineral	Ratio of Requirements to 2025 Base		Status in India	Self-Sufficiency (%)	CSEP	MoM
	2047 Base Case	2047 Net Zero				
Lithium	358	495	Resources	0	Critical	✓
Cobalt			Resources	0	Critical	✓
Nickel			Resources	0	Critical	✓
Manganese			Production	42	Critical	–
Graphite			Production	72	Critical	✓
Copper			Production	43	EI	✓
Vanadium			Resources	0	SR	✓

Source: Authors' computations, Chadha, Sivamani, & Bansal (2023a), Ministry of Mines (2023).

Table 20: Total Annual Mineral Requirements for Solar PVs, Wind Turbines, and BESS (t) – Base Case

Mineral	2025	2026	2027	2030	2032	2037	2042	2047
Boron	5	6	22	21	23	38	44	67
Cadmium	23	29	35	67	29	41	50	62
Chromium	3,096	3,502	7,877	6,826	4,980	10,626	9,261	11,549
Cobalt	17	49	147	3,878	786	2,667	3,370	5,914
Copper	98,500	1,21,160	1,64,232	3,75,091	1,40,454	2,30,649	2,73,396	3,68,143
Dysprosium	26	31	90	82	80	144	153	220
Gallium	1	2	2	4	2	3	3	4
Germanium	3	3	4	8	3	5	6	7
Graphite	609	1,814	5,405	1,42,892	28,966	98,259	1,24,153	2,17,884
Indium	6	7	8	16	7	10	12	15
Lithium	58	174	517	13,671	2,771	9,401	11,878	20,845
Manganese	4,908	5,583	12,582	15,470	8,662	19,727	18,263	24,748
Molybdenum	647	732	1,646	1,425	1,038	2,215	1,926	2,399
Neodymium	223	261	830	766	788	1,368	1,503	2,201
Nickel	2,629	3,057	6,663	17,492	6,008	16,349	17,071	26,203
Praseodymium	26	31	123	115	133	214	250	381
Selenium	13	16	20	37	16	23	28	34
Silicon	73,954	91,330	1,12,789	2,13,051	91,596	1,29,331	1,58,413	1,97,077
Silver	370	457	564	1,065	458	647	792	985
Tellurium	24	30	37	70	30	42	52	64
Terbium	5	6	25	24	27	44	51	77
Vanadium	43	129	384	56,255	2,060	6,988	8,830	15,496
Zinc	34,253	38,684	86,863	74,692	53,725	1,14,797	98,288	1,21,433

Source: Authors' computations.

where India has reserves of a mineral, but a relatively high share of demand is being met through imports (i.e., low self-sufficiency), efforts may be made to allocate more mining blocks to boost production levels.

For minerals where there are known resources in India but no economically mineable reserves, policymakers may focus on encouraging and incentivising exploration activities, including participation from the private sector (Chadha, Sivamani, & Bansal, 2023b). The MoM announced the auctions of two tranches of critical mineral assets (with twenty blocks in the first tranche and seventeen in the second tranche) in November 2023 and February 2024. Many of these assets are still at the resource stage, requiring further exploration, which may later translate to reserves that can be mined (PIB, 2024b).

There are certain minerals for which there are no known resources in India. Policymakers need to promote reconnaissance in greenfield areas (regions where mining activities have not yet taken place) with high geological potential. Industries manufacturing green technology equipment would need to look at foreign sources to secure their mineral requirements in either ores, processed ores or embedded components. The Government of India has incorporated a joint venture company called Khanij Bidesh India Ltd. (KABIL) with the objective of acquiring critical mineral assets abroad to ensure a consistent and secure supply of minerals to the country (PIB, 2023). In January 2024, KABIL announced an investment of ₹211 crore for the exploration and development of a lithium asset in Argentina (Law, 2024). KABIL may also look to facilitate any private sector organisations in India looking to invest in foreign assets.

Policymakers must also give attention to domestic mineral processing. For cases in which India starts mining new minerals (such as lithium), the extracted ore would have to be sent abroad for processing and value addition before the domestic manufacturing sector can use it. Alternatively, the minerals can be sent to foreign facilities owned by Indian companies. Policymakers should focus on developing both mines for new minerals and their processing operations simultaneously. Aside from developments in mineral extraction and processing, research and development investments into technology efficiency improvements can help reduce the quantities of minerals required. Additionally, the promotion of recycling and the use of recycled materials for manufacturing inputs would reduce the requirements from mines while also having sustainability benefits.

India may also look towards multilateral cooperation to build resilient critical mineral supply chains. India joined the US-led Minerals Security Partnership (MSP) in 2023, which consists of a group of countries seeking to develop diverse critical energy minerals supply chains (Chadha & Sivamani, 2023b). Other avenues of international cooperation include friend-shoring (which refers to shifting supply chains to friendly nations) and technology and knowledge sharing, which may be pursued with other multilateral fora such as the G20 (Narula, et al., 2023), the Quad (Chadha & Sivamani, 2024), or with other allied countries (Chadha & Bansal, 2024).

Various strategies to create more resilient critical mineral supply chains are summarised in Table 21, differentiated based on the status of domestic production, geological potential, and self-sufficiency.

Table 21: Strategies to Create Resilient Critical Mineral Supply Chains

	High Self-Sufficiency	**Low Self-Sufficiency**
Domestic Production & Resources Available	Technology and expertise sharing with partner countries; investing abroad; expanding domestic value chains to export value-added components and technologies. Minerals: chromium, zinc, graphite	Allocating new mineral assets and expanding existing capacities. Minerals: copper, manganese, silver, REEs
No Domestic Production & Resources Available	N/A	Incentivising exploration of resources to convert them to economically mineable reserves. Minerals: lithium, cobalt, vanadium
No Domestic Production & No Resources Available	N/A	Reconnaissance of areas with geological potential; acquisition of foreign mineral assets for extraction and processing; global critical minerals collaboration. Minerals: gallium, germanium

Source: Authors' elaboration.

8. Concluding Remarks and Policy Recommendations

The demand for critical minerals in the clean energy transition will rise manifold over the coming decades. To achieve the various targets, India will have to install large quantities of solar panels, wind turbines, and batteries for energy storage, which in turn require substantial quantities of critical minerals. For this, India would have to procure either the minerals required to manufacture these technologies or components that are embedded with these minerals. With the introduction of PLI schemes, there will be a push towards indigenising these supply chains, including upstream mining and mineral processing activities.

This study quantifies the magnitude of the challenge ahead, which can help policymakers focus their attention on key minerals that will be in high demand and may have supply bottlenecks in the future. Many of the minerals required to manufacture clean energy technologies have been identified as critical by the CSEP and MoM reports. For these requisite minerals, especially for those with no known domestic resources, mineral-wise strategies are required to ensure robust access for India's manufacturing needs and climate change mitigation ambitions.

India is a mineral-rich country and produces some of the minerals required for the clean energy transition. However, even for some of these minerals, such as copper and manganese, India remains relatively import-reliant despite having large resources and reserves. India also has large resources of various critical minerals like cobalt, lithium, and REEs, which are mostly untapped. Only a small percentage of these resources have been converted to mineable reserves. Many critical minerals are deep-seated, thus requiring high-risk investments in exploration and mining. A key policy focus must be incentivising private-sector investment in domestic mineral exploration.

Critical mineral processing is still at a nascent stage in India, with domestic processing capacity available for only a few minerals, including copper, zinc and graphite. It is important to create strategies for processing critical minerals that are domestically mined, providing incentives to mineral processing companies. There are various critical minerals for which India has no known resources or geological potential. For these, India must consider acquiring extraction and processing facilities abroad. KABIL has been tasked with these responsibilities. KABIL may also facilitate the private sector to invest in foreign assets to meet their domestic material requirements.

The MSP can help with global technology cooperation in exploration, mining, processing and recycling. Cooperation and information sharing can also help reduce the negative externalities across critical mineral value chains in India by imbibing international good practices and standards. India's government and private sector need to increase their investment in technology development to boost their domestic mineral capacity. The study also shows that promoting recycling and the use of recycled materials in supply chains can help mitigate additional requirements for mines, as would improvements in mineral intensities and technology efficiencies.

While this study projects the critical mineral requirements of clean energy technologies, other green technologies key to the net zero transition also need attention. A subsequent study must consider various scenarios on the rise in demand for EVs, amongst other green technologies, and the technology options available to compute the critical mineral needs to manufacture EVs. These projection studies should also be updated regularly to account for both changes in available technologies (including both reducing mineral intensities and technological disruptions) and any new policies which redirect efforts towards different green devices.

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Appendix A: Results of Mineral Demand Projections Using Only NITI Aayog IESS 2047 Scenarios

Table A1: Solar PV Annual Mineral Requirements (t) – Base Case (NITI Aayog IESS 2047 Level 1 Pathway)

Minerals (t)	2025	2026	2027	2030	2032	2037	2042	2047
Copper	44,671	50,871	57,932	83,729	1,10,411	1,55,898	1,90,953	1,59,535
Silicon	37,059	42,202	48,060	69,461	91,596	1,29,331	1,58,413	1,32,348
Silver	185	211	240	347	458	647	792	662
Cadmium	12	13	15	22	29	41	50	42
Tellurium	12	14	16	23	30	42	52	43
Indium	3	3	4	5	7	10	12	10
Gallium	1	1	1	1	2	3	3	3
Selenium	6	7	8	12	16	23	28	23
Germanium	1	2	2	3	3	5	6	5
GW Addition	10	11	13	18	24	34	42	35

Source: Author's computations.

Table A2: Solar PV Annual Mineral Requirements (t) – Base Case (NITI Aayog IESS 2047 Level 2 Pathway)

Minerals (t)	2025	2026	2027	2030	2032	2037	2042	2047
Copper	58,744	68,863	80,725	1,28,491	1,78,270	2,41,496	2,89,020	2,63,663
Silicon	48,734	57,128	66,968	1,06,594	1,47,891	2,00,342	2,39,767	2,18,732
Silver	244	286	335	533	739	1,002	1,199	1,094
Cadmium	15	18	21	34	47	63	75	69
Tellurium	16	19	22	35	48	66	78	72
Indium	4	4	5	8	11	15	18	16
Gallium	1	1	1	2	3	4	5	4
Selenium	8	10	12	19	26	35	42	38
Germanium	2	2	3	4	6	8	9	8
GW Addition	13	15	18	28	39	52	63	57

Source: Author's computations.

Table A3: Solar PV Annual Mineral Requirements (t) – Base Case (NITI Aayog IESS 2047 NZE Pathway)

Minerals (t)	2025	2026	2027	2030	2032	2037	2042	2047
Copper	81,211	99,068	1,20,853	1,50,752	2,06,982	2,80,384	3,31,210	3,38,540
Silicon	67,371	82,186	1,00,258	1,25,062	1,71,710	2,32,603	2,74,768	2,80,849
Silver	337	411	501	625	858	1,163	1,374	1,404
Cadmium	21	26	32	39	54	73	86	88
Tellurium	22	27	33	41	56	76	90	92
Indium	5	6	7	9	13	17	21	21
Gallium	1	2	2	2	3	5	5	6

Minerals (t)	2025	2026	2027	2030	2032	2037	2042	2047
Selenium	12	14	17	22	30	41	48	49
Germanium	3	3	4	5	6	9	10	11
GW Addition	18	22	26	33	45	61	72	74

Source: Author's computations.

Table A4: Wind Turbines Annual Mineral Requirements (t) – Base Case (NITI Aayog IESS 2047 Level 1 Pathway)

Mineral	2025	2026	2027	2030	2032	2037	2042	2047
Boron	3	3	17	14	20	37	43	55
Chromium	1,444	1,538	5,544	4,204	4,950	10,602	9,237	9,121
Copper	4,314	4,623	18,749	14,176	17,812	35,741	33,179	35,909
Dysprosium	14	15	67	53	73	140	149	180
Manganese	2,256	2,398	8,712	6,558	7,685	16,424	14,091	13,728
Molybdenum	301	321	1,158	877	1,032	2,210	1,921	1,894
Neodymium	124	137	622	498	701	1,325	1,454	1,806
Nickel	1,170	1,238	4,311	3,222	3,634	8,004	6,522	5,905
Praseodymium	16	18	95	76	114	205	240	315
Terbium	3	4	19	16	23	42	49	64
Zinc	15,784	16,777	61,008	45,880	53,725	1,14,797	98,288	95,579
GW Addition	3	3	11	8	10	21	18	17

Source: Authors' computations.

Table A5: Wind Turbines Annual Mineral Requirements (t) – Base Case (NITI Aayog IESS 2047 Level 2 Pathway)

Mineral	2025	2026	2027	2030	2032	2037	2042	2047
Boron	4	5	23	22	37	49	53	74
Chromium	2,762	3,075	7,346	5,994	7,337	11,853	9,933	11,571
Copper	8,150	9,114	25,151	21,102	28,596	42,396	37,757	47,058
Dysprosium	24	27	91	82	124	176	176	236
Manganese	4,354	4,839	11,544	9,345	11,368	18,319	15,125	17,468
Molybdenum	577	642	1,535	1,251	1,530	2,470	2,066	2,403
Neodymium	205	236	850	786	1,231	1,706	1,751	2,381
Nickel	2,290	2,536	5,680	4,493	5,128	8,642	6,761	7,387
Praseodymium	24	28	131	126	212	278	299	420
Terbium	5	6	27	26	43	57	61	85
Zinc	30,501	33,895	80,841	65,368	79,457	1,28,002	1,05,470	1,21,670
GW Addition	6	6	15	12	14	23	19	22

Source: Authors' computations.

Table A6: Wind Turbines Annual Mineral Requirements (t) – Base Case (NITI Aayog IESS 2047 NZE Pathway)

Mineral	2025	2026	2027	2030	2032	2037	2042	2047
Boron	5	6	24	24	39	55	64	91
Chromium	3,339	3,781	8,205	6,868	8,529	14,309	12,959	15,073
Copper	9,832	11,178	27,639	23,695	32,161	49,982	47,925	59,877
Dysprosium	28	33	97	90	136	203	219	296
Manganese	5,274	5,962	12,906	10,719	13,235	22,132	19,755	22,764
Molybdenum	698	790	1,714	1,433	1,779	2,983	2,695	3,131
Neodymium	240	281	905	854	1,330	1,953	2,161	2,981
Nickel	2,781	3,134	6,405	5,212	6,099	10,578	8,988	9,784
Praseodymium	28	33	137	134	224	313	363	521
Terbium	6	7	28	27	45	64	74	106
Zinc	36,954	41,769	90,387	74,994	92,527	1,54,655	1,37,778	1,58,564
GW Addition	7	8	16	14	17	28	25	29

Source: Authors' computations.

Table A7: BESS Annual Mineral Requirements (t) – Base Case (NITI Aayog IESS 2047 Level 1 Pathway)

Mineral	2025	2026	2027	2030	2032	2037	2042	2047
Lithium	0	0	0	0	0	0	11,596	569
Cobalt	0	0	0	0	0	0	3,290	161
Nickel	0	0	0	0	0	0	10,347	508
Manganese	0	0	0	0	0	0	4,069	200
Graphite	0	0	0	0	0	0	1,21,209	5,949
Copper	0	0	0	0	0	0	47,719	2,342
Vanadium	0	0	0	0	0	0	8,620	423
GWh Addition	0	0	0	0	0	0	117	6

Source: Authors' computations.

Table A8: BESS Annual Mineral Requirements (t) – Base Case (NITI Aayog IESS 2047 Level 2 Pathway)

Mineral	2025	2026	2027	2030	2032	2037	2042	2047
Lithium	0	0	0	0	4,889	17,085	17,643	18,148
Cobalt	0	0	0	0	1,387	4,847	5,005	5,149
Nickel	0	0	0	0	4,362	15,244	15,742	16,192
Manganese	0	0	0	0	1,715	5,994	6,190	6,367
Graphite	0	0	0	0	51,101	1,78,576	1,84,413	1,89,687
Copper	0	0	0	0	20,118	70,303	72,601	74,678
Vanadium	0	0	0	0	3,634	12,700	13,115	13,490
GWh Addition	0	0	0	0	49	173	179	184

Source: Authors' computations.

Table A9: BESS Annual Mineral Requirements (t) – Base Case (NITI Aayog IESS 2047 NZE Pathway)

Mineral	2025	2026	2027	2030	2032	2037	2042	2047
Lithium	0	0	0	0	14,438	16,633	22,537	22,422
Cobalt	0	0	0	0	4,096	4,719	6,394	6,361
Nickel	0	0	0	0	12,882	14,841	20,109	20,006
Manganese	0	0	0	0	5,066	5,836	7,907	7,867
Graphite	0	0	0	0	1,50,914	1,73,855	2,35,566	2,34,360
Copper	0	0	0	0	59,413	68,445	92,740	92,265
Vanadium	0	0	0	0	10,733	12,364	16,753	16,667
GWh Addition	0	0	0	0	146	168	228	227

Source: Authors' computations.

Table A10: Total Annual Mineral Requirements for Solar PVs, Wind Turbines, and BESS (t) – Base Case (NITI Aayog IESS 2047 Level 1 Pathway)

Mineral	2025	2026	2027	2030	2032	2037	2042	2047
Boron	3	3	17	14	20	37	43	55
Cadmium	12	13	15	22	29	41	50	42
Chromium	1,444	1,538	5,544	4,204	4,950	10,602	9,237	9,121
Cobalt	0	0	0	0	0	0	3,290	161
Copper	48,985	55,494	76,681	97,905	1,28,223	1,91,638	2,71,851	1,97,785
Dysprosium	14	15	67	53	73	140	149	180
Gallium	1	1	1	1	2	3	3	3
Germanium	1	2	2	3	3	5	6	5
Graphite	0	0	0	0	0	0	1,21,209	5,949
Indium	3	3	4	5	7	10	12	10
Lithium	0	0	0	0	0	0	11,596	569
Manganese	2,256	2,398	8,712	6,558	7,685	16,424	18,160	13,928
Molybdenum	301	321	1,158	877	1,032	2,210	1,921	1,894
Neodymium	124	137	622	498	701	1,325	1,454	1,806
Nickel	1,170	1,238	4,311	3,222	3,634	8,004	16,869	6,413
Praseodymium	16	18	95	76	114	205	240	315
Selenium	6	7	8	12	16	23	28	23
Silicon	37,059	42,202	48,060	69,461	91,596	1,29,331	1,58,413	1,32,348
Silver	185	211	240	347	458	647	792	662
Tellurium	12	14	16	23	30	42	52	43
Terbium	3	4	19	16	23	42	49	64
Vanadium	0	0	0	0	0	0	8,620	423
Zinc	15,784	16,777	61,008	45,880	53,725	1,14,797	98,288	95,579

Source: Authors' computations.

Table A11: Total Annual Mineral Requirements for Solar PVs, Wind Turbines, and BESS (t) – Base Case (NITI Aayog IESS 2047 Level 2 Pathway)

Mineral	2025	2026	2027	2030	2032	2037	2042	2047
Boron	4	5	23	22	37	49	53	74
Cadmium	15	18	21	34	47	63	75	69
Chromium	2,762	3,075	7,346	5,994	7,337	11,853	9,933	11,571
Cobalt	0	0	0	0	1,387	4,847	5,005	5,149
Copper	66,895	77,977	1,05,876	1,49,592	2,26,984	3,54,196	3,99,378	3,85,400
Dysprosium	24	27	91	82	124	176	176	236
Gallium	1	1	1	2	3	4	5	4
Germanium	2	2	3	4	6	8	9	8
Graphite	0	0	0	0	51,101	1,78,576	1,84,413	1,89,687
Indium	4	4	5	8	11	15	18	16
Lithium	0	0	0	0	4,889	17,085	17,643	18,148
Manganese	4,354	4,839	11,544	9,345	13,083	24,314	21,315	23,836
Molybdenum	577	642	1,535	1,251	1,530	2,470	2,066	2,403
Neodymium	205	236	850	786	1,231	1,706	1,751	2,381
Nickel	2,290	2,536	5,680	4,493	9,490	23,886	22,503	23,579
Praseodymium	24	28	131	126	212	278	299	420
Selenium	8	10	12	19	26	35	42	38
Silicon	48,734	57,128	66,968	1,06,594	1,47,891	2,00,342	2,39,767	2,18,732
Silver	244	286	335	533	739	1,002	1,199	1,094
Tellurium	16	19	22	35	48	66	78	72
Terbium	5	6	27	26	43	57	61	85
Vanadium	0	0	0	0	3,634	12,700	13,115	13,490
Zinc	30,501	33,895	80,841	65,368	79,457	1,28,002	1,05,470	1,21,670

Source: Authors' computations.

Table A12: Total Annual Mineral Requirements for Solar PVs, Wind Turbines, and BESS (t) – Base Case (NITI Aayog IESS 2047 NZE Pathway)

Mineral	2025	2026	2027	2030	2032	2037	2042	2047
Boron	5	6	24	24	39	55	64	91
Cadmium	21	26	32	39	54	73	86	88
Chromium	3,339	3,781	8,205	6,868	8,529	14,309	12,959	15,073
Cobalt	0	0	0	0	4,096	4,719	6,394	6,361
Copper	91,042	1,10,247	1,48,492	1,74,447	2,98,557	3,98,811	4,71,875	4,90,683
Dysprosium	28	33	97	90	136	203	219	296
Gallium	1	2	2	2	3	5	5	6
Germanium	3	3	4	5	6	9	10	11
Graphite	0	0	0	0	1,50,914	1,73,855	2,35,566	2,34,360
Indium	5	6	7	9	13	17	21	21
Lithium	0	0	0	0	14,438	16,633	22,537	22,422
Manganese	5,274	5,962	12,906	10,719	18,301	27,967	27,662	30,631

Molybdenum	698	790	1,714	1,433	1,779	2,983	2,695	3,131
Neodymium	240	281	905	854	1,330	1,953	2,161	2,981
Nickel	2,781	3,134	6,405	5,212	18,981	25,419	29,097	29,790
Praseodymium	28	33	137	134	224	313	363	521
Selenium	12	14	17	22	30	41	48	49
Silicon	67,371	82,186	1,00,258	1,25,062	1,71,710	2,32,603	2,74,768	2,80,849
Silver	337	411	501	625	858	1,163	1,374	1,404
Tellurium	22	27	33	41	56	76	90	92
Terbium	6	7	28	27	45	64	74	106
Vanadium	0	0	0	0	10,733	12,364	16,753	16,667
Zinc	36,954	41,769	90,387	74,994	92,527	1,54,655	1,37,778	1,58,564

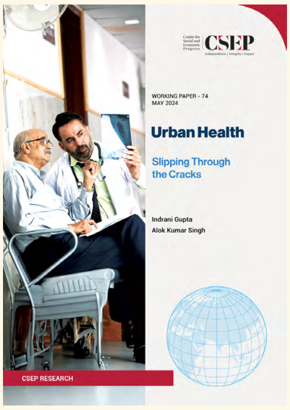
Source: Authors' computations.

About the authors

Rajesh Chadha is a Senior Fellow at CSEP. He was formerly a Professor and Research Director at the National Council of Applied Economic Research (NCAER) and, before that, an Associate Professor of Economics at Hindu College, University of Delhi. Rajesh has worked extensively on the issues of international trade, FDI and non-fuel minerals & mining in India. He has been a Visiting Scholar at the Universities of Michigan, Melbourne, and Monash and a Visiting Faculty at many prestigious academic and research institutes in India. Rajesh was nominated as GTAP Research Fellow (2004-2007) by the Global Trade Analysis Project, Purdue University. He received his PhD in Economics from the Indian Institute of Technology, New Delhi.

Ganesh Sivamani is an Associate Fellow on the Non-Fuel Minerals and Mining research project. He has worked on various issues pertaining to this sector including, the auctions process, securing India's critical minerals needs, international good practices, and economic linkages of the mining sector through the construction of Input-Output Transactions Tables and a Social Accounting Matrix. His other research interests include the impacts of climate change and its mitigation measures, with a focus on India's clean energy transition. Ganesh holds a Master of Engineering degree from the University of Cambridge, with a specialisation in Energy, Sustainability, and the Environment.

Other publications



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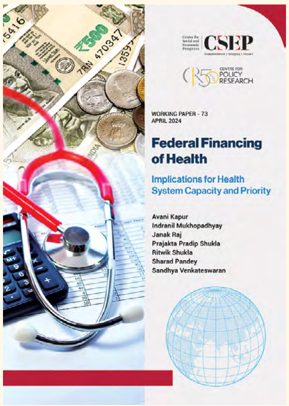

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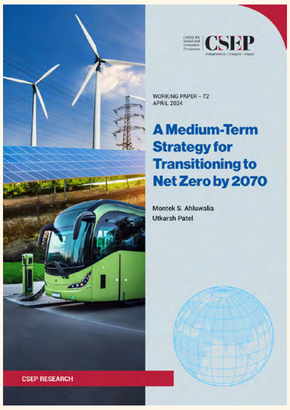

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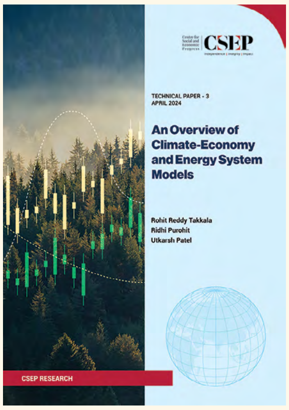

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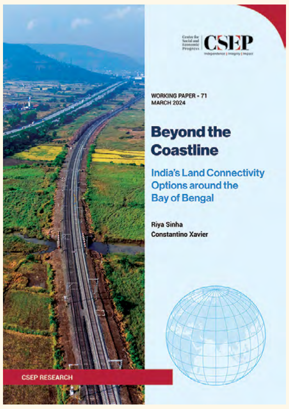

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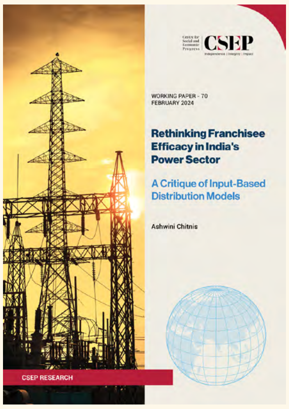

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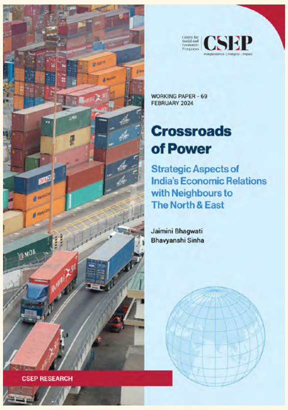

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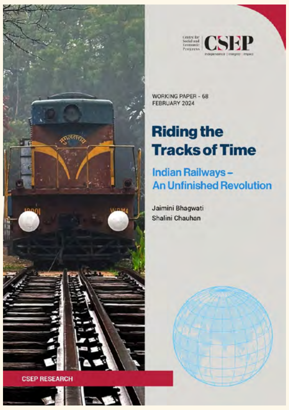

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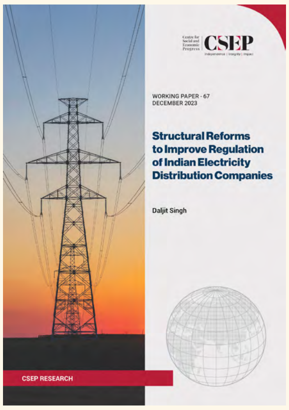

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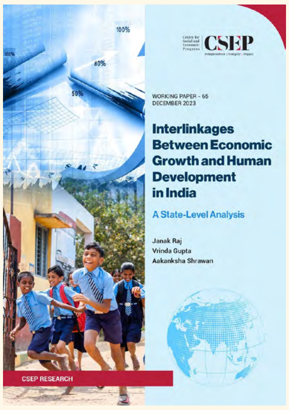

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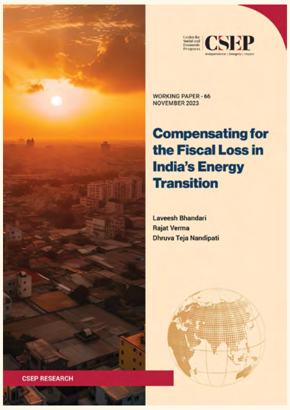

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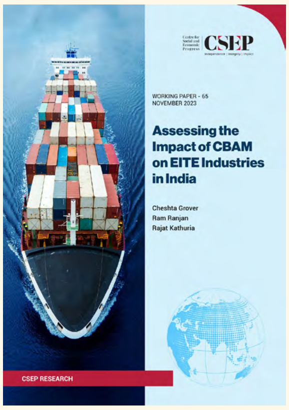

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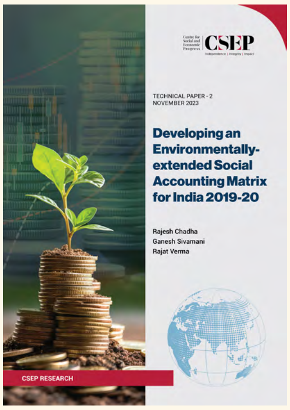

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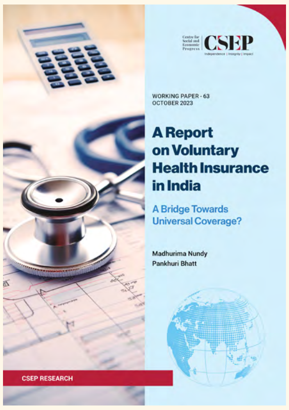

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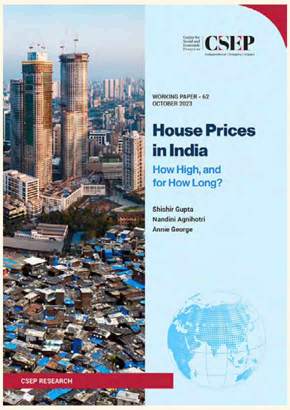

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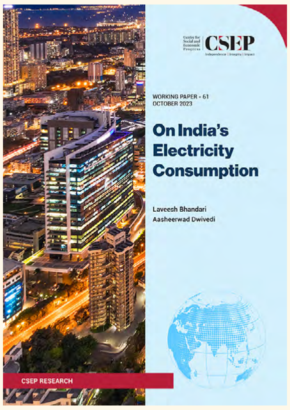

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