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NITI Aayog

SCENARIOS TOWARDS VIKSIT BHARAT AND NET ZERO

CRITICAL MINERAL ASSESSMENT: DEMAND AND SUPPLY

(VOL. 10)

NITI Aayog
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CRITICAL MINERAL ASSESSMENT: DEMAND AND SUPPLY

(VOL. 10)

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MESSAGE

India stands at a defining moment in its development journey. As we pursue the twin national goals of becoming a developed, high-income economy by 2047 under *Viksit Bharat @2047* and achieving Net Zero emissions by 2070, the foundations of our growth model must evolve in fundamental ways. Clean energy, electric mobility, and green hydrogen will be central to this transformation, but their success will depend on something more elemental: secure, affordable, and responsible access to critical energy-transition minerals.

Critical minerals are the building blocks of the energy transition. From solar panels, wind turbines, batteries, electric vehicles, to electrolysers, these technologies are inherently mineral-intensive. As India scales them to meet its developmental and climate goals simultaneously, demand for such minerals will rise sharply. This raises a fundamental question: will the energy transition simply replace today's fossil-fuel dependencies with a new set of mineral dependencies?

Without strategic intervention, the answer could be yes. Global supply chains for many critical minerals are highly concentrated, geographically and politically. Over-reliance on a narrow set of external suppliers could expose India to price volatility, supply disruptions, and strategic vulnerabilities, undermining both economic resilience and energy security. In this context, the energy transition is not only a technological or environmental challenge, but also a geopolitical and industrial one. If addressed proactively, the rising demand for critical minerals can become an opportunity rather than a constraint, supporting domestic manufacturing, generating skilled employment, and enhancing India's strategic autonomy.

स्वच्छ भारत
एक कदम स्वच्छता की ओर

The choices made today will determine whether critical minerals emerge as a bottleneck to India's green transition or as a cornerstone of a secure, sustainable, and self-reliant development pathway.

This report provides a comprehensive and timely vision for strengthening India's critical minerals ecosystem in this evolving context. It clearly lays out strategic priorities across the entire value chain, from accelerating domestic exploration and processing, to building robust recycling and circular-economy systems, advancing research and development, and deepening international partnerships to diversify and secure supply. Importantly, it offers clarity on risks, trade-offs, sequencing, and timing, recognising that when demand materialises is as important as how large it becomes. Such clarity is essential for informed policymaking and long-term investment decisions.

I would like to commend and thank the authors for their rigorous analysis and thoughtful articulation of these challenges and opportunities. This work speaks directly to our broader national purpose: enabling a transition that is ambitious yet realistic, resilient yet responsible, and firmly aligned with India's developmental and strategic aspirations.

Saraswat

(Dr. V. K. Saraswat)

New Delhi
02.02.2026

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FOREWORD

The energy sector lies at the core of India's net-zero transition. Clean energy technologies will have to be deployed on a very large scale to meet our future energy needs. This includes solar and wind power, battery energy storage, electric mobility, and green hydrogen. These technologies are significantly mineral intensive and require an uninterrupted supply of critical minerals. India's clean energy ambitions are therefore intrinsically linked to the availability, affordability, and sustainability of critical mineral supply chains.

However, global supply chains for many of these minerals are concentrated, exposed to geopolitical risks, and prone to price volatility. Exposure to unmanaged mineral dependencies could emerge as a new strategic vulnerability. The government has already initiated important steps to strengthen domestic capabilities across the critical minerals value chain. Recent policy measures include the announcement of dedicated rare-earth mineral corridors across key coastal states and basic customs duty exemptions on capital goods for critical mineral processing.

Recognizing this emerging dimension of energy security, NITI Aayog has undertaken a comprehensive assessment of India's critical mineral demand and supply outlook. The report estimates the cumulative mineral requirements arising from India's deployment of clean technologies across key segments: Solar PV, Wind, Battery Energy Storage Systems, Electric Vehicles (batteries and motors), and Electrolysers. It identifies areas of strategic exposure as well as potential competitive advantage in the evolving global minerals landscape.

The report details specific policy recommendations anchored in five strategic pillars: strengthening domestic exploration and mining; building domestic innovation and technological capabilities for critical raw materials; diversifying international supply sources and reducing import risks; scaling circularity and refining capacities; and enabling an institutional architecture for national critical raw materials governance.

I thank Dr. V. K. Saraswat, Member, NITI Aayog, for chairing this working group. I also thank all the working group members for their keen interest and engagement. I congratulate the NITI Aayog team led by Dr. Anshu Bharadwaj, Shri Rajnath Ram, Shri Venugopal Mothkoor, Shri Manoj Upadhyay, Dr. Anjali Jain and Shri Nitin Bajpai for their work on this report. I also acknowledge and thank Shri Vivek Chandran for his valuable independent contribution. I am confident that this report will go a long way in securing our supply of critical minerals for the future.

5/2

Dated: 5th February, 2026

[B.V.R. Subrahmanyam]

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List of Abbreviations

AEL	Alkaline Electrolysers
ARCI	International Advanced Research Centre for Powder Metallurgy and New Materials
ASEAN	Association of Southeast Asian Nations
ASSB	All Solid-State Batteries
BESS	Battery Energy Storage System
BWMR	Battery Waste Management Rules
CAM	Cathode Active Material
CEEW	Consumer Electrical and Electronics Waste
CET	Clean Energy Technology
CETM	Critical Energy Transition Minerals
CPS	Current Policy Scenario
CSP	Concentrated Solar Power
CTO	Consent to Operate
DMF	District Mineral Foundation
EC	Environmental Clearance
EL	Exploration Licence
EOL	End-of-Life
EPR	Extended Producer Responsibility
EVs	Electric Vehicles
FC	Forest Clearance
FCFS	First Come First Serve
FPIC	Free, Prior and Informed Consent
HCL	Hindustan Copper Limited
HS	Harmonised System
ICMM	International Council on Mining and Metals
IESS	India Energy Security Scenarios
IREL	Indian Rare Earths Limited
IRMA	Initiative for Responsible Mining Assurance
ITEW	Information Technology and Telecommunication Equipment Waste
JV	Joint Venture
KMML	Kerala Minerals and Metals Limited

LCA	Life-Cycle Assessment
LCT	Low-Carbon Technology
LFP	Lithium Iron Phosphate
LTO	Lithium Titanate Oxide
MMDR	Mines and Minerals (Development and Regulation) Act
MRV	Monitoring, Reporting, Verification
MSP	Mineral Security Partnership
Mt	Million Tonnes
NASICON	Sodium Superionic Conductor
NMC	Nickel Manganese Cobalt
NMET	National Mineral Exploration Trust
NPE	National Policy on Electronics
NZS	Net Zero Scenario
OEM	Original Equipment Manufacturer
PEMEL	Proton Exchange Membrane Electrolysers
PLI	Production Linked Incentive
PMSM	Permanent Magnet Synchronous Motors
PV	Photovoltaic
QCI-NABET	Quality Council of India – National Accreditation Board for Education and Training
QUAD	Quadrilateral Security Dialogue
REE	Rare Earth Elements
RPO	Renewable Purchase Obligations
S&T PRISM	The Science and Technology Promotion of Research and Innovation in Startups and MSMEs
SOEL	Solid Oxide Electrolysers
SRM	Switched Reluctance Motors
TAF	Technology Assessment Framework
TEE	Technical, economic and environmental
TIMES	The Integrated MARKAL-EFOM System
TOPSIS	Technique for Order Preference by Similarity to Ideal Situation
TQB	Technically Qualified Bidders
TRL	Technology Readiness Level
WLC	Wildlife Clearance
ZEV	Zero-Emission Vehicle

Executive Summary

India's pathway to Net Zero by 2070 will be materially shaped by secure, affordable and responsible access to Critical Energy Transition Minerals (CETMs). This report estimates cumulative mineral needs arising from India's deployment of clean technologies across selected key segments: Solar PV, Wind, Battery Energy Storage Systems, EVs (Batteries and Motors), and electrolysers, and benchmarks them against global demand to assess strategic exposure and leverage. In 2050, India's demand under a Net Zero Scenario (NZS) averages about 9% of global demand across shared CETMs. This is sizable in absolute terms but insufficient for price-setting power, highlighting the need for a deliberate supply-chain strategy. Beyond scale, timing matters: over two-thirds of cumulative demand arrives after mid-century, creating both urgency to de-risk supply now and opportunity to localise value chains and recycling as volumes mature. Illustratively, by 2050, copper requirements exceed 20 million tonnes (Mt), and graphite alone surpasses 14 Mt, justifying robust planning for domestic mining, processing, and recycling.

The Modelling Exercise and Scenarios

This study links technology deployment pathways to embedded mineral demand through 2070 under two scenarios: Current Policy Scenario (CPS) and Net Zero Scenario (NZS). This report leverages inputs from other working groups, namely power and transport, to estimate the critical mineral requirements.

Inputs such as technology-specific deployment trajectories (solar, wind, battery storage, electrolysers) and derived Electric Vehicle (EV) sales from the other working groups are used to assess mineral requirements. The analysis further examines how this demand can be met through domestic resources and reserves, while accounting for import exposure, geopolitical risk, and policy instruments, including the National Critical Minerals Mission (NCMM). It considers circularity potential and Research and Development (R&D) readiness in processing/recycling.

Due to certain limitations in this study (e.g., static material intensities; partial sectoral coverage), the results are intended as a directional decision aid that will need to be refined as technologies and markets evolve.

Key Demand Modelling Insights

1. **Scale and timing:** Over 66% of cumulative Critical Energy Transition Minerals (CETMs) demand materialises after 2050. Therefore, planning must front-load exploration, processing, circularity, and strategic sourcing.
2. **Absolute needs:** Cumulative Critical Energy Transition Minerals (CETMs) needs projected under Net Zero Scenario (~169 Mt) are 51% more than CPS (~112 Mt), with

the rise concentrated in battery-linked minerals. By 2050, copper demand is estimated to exceed 20 Mt, and that of graphite to surpass 14 Mt, signalling the magnitude of midstream/refining and recycling systems India must build even if its global market share remains modest.

3. **Drivers by technology**

   i. **Batteries (EVs, battery storage):** EVs and Battery Energy Storage Systems (BESS) together dominate future Critical Energy Transition Minerals' demand, accounting for approximately 55% and 5%, respectively, with concentrated mineral requirements for graphite, lithium, nickel, phosphorous, cobalt and vanadium, making storage security pivotal.

   ii. **EV Motors & Wind:** These hinge on rare earths (Neodymium, Praseodymium, Dysprosium, Terbium) for permanent magnets, critical to domestic manufacturing ambitions.

   iii. **Solar Photovoltaic (PV):** Second-highest total demand with a share of about 31%, driven by large volumes of silicon and copper, with additional strategic exposure to gallium, germanium, and tellurium in advanced PV variants.

   iv. **Electrolysers:** Smaller volumes overall but there is reliance on scarce, high-cost catalysts such as Platinum and Iridium.

Priority Challenges

1. **High import exposure and concentration risk:** For several priority minerals such as graphite, India is highly import-dependent with exposure to geopolitically sensitive or single-supplier sources.
2. **Domestic capacity gaps:** Even where domestic resources exist (e.g., copper/graphite), bottlenecks in exploration, mine operationalisation, refining and recycling slow value-chain development. Private participation too remains constrained by commercial risk and permitting frictions.
3. **Vulnerabilities in global mineral supply chains:** Export restrictions, foreign control of upstream assets, long-term offtake lock-ups and price volatility limit late-entrant access. In areas of narrow dependence, disruption risks persist even with friendly suppliers.
4. **Circularity at insufficient scale (near-term):** While recycling can materially help for battery minerals, it cannot be a viable substitute for primary supply due to outpaced demand in early years. Further, collection efficiency, technology maturity, and feedstock access limit attainable shares before 2050.
5. **R&D limitations:** India has mature capabilities in select minerals and streams, but overall readiness is uneven across 18 mapped Critical Energy Transition Minerals (CETMs). Sustained, mission-oriented R&D is required in processing and recycling to onshore value addtion.

Policy Suggestions

India's critical minerals challenge is defined by a combination of rapidly rising demand, high import dependence, concentrated global supply chains, long development timelines and increasing expectations around environmental and social performance. While multiple initiatives address parts of this challenge, supply security will ultimately depend on how well demand growth, domestic capacity creation, international engagement, innovation and governance are aligned over time.

The Suggestions are primarily aimed toward de-risking Critical Energy Transition Mineral supply chains, to be guided by six principles and operationalised through interlinked pillars spanning domestic exploration and innovation, international sourcing, midstream capacity & circularity, and supported by cross-cutting institutional reforms. Together, these Suggestions attempt to provide a coherent framework for action while remaining adaptable to uncertainty and evolving market conditions.

Six Guiding Principles

1. **Empower private sector leadership across the value chain**: Enable private investment and operational leadership by aligning regulatory, fiscal and compliance frameworks with the risk and timelines of Critical Energy Transition Mineral activities.
2. **Recognise differentiated timelines across supply sources**: Sequence interventions across recycling, refining, overseas sourcing and mining based on realistic development horizons.
3. **Build diversified and mutually beneficial international partnerships**: Reduce concentration risk through strategic, value-chain–based cooperation with trusted partners.
4. **Embed environmental and social safeguards as supply-security enablers**: Treat environmental standards, social licence and transparency as core to long-term project viability and market access.
5. **Drive mission-oriented innovation and R&D**: Focus public R&D on deployment-ready and next-generation technologies that reduce dependence and improve competitiveness.
6. **Strengthen institutional capacity, data systems and coordination**: Anchor decision-making in robust data, modelling and centre–state coordination mechanisms.

Pillars of Policy Action

Pillar-1: Strengthen Domestic Exploration and Mining

a. **Rebalance exploration and licensing regimes**: Introduce conditional First Come, First Served (FCFS) access for early-stage exploration of priority Critical Energy Transition Minerals with milestones, data disclosure and rights-based progression.
b. **Make private participation the default in early-stage exploration**: Prioritise private explorers for exploration licences using conditional First Come, First Served (FCFS) mechanisms suited to geological uncertainty.
c. **Improve geological knowledge and data credibility**: Mandate Committee for Mineral Reserves International Reporting Standards (CRIRSCO) aligned reporting and strengthen pre-competitive geological intelligence for regulatory decision-making.

d. **Align public-sector mining capabilities with Critical Energy Transition Mineral priorities**: Review and realign PSU mandates, assets and investment priorities with national critical minerals objectives.

e. **Preserve environmental and social accountability**: Retain public consultation, restrict expedited approvals to compliant proponents and mandate independent audits.

f. **Improve permitting efficiency and coordination**: Establish coordinated centre–state permitting mechanisms, including Chief Secretary–led committees and digital tracking systems.

Pillar-2: Build Domestic Innovation and Technology Capability

a. **Establish a mission-oriented critical raw materials R&D framework**: Shift from fragmented projects to outcome-oriented missions aligned with national risk and deployment priorities.

b. **Create pilot-to-commercialisation pathways**: Develop shared pilot and demonstration infrastructure and deploy First-of-a-Kind (FOAK) risk-sharing instruments tied to performance benchmarks.

c. **Enable structured international technology co-development and absorption**: Pursue joint R&D and pilots while embedding domestic capability-building and localisation requirements.

Pillar-3: Diversify International Supply Sources and Reduce Import Risk

a. **Adopt risk-differentiated international engagement strategies**: Classify minerals by concentration and geopolitical exposure and tailor overseas engagement accordingly.

b. **Embed India in resilient global value-chain arrangements**: Identify minerals suitable for shared processing and refining hubs through bilateral and plurilateral frameworks.

c. **De-risk overseas access through aggregation and facilitation**: Provide project-preparation support, aggregate demand for equity and offtake, and coordinate overseas engagement through a single-window platform.

d. **Strengthen KABIL for overseas Critical Energy Transition Mineral execution**: Enhance capitalisation, specialist capabilities and execution partnerships with experienced overseas-facing PSUs and financial institutions.

e. **Improve price discovery and market risk management**: Facilitate access to global exchanges and hedging instruments and integrate market signals into sourcing and stockpiling decisions.

Pillar-4: Scale Circularity and Refining

a. **Unlock reliable secondary feedstock for Critical Energy Transition Minerals:** Permit controlled imports of high-value scrap, enable authorised access to mine tailings and legacy waste, and undertake a national assessment of tailings potential.

b. **Make refining and advanced recycling economically viable**: Deploy a targeted package of capital support, output-linked incentives and tax rationalisation for refining and advanced recycling facilities.

c. **Enable clustered refining and recycling capacity**: Extend National Critical Mineral Mission (NCMM)-linked processing cluster support to advanced recycling hubs, including common infrastructure and anchor-firm-led models.

d. **Secure access to critical refining and recycling technologies**: Facilitate bilateral and plurilateral technology access arrangements with embedded domestic capability-building requirements.

e. **Strengthen environmental and compliance safeguards**: Reinforce Extended Producer Responsibility (EPR) verification, traceability and third-party audits to ensure incentives accrue only to compliant operators.

Pillar-5: Institutional Architecture

a. **Establish a National Critical Raw Material (CRM) Analytical Strategy Unit**: Create a mandate-neutral, non-executing strategic function responsible for system-level CRM risk assessment, strategic prioritisation, and preparation of the Net Zero Technology and Materials Roadmap and National Critical Raw Materials Strategy.

b. **Institutionalise a National Critical Raw Materials Strategy and early-warning system**: Prepare strategy integrating demand signals, supply-risk assessments and strategic priorities, supported by periodic assessment of critical raw material risk and early-warning.

c. **Enable strategic project designation and coordination**: Identify a limited set of strategic critical raw material projects and apply enhanced inter-ministerial and centre–state coordination to resolve bottlenecks, without diluting statutory safeguards.

d. **Improve calibration and coordination of policy and market instruments**: Review the adequacy and sequencing of approvals, incentives, finance and market instruments to support the timely execution of priority Critical Raw Material (CRM) projects.

1

INTRODUCTION

1

Introduction

Low-Carbon Technologies (LCTs), such as solar photovoltaic panels (PV), Battery Energy Storage Systems (BESS), wind turbines, and Zero Emission Vehicles (ZEVs), will need to be deployed at a progressively larger scale to enable India's energy transition to achieve Net Zero Emissions by 2070. India has a nascent but rapidly expanding LCT manufacturing industry, which is essential to achieving its ambitious climate targets, while creating jobs and strengthening economic resilience. These technologies rely on critical minerals such as lithium, nickel, cobalt and rare-earth elements, which are currently mined and processed by a limited number of countries globally (International Energy Agency, 2024). The high reliance on imported minerals and the concentration of their global supply chain present significant risks of price volatility and supply disruptions. Some of the vulnerabilities arise from overseas geological concentration and the governance challenges in exporting countries, environmental, social and governance concerns at mining and processing sites, and systemic shocks including natural disasters and pandemics such as COVID-19.

Recognising the economic importance and supply risks associated with such minerals, Ministry of Mines released a list of 30 critical minerals in June 2023, identified from a range of industries including electronics, defence, and renewable energy (Committee on identification of Critical Minerals, 2023). This list comprises 28 distinct elements along with 17 Rare Earth Elements (REEs) Group and 6 Platinum Group Elements (PGEs), totalling 51 individual elements. 24 minerals were classified as 'Critical and Strategic Minerals' under the MMDR Act. Of these, 21 of the 28 individual elements, and the two group elements of REE and PGE were common between the two lists (See Annex A.1).

NITI Aayog launched a comprehensive initiative to develop a Net Zero aligned development roadmap for critical minerals. A set of inter-ministerial working groups was convened to assess the impact of long-term transition pathways across key domains like macroeconomic aspects of transition, sectoral transformations in transport, power, industry, buildings, and agriculture, financing for climate action, critical minerals, R&D and manufacturing, and the social implications of transition. Within this effort, the Inter-Ministerial Working Group on Critical Minerals is tasked with the following terms of reference:

i. **Demand assessment for Renewable Energy (RE):** Assess the demand for critical minerals/materials in view of increased demand for renewable energy technologies (Energy Storage, Solar, Wind, Electrolyser, Grid inverter etc) in Net Zero Scenario.

ii. **Demand assessment for transport:** Assess the demand for critical minerals/materials for the automobile sector in India (2-wheelers (2W), 3-wheelers (3W), 4 -wheelers (4W), Light Commercial Vehicle (LCV) – EVs and Hybrid)

iii. **Supply chain risks:** Assess the risks in supply chain of critical minerals/materials and suggest Suggestions for domestic exploration, enhancing domestic production and suggesting measures for external trade such as friend shoring, acquisition of assets overseas etc.

iv. **Examine the role of circular economy** in recycling and re-use of critical minerals.

v. **Examine the domestic mining policy** of basic metals from the perspective of Aatmanirbhar Bharat.

vi. **Assess the crucial and emerging clean energy technologies** relevant to India's Net Zero transition and readiness.

vii. **Suggest appropriate R&D and industrial ecosystem** for promoting indigenous processing and recycling of minerals.

1.1 SCOPE AND METHODOLOGY

To address both demand and supply-side aspects of the critical minerals required for India's clean energy transition through 2070, and to guide policy and technological interventions, this study employs the following structured approach:

As illustrated in Figure 1.1, the analysis begins with scenario-based projections of low-carbon technology deployment derived from the integrated assessment modelling undertaken by NITI Aayog to develop India's Net Zero transition pathways. Based on these projections, embedded critical mineral demand is estimated using technology-specific market share assumptions. The study then assesses supply options by mapping this demand against domestic reserve availability, circular economy potential, and imports. The detailed methodology is described below:

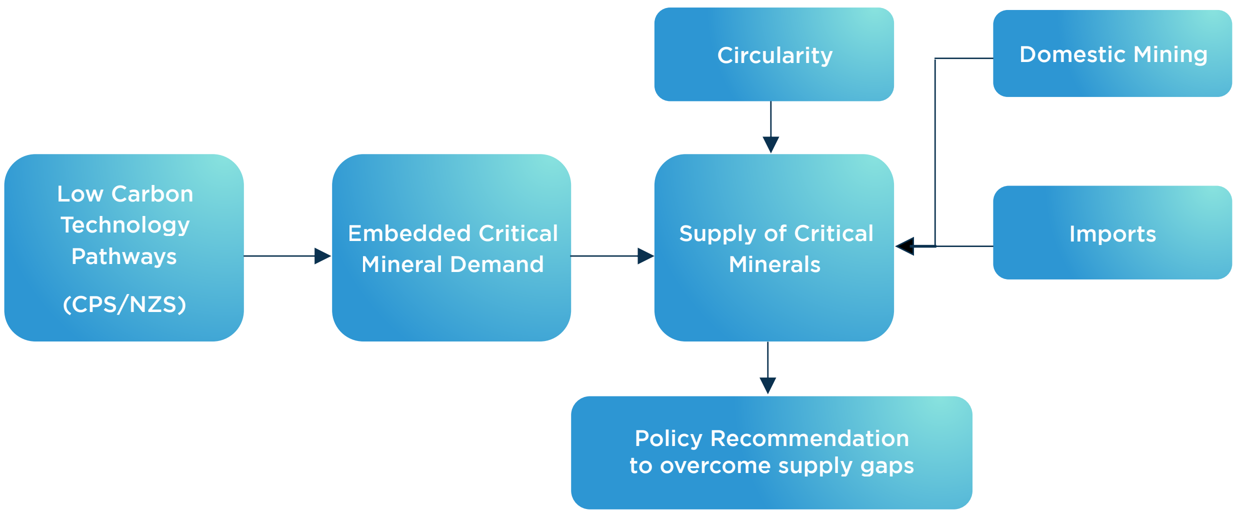


Figure 1.1: Methodology Adopted for Supply-Side Assessment

I. Low-Carbon Technology Pathways

An integrated energy sector model, developed by NITI Aayog, projects future energy demand, fuel consumption, and emissions across the entire energy system under two scenarios:

Current Policy Scenario (CPS) represents a continuation of policies implemented up to 2023, projecting current trends in technology deployment and energy use. While the scenario allows for the introduction of new low-carbon technologies, their adoption is assumed to advance gradually, accelerating only once commercial viability is achieved.

Net Zero Scenario (NZS) incorporates both existing measures and additional policy interventions required for India to achieve Net Zero GHG emissions by 2070. It assumes a proactive, sustained and large-scale deployment of low-carbon technologies, supported by enabling policies, targeted investments, and infrastructure development.

This study uses five-year projections (2025-2070) of new capacity additions for key low-carbon technologies, including solar, onshore and offshore wind, Battery Energy Storage Systems (BESS), green hydrogen electrolysers, Electric Vehicles (EVs), covering both growing demand and replacement of ageing infrastructure.

Managing Uncertainty

To account for inherent uncertainties in long-term modelling, the results from both the scenarios were interpreted with a ±10% variation margin. However, as the objective is to support forward-looking planning and preparedness under a range of possible futures, the upper bound of the projected capacity additions under both the scenarios has been used. This ensures a precautionary estimate for Critical Energy Transition Mineral (CETM) demand, to enable strategic readiness for higher levels of deployment aligned with a Net Zero pathway.

Key Trends in Current Policy Scenario (CPS) and Net Zero Scenario (NZS)

New capacity additions reveal sharply differing trajectories between CPS and NZS, with implications for the scale and timing of Critical Energy Transition Mineral (CETM) demand. The projected capacity of key technologies studied here, derived from detailed energy sector modelling by NITI Aayog, is provided in Table below:

Table 1.1: Projected Capacities of Various Technologies and EV Sales Penetration

Technology Name	Current Policy Scenario		Net Zero Scenario	
	2050	2070	2050	2070
Cumulative Capacities				
Solar (GW)	1,430-1,650	3,150-3,250	2,400-2,500	4,900-5,650
Wind (GW)	430-500	900-1,050	700-770	1,050-1,300
Grid Storage (GW)	420-520	1,300-1,400	900-1,150	2,500-3,000
Green Hydrogen (million tonnes)	8.5	24	25	50
EV Penetration in New Sales				
2W	100%	100%	100%	100%
3W	90%	90%	100%	100%
4W-Car	60%	80%	70%	85%
4W-Taxi	60%	80%	95%	95%

Bus	80%	80%	90%	90%
Vehicles payload up to 3.5 tonnes	60%	80%	90%	95%
Vehicles payload from 3.5-12 tonnes	15%	60%	50%	95%
Vehicles payload above 12 tonnes	4%	50%	25%	80%

Overall, the Net Zero pathways represent an earlier and more intense expansion of clean technologies, implying earlier and more intense mineral demand compared to CPS. This has direct implications for supply chain readiness, exploration timelines, and the need for near-term action on mineral sourcing and processing infrastructure.

II. Embedded Critical Mineral Demand Assessment

The methodology (detailed in Annex B) used to estimate demand for India's Critical Energy Transition Minerals (CETMs) through 2070 is structured into four core steps:

Step 1: Technology Deployment Scenarios

The demand assessment of Critical Energy Transition Minerals (CETMs) is based on the anticipated scale and composition of low-carbon technology deployment. It covers a defined group of technologies central to this transition, including solar PVs, concentrated solar, wind turbines, EVs, BESS, and hydrogen electrolysers. Demand is assessed at multiple milestone years through 2070, under two scenarios: Current Policy Scenario and Net Zero Scenario, allowing temporal comparison of material needs under different levels of ambition.

The analysis focuses on embedded mineral demand, which is the total mineral content required to deploy each unit of a given low-carbon technology, irrespective of where that technology is manufactured. This approach does not distinguish between domestic production and import, captures the full mineral requirement associated with India's deployment targets. This framing offers a robust proxy for understanding the scale of India's future mineral footprint, independent of future uncertainties in domestic manufacturing capacity or import dependence.

Step 2: Technology Variants and Market Share Projections

Within each technology category, specific technology variants (e.g., lithium battery chemistries such as Lithium Iron Phosphate (LFP) and Nickel Manganese Cobalt (NMC)) were identified based on Technology Readiness Level (TRL), efficiency, and End-of-Life (EOL) characteristics. Due to data limitations, a heuristic approach was used to project market shares (Annex D): the assumption is for the share of mature technologies (TRL 8–9) to decline, and of emerging ones with greater efficiencies (TRL 4–7) to grow over time as they commercialise, scale, and become cheaper.

Step 3: Estimating Mineral Intensity

Mineral intensity values (in tonnes per unit capacity) were sourced from secondary literature and applied per technology variant. These intensities are expressed in tonnes per Gigawatt (t/GW) for generation technologies and tonnes per Gigawatt hour (t/GWh) for storage systems.

Electrolyser capacities were inferred from green hydrogen production targets and efficiency assumptions (See Annex C).

Step 4: Calculating Cumulative Embedded Mineral Demand

The cumulative demand for each critical mineral was computed using annual installation projections, market share of each variant, and its mineral intensity.

Demand growth reflects both increasing clean-technology deployment and evolving variant shares, while mineral intensities remain constant. The final Critical Energy Transition Mineral (CETM) demand estimates were aggregated across all variants and technologies for 2030, 2047, and 2070, offering a long-term outlook on India's mineral needs.

III. Critical Mineral Supply Assessment

This assessment examines India's options for securing access to Critical Energy Transition Minerals (CETMs) through a combination of domestic reserves, international trade, and circular economy pathways. The study assesses vulnerabilities across key dimensions, including geopolitical vulnerabilities, market concentration, environmental and social risks in upstream supply regions, and institutional constraints. The study also identifies critical gaps in R&D for mineral processing, refining and recycling, the lack of which could constrain India's ability to onshore CETM value chains.

Finally, the study also reviews the existing policy ecosystem to determine its adequacy and highlight gaps and opportunities for strengthening institutional frameworks, innovation ecosystems, and strategic partnerships.

The Suggestions from this study focus on long-term strategic priorities for de-risking India's mineral supply chains, including innovation, circularity, international partnerships, and institutional strengthening. The aim is to provide a forward-looking policy framework rather than a detailed roadmap.

Key Limitations

The projections for Critical Energy Transition Minerals in this study should be interpreted as directional estimates rather than prescriptive forecasts due to the following limitations:

i. Some systems, such as grid infrastructure and embedded electronics, were excluded due to data and modelling limitations. As a result, the demand estimates presented here should be interpreted as conservative, representing only a subset of India's broader mineral demand landscape for a Net Zero transition

ii. Static mineral intensity assumptions, which may not reflect future technological improvements

iii. Heuristic assumptions regarding market shares of technology variants.

iv. Exclusion of several energy-sector components and cross-economy mineral uses (e.g., copper in electronics and construction), which may increase total demand.

v. Rapid evolution of clean-energy technologies, environmental and social compliance requirements and global trade and regulatory regimes, all of which may influence future mineral needs.

These uncertainties should be considered when considering the findings and suggestions of this study.

2

CRITICAL MINERALS REQUIRED FOR INDIA'S NET ZERO TRANSITION

Critical Minerals Required for India's Net Zero Transition

2

At the heart of India's Net Zero ambitions lies a fundamental question: what minerals are required to power the low-carbon technologies driving this transition, and in what quantities? This chapter addresses that question by estimating the total critical minerals required to deploy low-carbon technologies in India through 2070.

Drawing from the broader list of 30 critical minerals identified by the Ministry of Mines, this chapter identifies the Critical Energy Transition Mineral (CETM) subset most essential to the energy transition. It maps CETMs to specific technologies, outlines their functional roles, and highlights materials used across multiple systems. By calculating the long-term, cumulative requirement of each CETM under Current Policy Scenario and Net Zero Scenario, this chapter provides the foundation for supply-side actions, including risk mitigation, circularity potential, and policy priorities on critical minerals.

The chapter concludes with a comparative analysis of India's projected CETM demand against global estimates, offering insight into India's potential influence and exposure within international supply chains.

2.1 EMBEDDED MINERAL REQUIREMENTS BY TECHNOLOGY

2.1.1 Solar

Solar PV technologies are categorised into crystalline silicon (including monocrystalline, polycrystalline, and heterojunction), thin-film (such as cadmium telluride [CdTe] and copper indium gallium selenide [CIGS]), and emerging perovskite-based systems (including tandem and all-perovskite types). Concentrated Solar Power (CSP) systems include parabolic troughs and solar towers, representing linear and point-focus designs, respectively. In total, the solar analysis covers 16 critical minerals: silicon, copper, graphite, indium, gallium, tellurium, cadmium, selenium, tin, titanium, tungsten, germanium, molybdenum, nickel, vanadium and niobium, each linked to specific sub-technologies depending on its material composition and performance characteristics.

Market Shares

Market share trajectories strongly shape the mineral demand profile across Current Policy Scenario and Net Zero Scenario. Table 2.1 provides the market share of a few major technologies for solar PV and Concentrated Solar Power under both the scenarios. For detailed technological market share, refer to Annexures D.

Table 2.1: Market Share of Technologies under Solar PV and Concentrated Solar Power

Technology	Current Policy Scenario			Net Zero Scenario		
	2030	2050	2070	2030	2050	2070
Solar PV Technology						
Monocrystalline Silicon (mono-Si) PV	52%	40%	32%	50%	32%	24%
Polycrystalline Silicon (poly-Si) PV	27%	19%	17%	28%	12%	5%
Heterojunction Silicon (HJT) PV	10%	17%	19%	10%	18%	20%
Copper Indium Gallium Selenide / (CIGS) Thin-film PV	3%	7%	12%	5%	11%	16%
Perovskite-based technologies	0%	11%	13%	0%	14%	22%
Concentrated Solar Power (CSP)						
Parabolic troughs	94%	86%	80%	75%	30%	20%
Solar power towers	6%	14%	20%	25%	70%	80%

As indicated in the Table 2.1, the shifts toward low-silicon PVs and tower-based CSP carry significant implications for future mineral demand, particularly for thin-film and perovskite materials that rely on a broader set of specialty minerals.

Mineral Demand

Solar PV and Concentrated Solar Power (CSP) show distinct mineral patterns under both scenarios (see Figures 2.1 and 2.2). Copper and silicon are the most critical minerals for solar PV. Copper demand grows steadily across both scenarios because nearly all PV sub-technologies use copper extensively. Under Net Zero Scenario, copper demand sits consistently above Current Policy Scenario (10% in 2025-30, rising to ~55% in 2031-50, and ~64% in 2051-70). This is driven by higher overall PV deployment and the continued dominance of crystalline-silicon families, which have high copper intensity (~4,450-4,600 t/GW). Silicon demand, by contrast, grows more slowly than copper in both scenarios as market shares shift from mono-Si and poly-Si toward emerging low-silicon alternatives.

Thin-film and by-product metals see sharper uplifts under Net Zero Scenario, because this scenario grows CdTe and CIGS shares faster than Current Policy Scenario (e.g., by mid-century Net Zero Scenario assigns CdTe 9–13% and CIGS 7–14% vs lower shares under Current Policy Scenario). This drives up demand for materials such as tin, cadmium, molybdenum, indium, tellurium, and selenium, all of which show similar–shaped growth curves due to shared use across thin-film PV. Growth in perovskite APT technologies also increases graphite demand sharply post-2040.

Germanium demand under Net Zero Scenario (NZS) initially dips (~48%) because amorphous-Si shares decline early and faster in NZS than Current Policy Scenario. However, because NZS has a larger PV base overall due to higher demand electrification, germanium demand rises again during 2050–70 before eventually phasing out under both scenarios as amorphous-Si is fully phased out.

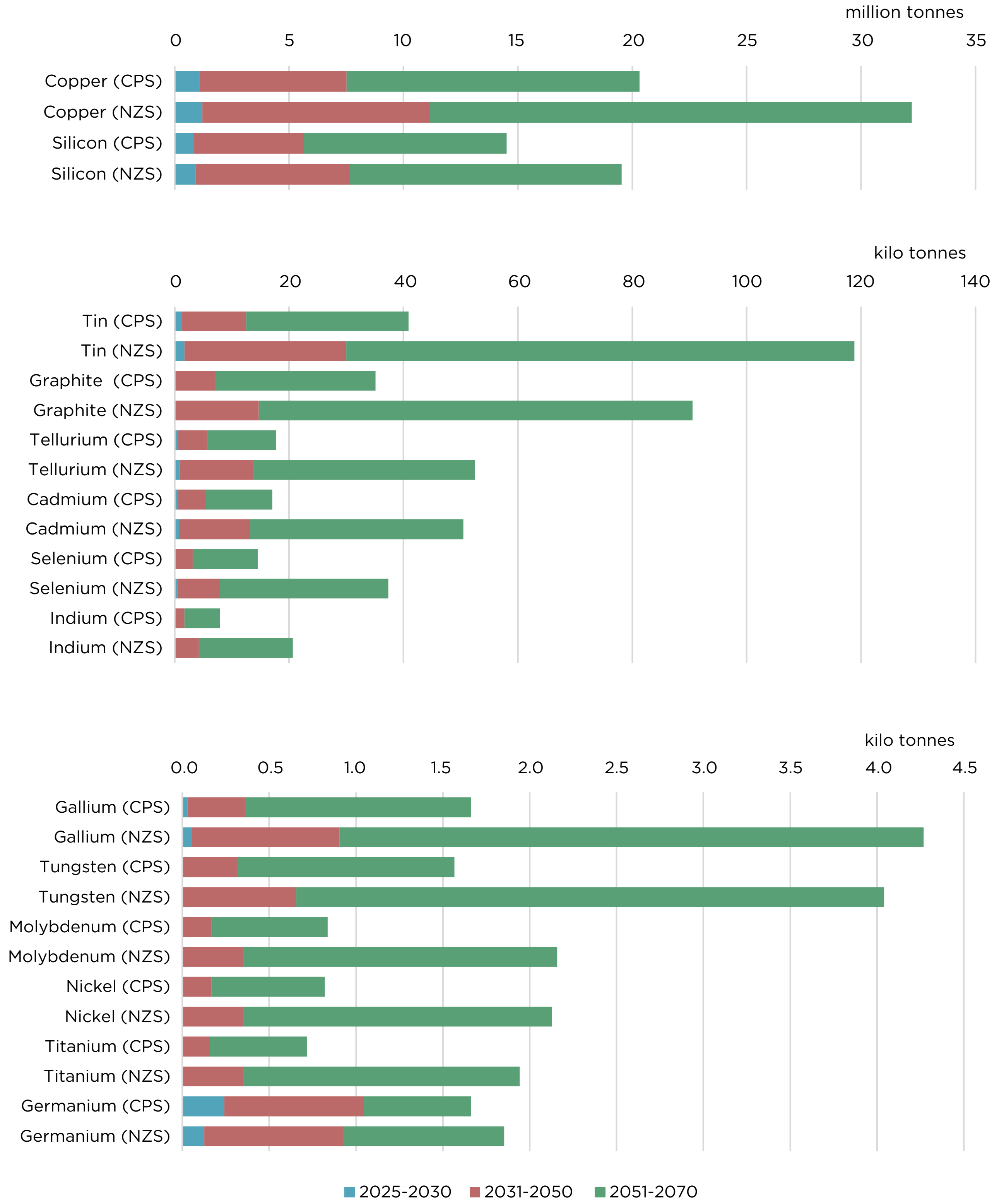


Figure 2.1: Solar PV – Embedded Mineral Requirements under Current Policy Scenario (CPS) and Net Zero Scenario (NZS)

Gallium, molybdenum, titanium, nickel and tungsten show moderate growth, shaped by their limited application in thin-film and perovskite variants, emerge from negligible Current Policy Scenario bases and scale in Net Zero Scenario, yielding ~108–120% in 2031–50 and ~170–185% in 2051–70.

In Concentrated Solar Power (CSP) technologies, mineral demand is concentrated in copper, nickel, molybdenum, vanadium, titanium, and niobium. Demand for copper and nickel is especially significant due to its high intensity of use in both CSP sub-technologies, although overall copper's demand trajectory falls and nickel's increases due to shifting market shares between parabolic troughs and solar towers. In the Net Zero Scenario, copper, molybdenum, and titanium demand reduces, due to lowering of parabolic troughs in favour of towers. In contrast, towers are more nickel-intensive (~1,800 vs ~940 t/GW) and include use of niobium (~140 t/GW).

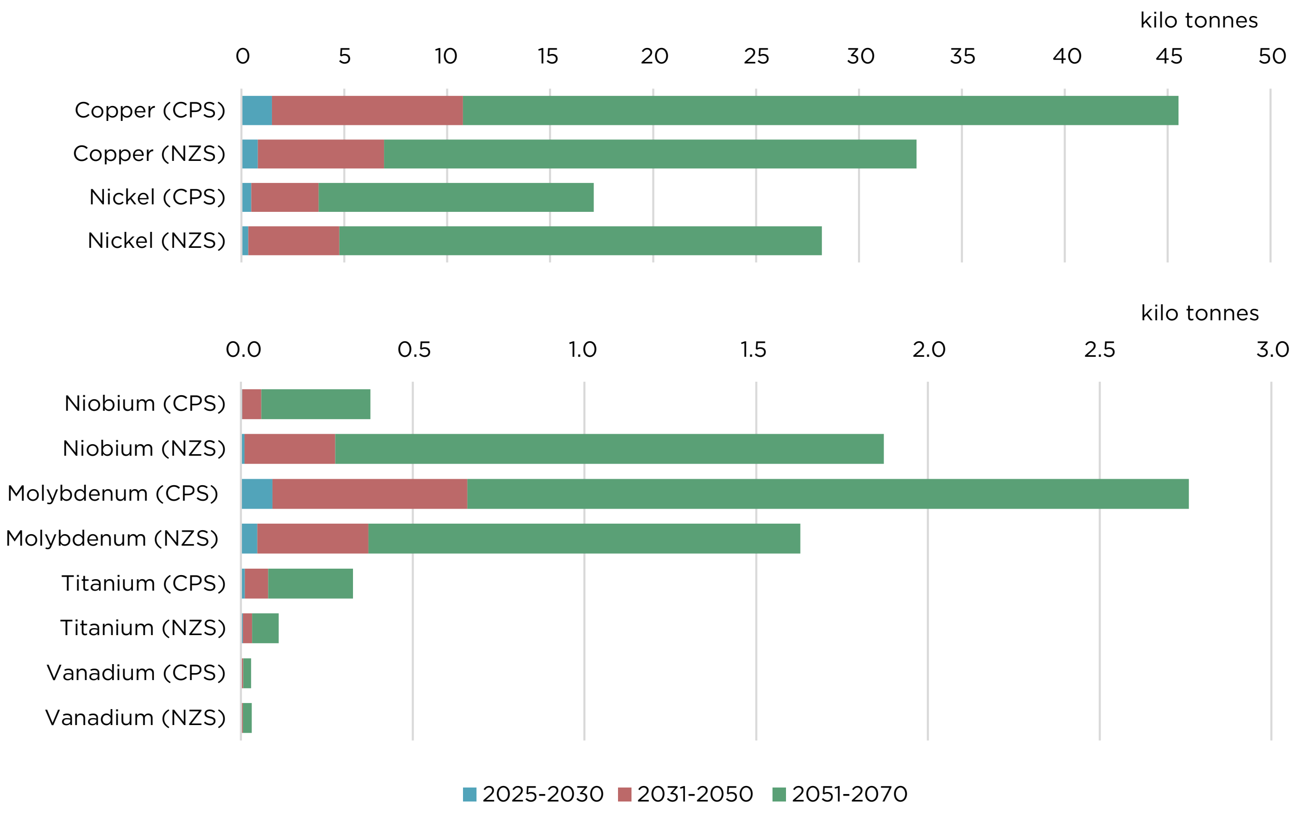


Figure 2.2: Solar CSP – Embedded Mineral Requirements under Current Policy Scenario (CPS) and Net Zero Scenario (NZS)

When viewed together, these findings highlight copper as the most consistently demanded mineral across both PV and CSP technologies. Silicon stands out as the only mineral whose rate of demand declines[1] under Net Zero Scenario, reflecting a major shift in the technology mix. The rise of perovskite PV introduces new material dependencies (nickel, graphite, tungsten, molybdenum and titanium), reshaping the mineral demand profile of solar deployment.

Although Concentrated Solar Power (CSP) contributes a relatively modest share of total solar-

1 The total installed capacity of solar PV in Net Zero Scenario is almost 1.5 times than the installed capacity in Current Policy Scenario. However, the demand of silicon per GW in Net Zero Scenario is lower than the demand per GW in Current Policy Scenario due to technology shift.

sector mineral demand, its reliance on materials such as nickel and vanadium suggests emerging supply risks if CSP deployment expands. Taken as a whole, solar's mineral requirements are not only scale-dependent but also highly sensitive to technology transitions, especially under a Net Zero aligned pathway.

2.1.2 Wind

Wind-turbine mineral requirements are shaped primarily by drivetrain design, making it essential to understand how gearbox-based and direct-drive systems differ in their material intensity. This analysis focuses on turbine-level components; therefore, higher mineral intensities typically associated with offshore wind foundations and subsea infrastructure are not modelled here. Wind turbines are broadly categorised into two drivetrain configurations: gearbox-based systems, which use a mechanical gearbox to increase rotor speed before electricity generation, and direct-drive systems, which eliminate the gearbox and connect the rotor directly to a low-speed, high-torque generator.

While gearbox-based turbines are currently more prevalent due to their lower capital costs, direct-drive configurations are gaining traction particularly in offshore and remote settings owing to superior reliability and reduced maintenance needs. Direct-drive systems, however, rely more heavily on rare earth permanent magnets containing neodymium, praseodymium, dysprosium, and terbium. This section examines turbine-level mineral requirements across copper, nickel, molybdenum, neodymium, praseodymium, dysprosium, terbium, and yttrium. The Table 2.2 shows differences across Current Policy Scenario and Net Zero Scenario in technology configuration, for a few major technologies for wind on-shore and wind off-shore. For detailed technological market share, refer to Annex D.

Table 2.2: Market Share of Technologies under On-Shore Wind and Off-Shore Wind[2]

Technology	Current Policy Scenario			Net Zero Scenario		
	2030	2050	2070	2030	2050	2070
Onshore wind						
GB-HS-PMSG (GB HS PMG)	37%	41%	45%	43%	45%	45%
GB-DFIG	22%	11%	5%	7%	0%	0%
DD-EESG	32%	35%	37%	24%	27%	28%
DD-PMSG	8%	11%	12%	25%	28%	28%
Offshore wind						
GB-SCIG	57%	50%	45%	5%	4%	3%
DD-PMSG	31%	26%	24%	82%	87%	88%
GB-MS PMG	12%	13%	14%	12%	10%	9%

As drivetrain preferences evolve, so will the distribution of mineral demand. Increasing adoption of permanent-magnet machines, especially in Net Zero Scenario, amplifies dependence on

2 DD – Direct Drive; DFIG – Doubly Fed Induction Generator; EESG - Electrically Excited Synchronous Generator; GB -Gearbox; HS – High Speed; MS – Medium Speed; PMG – Permanent Magnet Generator; PMSG – Permanent Magnet Synchronous Generator; SCIG – Squirrel Cage Induction Generator

copper and rare earth elements, highlighting the need for proactive supply-chain and materials-strategy planning.

Mineral Demand

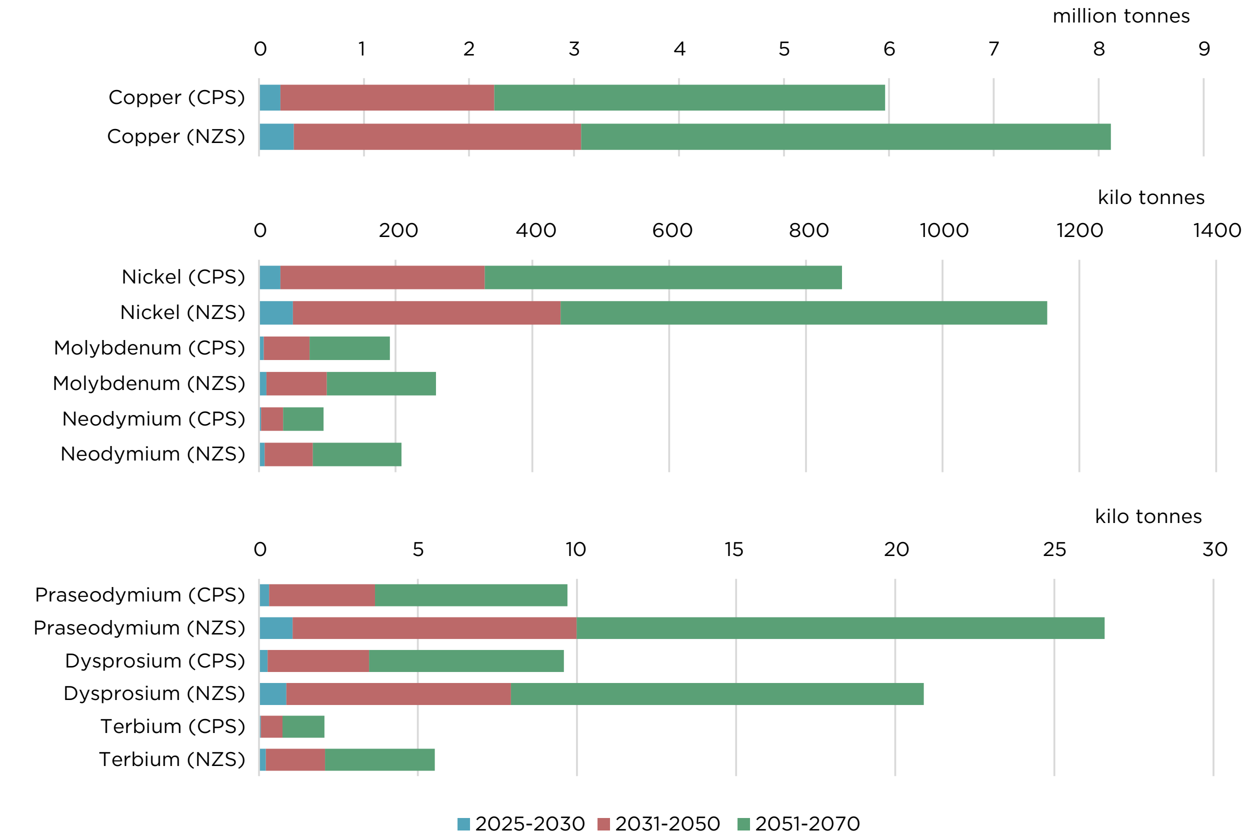


Figure 2.3: Onshore Wind – Embedded Mineral Requirements under Current Policy Scenario (CPS) and Net Zero Scenario (NZS)

Onshore wind is the primary driver of mineral demand in the near term. Under Net Zero Scenario (NZS), mineral requirements for onshore wind are consistently higher than Current Policy Scenario (CPS) due to greater capacity additions and a larger share of permanent-magnet machines (see Figure 2.3). Copper shows the highest increase, approximately 62%, 34% and 36% above CPS across the three periods, reflecting its widespread use in wiring, generators and power systems. Nickel and molybdenum, used in high-strength steel components, contribute steadily to overall demand. The sharpest increases appear in rare-earth elements, namely neodymium, praseodymium, dysprosium and terbium driven by the expanding use of Neodymium Iron Boron (NdFeB) magnets in Permanent Magnet Synchronous Generators (PMSGs).

Offshore wind shows broadly similar mineral demand patterns, though absolute volumes remain lower due to smaller cumulative deployment (see Figure 2.4). Rare-earth demand rises strongly because DD-PMSG[3] configurations are Rare Earth Element (REE)-intensive. Net Zero Scenario premia for these minerals grow sharply from mid- to late-century (e.g., praseodymium at ~159%,

3 Direct Drive-Permanent Magnet Synchronous Generator

201%, 325%), while Yttrium, required for Direct Drive High-Temperature Superconducting (DD-HTS) machines, albeit at very low volume, is absent due to the phase-out assumed in the Net Zero Scenario.

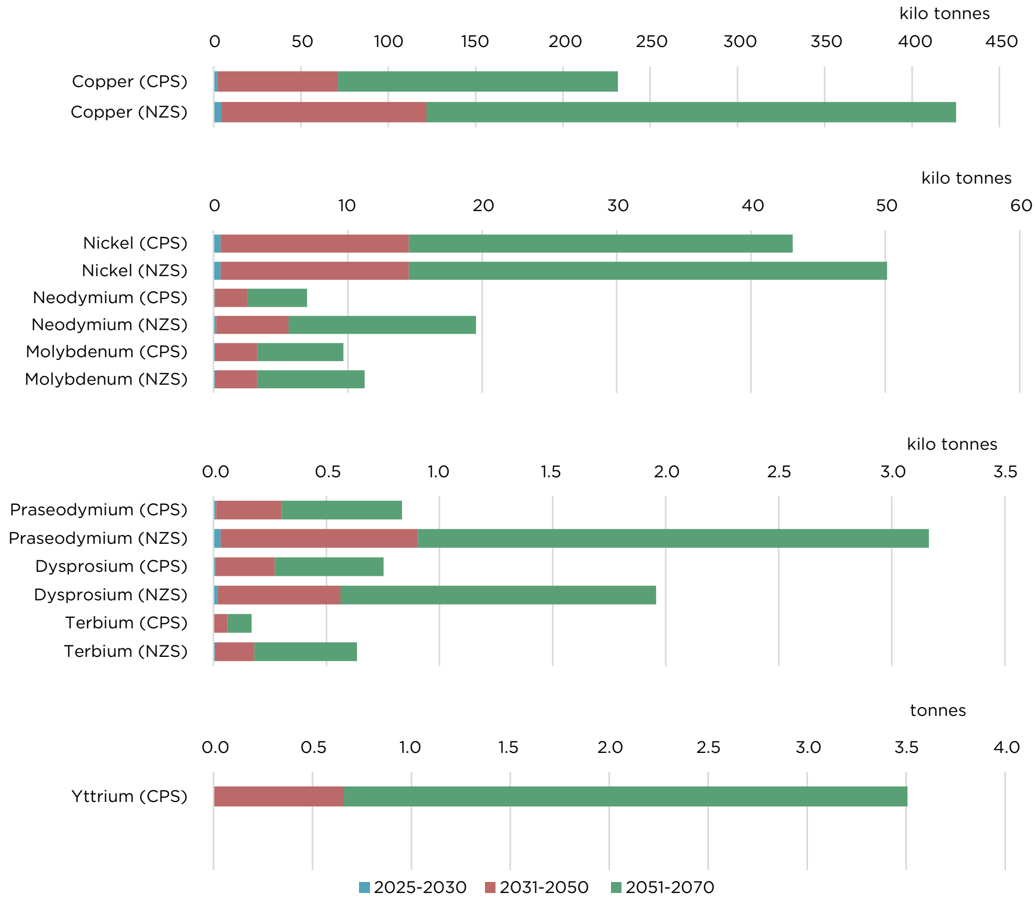


Figure 2.4: Offshore Wind – Embedded Mineral Requirements under Current Policy Scenario (CPS) and Net Zero Scenario (NZS)

Overall, mineral demand in wind energy is shaped primarily by capacity-addition trajectories and drivetrain market-share shifts. Copper and nickel consistently lead the total volumes, followed by rare earths used in direct-drive systems. Unlike solar, wind technologies experience fewer disruptive transitions; however, their continued reliance on imported REEs remains a critical supply risk, reinforcing the need for diversification, material substitution and long-term sourcing strategies.

2.1.3 Battery Energy Grid Storage Systems

The mineral requirements of Battery Energy Storage System (BESS) reflect the diversity of storage chemistries from lithium-ion systems to emerging sodium and flow batteries, each with its own critical-material profile. This analysis, thus, considers a wide range of BESS technologies, including lithium-ion chemistries (such as Nickel Manganese Cobalt (NMC), Lithium Iron Phosphate (LFP), and Lithium Titanate Oxide (LTO)), flow batteries (e.g. vanadium redox), solid-state batteries (SSBs), sodium-ion and bromine, zinc- and sulphur-based systems. The assessment tracks seven key critical minerals: graphite, lithium, cobalt, nickel, copper, vanadium, and phosphorous. While lithium-ion variants dominate in diversity and application (e.g., LFP), individual chemistries differ significantly in their reliance on critical minerals. For instance, NMC batteries are nickel- and cobalt-intensive, LFP avoids both entirely, and SSBs offer the potential to reduce graphite use.

The market-share trajectory reflects these characteristics and is identical for Current Policy Scenario (CPS) and Net Zero Scenario (NZS). Table 2.3 shows the market share for a few major technologies under BESS. For detailed technological market share, refer Annex D.

- The shares of Nickel Manganese Cobalt (NMC) 811, 622, and 523 decline from 2% each in 2025 to 0% by 2035.
- Lithium Iron Phosphate (LFP)'s share, meanwhile, decreases from 90% in 2025 to 46% in 2070.
- Lithium titanate chemistry goes from 0 to only 5.7% between 2025 and 2070.
- Na-ion chemistries share increases from 1% in 2025 to 22% in 2070, while vanadium redox flow batteries expand from 1% to 4% over the same period.

Collectively, these trends indicate a more diversified future battery market, with mineral demand spread across a wider range of chemistries, underscoring the need for parallel development of multiple critical mineral supply chains.

Table 2.3: Market Share of Technologies under Battery Energy Storage Systems

Technology	2030	2050	2070
Lithium Iron Phosphate	86.0%	65.8%	46.1%
Lithium Titanate	0.9%	3.3%	5.7%
Sodium Iron Phosphate ($NaFePO_4$)	1.0%	3.0%	4.4%
Prussian Blue Analogues ($Na_2Fe[Fe(CN)_6]$)	1.0%	3.0%	4.4%
NASICON ($Na_3V_2(PO_4)_3$	1.0%	3.0%	4.4%
Layered Sodium Manganese Oxide ($NaMnO_2$)	1.0%	3.0%	4.4%
Sodium Nickel Manganese Cobalt	1.0%	3.0%	4.4%
Vanadium Redox Flow Battery	1.5%	2.7%	4.0%

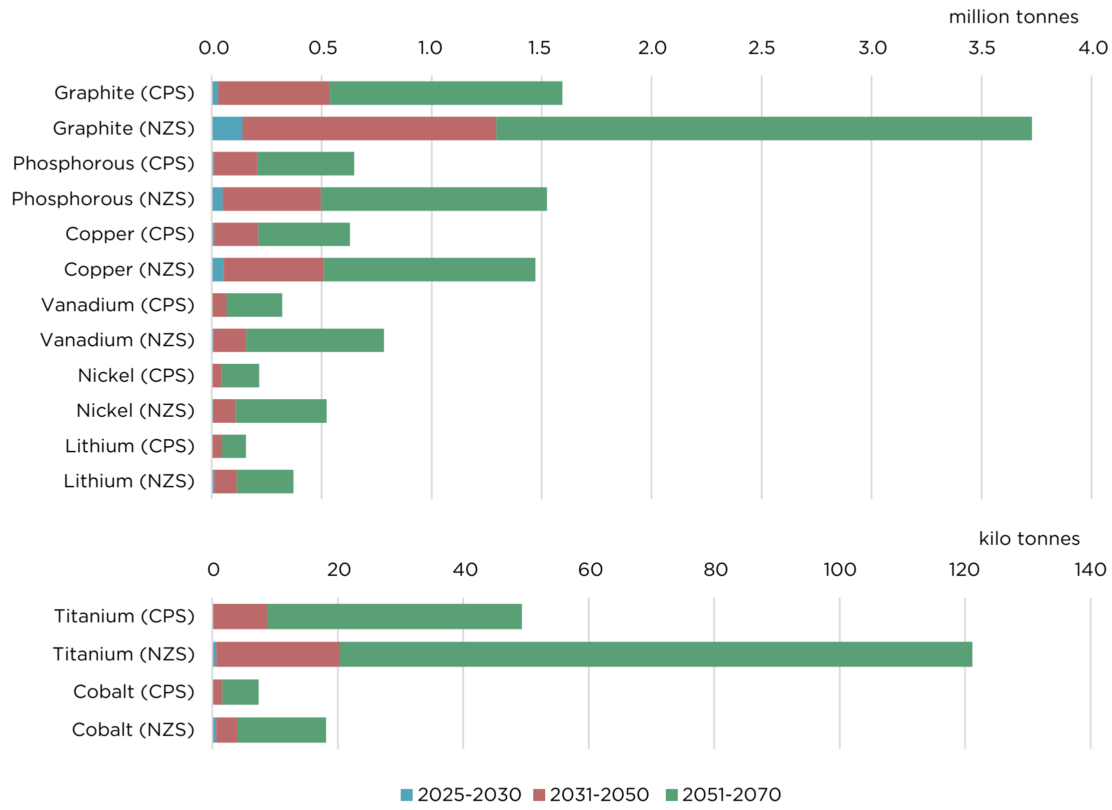


Figure 2.5: Stationary Battery Energy Storage – Embedded Mineral Requirements under Current Policy Scenario (CPS) and Net Zero Scenario (NZS)

Mineral Demand

BESS-related mineral demand rises sharply under Net Zero Scenario (NZS), largely due to higher installed storage capacity to support higher Renewable Penetration (see Figure 2.5). This yields a broad NZS rise of 4.7 times in 2025-230 and moderating to roughly 2.3 times in 2031-2070 as compared to CPS. Across both scenarios, the primary demand drivers are graphite, phosphorus and copper. Owing to their use across a wide range of chemistries, graphite and copper remain consistently high in demand throughout. Phosphorus and lithium also show steady demand due to the strong presence of Lithium Iron Phosphate (LFP) chemistries.

Vanadium demand increases from the 2030s onward as deployment of vanadium redox flow batteries accelerates, reaching around +146% above Current Policy Scenario (CPS) in 2051–70. Nickel maintains demand across all periods even as Lithium Nickel Manganese Cobalt (Li-NMC) chemistries are phased out, due to the emergence of nickel-bearing sodium-ion chemistries. Titanium and cobalt record the lowest demand for Battery Energy Storage System (BESS), reflecting the niche application of Lithium Titanate Oxide (LTO) and the progressive reduction of cobalt intensity across battery chemistries.

A notable caveat is the possibility that lithium demand for BESS may reduce significantly after 2040 if sodium-ferrous-phosphate chemistries mature faster than assumed in this study, particularly if they begin to displace their lithium-equivalent Lithium Iron Phosphate (LFP) chemistries due to comparable cost advantages.

2.1.4 Hydrogen Electrolyser

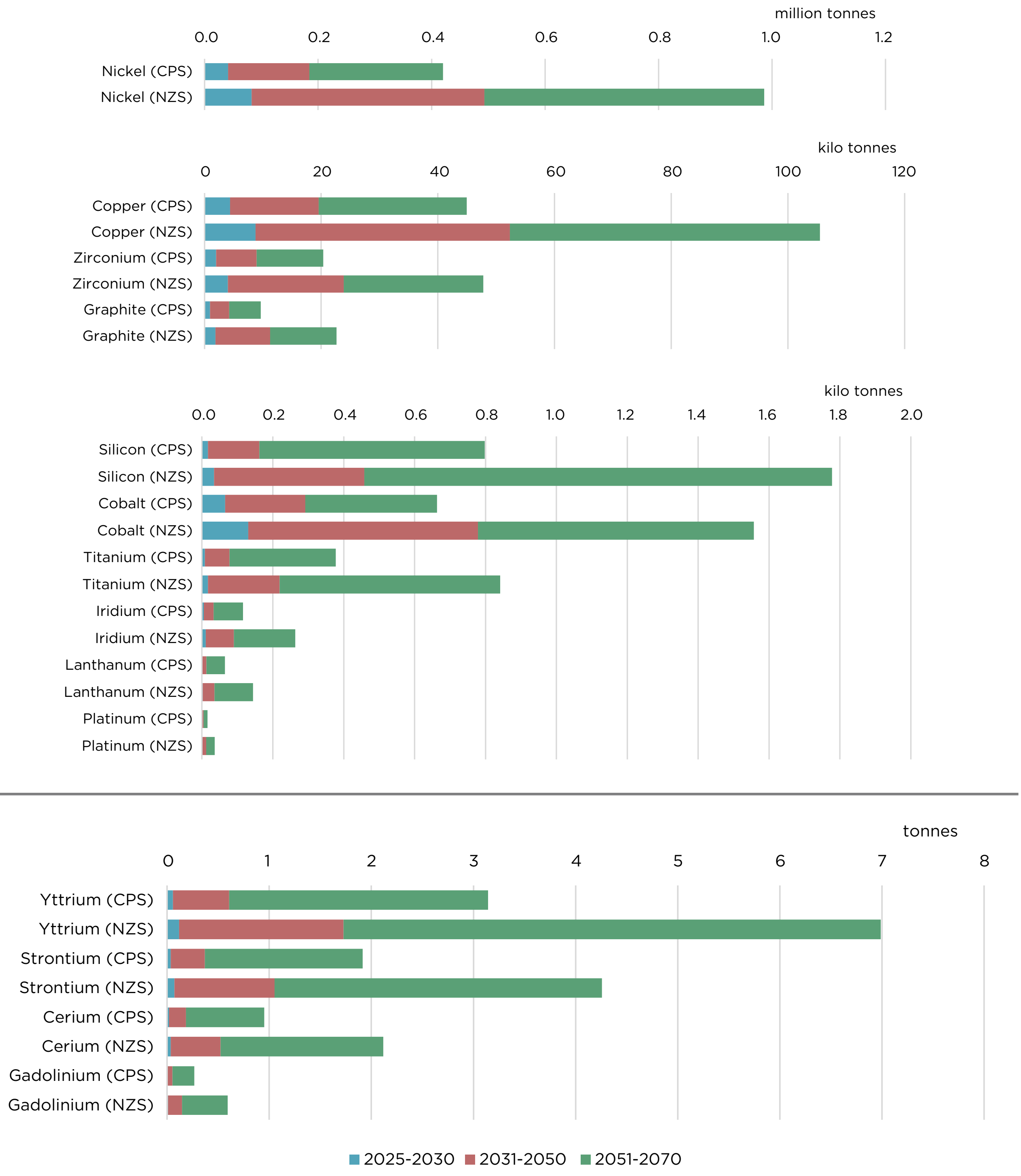


Figure 2.6: Hydrogen Electrolyser – Embedded Mineral Requirements under Current Policy Scenario (CPS) and Net Zero Scenario (NZS)

The total projected demand for Green Hydrogen is given in Table 1.1. Three key electrolyser technologies have been considered for this analysis: Alkaline Electrolysers (AEL), Proton Exchange Membrane Electrolysers (PEMEL), and Solid Oxide Electrolysers (SOEL). AELs, the most commercially mature (TRL 8–9), depend heavily on nickel, copper, zirconium, and graphite, with minor cobalt use. PEMELs, also at high readiness levels, require copper, graphite, silicon, and trace quantities of platinum-group metals such as iridium and platinum. SOELs, with lower maturity (TRL 5–6), use a broader and more diverse range of minerals, including nickel, zirconium, silicon, titanium, lanthanum, cerium, strontium, yttrium, and gadolinium. The market share trajectory reflects these characteristics and is identical for Current Policy Scenario (CPS) and Net Zero Scenario (NZS).

- Alkaline Electrolyser (AEL) dominates at 65% in 2025, and is projected to decline to 45% by 2050 and 25% by 2070
- Proton Exchange Membrane (PEMEL) increases from 23% in 2025 to 30% by 2050 and 34% in 2070.
- Solid Oxide Electrolyser (SOEL), which grows from just 10% in 2030 to 25% by 2050 and 41% by 2070, becoming the leading electrolyser type by the end of the projection period.

This shift implies a gradual move away from technologies reliant on PGMs and cobalt toward those requiring a broader set of critical minerals, especially rare earths and refractory metals, highlighting the increasing complexity of mineral demand linked to green hydrogen production.

Mineral Demand

Electrolyser-related mineral demand scales steeply under Net Zero Scenario (NZS), driven initially by rapid increases in installed capacity and later by changes in technology shares. Across both scenarios, nickel records the highest overall demand due to its central role as a catalyst and electrode material in AEL and SOEL. Copper, zirconium and graphite follow, with varying intensities across electrolyser types. Precious-metal catalysts (iridium, platinum) and titanium see a mid-period spike (around +190%) as PEMEL's share increases (Iridium ~1.4; Platinum ~0.19; Titanium ~1.05 t/GW), before declining as SOEL deployment accelerates after 2050.

As AEL and PEMEL shares fall and SOEL expands, demand for minerals such as silicon, titanium, lanthanum, cerium, strontium, yttrium and gadolinium becomes more stable and grows over the long term. SOEL's material profile (Silicon ~14.1; Titanium ~6.5; Lanthanum ~1.29; Strontium ~0.038; Cerium ~0.019; Yttrium ~0.063 t/GW) sustains late-century Net Zero Scenario (NZS) demand uplifts of roughly +108–110% for silicon, titanium and the lanthanides.

2.1.5 Electric Vehicle Motors

EVs primarily use either induction motors or Permanent Magnet Synchronous Motors (PMSMs). Among these, PMSMs dominate due to their high torque-to-weight ratio and superior efficiency, with their market share projected to exceed 90% in the coming years (Gauß et al., 2021). These motors commonly rely on neodymium and dysprosium (Dy), used in NdFeB (neodymium-iron-boron) permanent magnets, with each motor typically requiring 0.5 to 1.2 kg of REEs. Copper is also extensively used in stator windings and electrical interconnects (European Commission, 2020).

Alternative motor types such as Switched Reluctance Motors (SRMs) offer the possibility of avoiding rare earths altogether. However, they often involve trade-offs in terms of acoustic performance, efficiency, and control complexity. In the Indian context, where magnet production is largely import-dependent, any shift in motor designs could significantly impact rare earth demand forecasts. There is growing global R&D interest in replacing NdFeB magnets with ferrite or iron-nitride magnets, particularly in China and South Korea, which are scaling domestic production of non-REE-based motors (Alves et al., 2020).

Mineral Demand

Traction motor materials scale with deeper electrification under Net Zero Scenario (NZS) and continued preference for permanent-magnet traction in two-, three-, and four-wheelers. Copper demand increases steadily under both scenarios, with NZS significantly outpacing Current Policy Scenario (CPS) from 2030 onward (see Figure 2.7). By 2070, cumulative copper demand under NZS reaches nearly 4.4 million tonnes, ~40% higher than under CPS, reflecting greater electrification across vehicle segments and more aggressive EV adoption.

By 2070, cumulative demand under the NZS is projected to exceed 250 kilo tonnes for neodymium and nearly 127 kilo tonnes for dysprosium, primarily due to widespread use of PMSMs in four-wheelers and Heavy-Duty Vehicles (HDVs). Demand for cobalt, used in specialised magnetic alloys for certain motor designs, also increases under NZS compared to CPS.

Segment-wise, four-wheelers and HDVs are projected to account for the largest share of motor-related mineral demand after 2030, driven by higher power requirements and increased adoption of high-efficiency drivetrains. Two- and three-wheelers, though dominant in early volumes, contribute less intensively to copper and REE demand due to lower motor power ratings. Overall, NZS sits 2.2 times higher than CPS in 2025–30, moderating to 1.4 times in 2031–70 as overall EV uptake, rather than major design mix shifts, becomes the principal driver of demand.

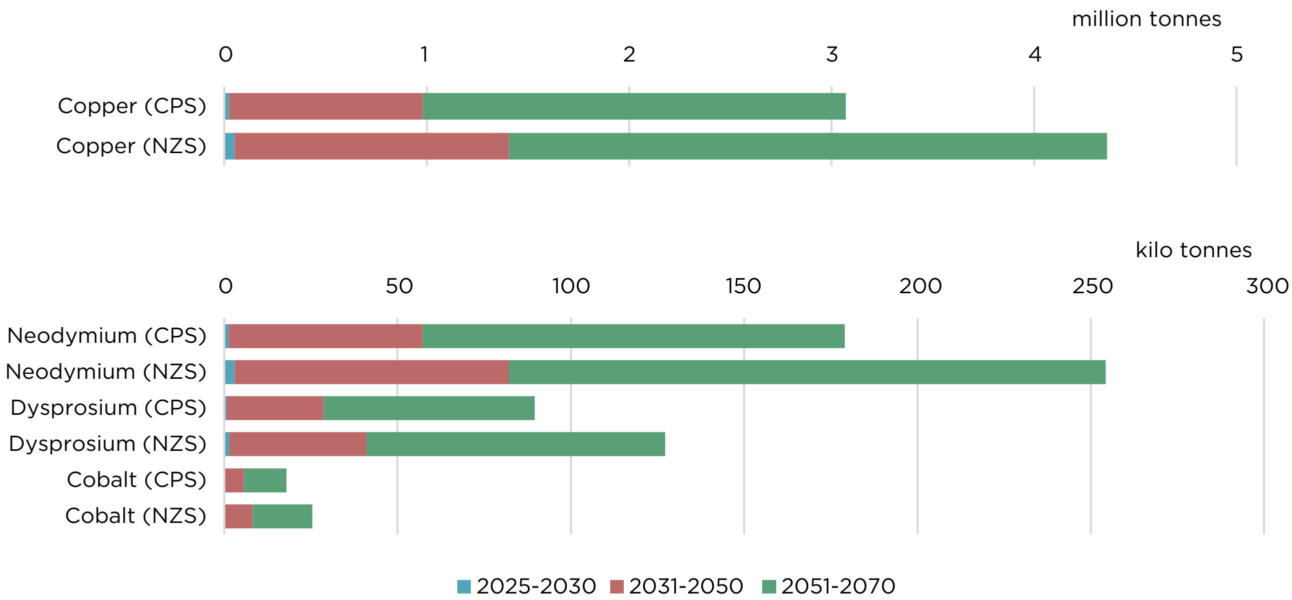


Figure 2.7: EV Motors – Embedded Mineral Requirements

2.1.6 Electric Vehicle Batteries

Lithium-ion batteries (LiBs) currently dominate electric vehicle battery technology and rely heavily on critical minerals, particularly in the cathode and anode compositions. The cathode chemistry is typically defined by the proportion of lithium, cobalt, nickel, manganese, and aluminium, each influencing performance, cost, and supply risks. Examples of common cathode chemistries include:

- **NMC 111 (Lithium-Nickel-Manganese-Cobalt Oxide):** A balanced formulation with moderate energy density and a cobalt content of ~20% by weight.
- **NMC 622 and NMC 811:** Higher in nickel (up to ~80%) and significantly lower in cobalt (<10%), resulting in higher energy density and lower cost.
- **LFP (Lithium Iron Phosphate):** A cobalt- and nickel-free alternative that uses lithium and phosphate, which is safer and more thermally stable, though lower in energy density.

The anode is typically composed of graphite, with a material intensity of ~0.8–1.2 kg per kWh of battery capacity. Silicon-rich and lithium-metal anodes are under development to reduce dependence on graphite while increasing energy density.

Electrolytes consist of lithium hexafluorophosphate ($LiPF_6$) dissolved in organic solvents. All Solid-State Batteries (ASSBs) replace liquid electrolytes with ceramic or polymer-based conductors, offering improved safety, durability, and greater thermal stability while potentially reducing reliance on graphite in anodes.

The Battery Management System (BMS) incorporates electronics-grade copper and trace metals like tantalum and silver used in circuitry and control systems. Copper also serves as a current collector.

The market-share trajectory reflects continued advances in battery technology and remains the same under CPS and NZS.

- Across all EV categories, cobalt- and nickel-heavy chemistries decline over time and give way to more mineral-efficient alternatives.
- NMC 111 and NMC 532, both higher in cobalt, are phased out completely by 2040.
- NMC 622 also declines, while NMC 811, a high-nickel, low-cobalt chemistry becomes dominant in two, three and four-wheelers, reaching a 67% share by 2040 and remaining stable thereafter.
- LFP gradually expands, particularly in commercial vehicles, where it consistently accounts for 80–90% of demand.
- ASSBs enter the market from 2035, reaching ~14–15% of market share by 2070, reflecting their potential to reduce dependence on graphite and liquid electrolytes.

Table 2.4 shows the market share for a few major battery technologies under different vehicle segments. For detailed technological market share, refer Annex D.

Table 2.4: Market Share of Battery Technologies under Electric Vehicles' Different Categories

Vehicle Category	Battery Type	2030	2050	2070
2-W & 3-W	NMC 811	63%	67%	67%
	LFP	8%	11%	15%
	ASSB	0%	14%	14%
4-W	NMC 811	22%	14%	4.4%
	LFP	50%	74%	3%
	ASSB	0%	12%	63%
Others	NMC 622	10%	10%	5%
	LFP	90%	80%	80%
	ASSB	0%	10%	15%

This transition in battery chemistry steadily alters the mineral-demand profile. Reduced use of cobalt-intensive chemistries, alongside the growth of LFP and ASSBs, points toward a long-term decrease in reliance on high-risk materials such as cobalt and a gradually more diverse set of mineral inputs driven by new battery technologies.

Mineral Demand

Battery-related mineral demand is consistently higher under Net Zero Scenario (NZS) across the full modelling horizon, with chemistry shifts shaping the relative gaps between scenarios (see Figure 2.8). Graphite remains the most consumed mineral by volume, reaching 42 Mt under NZS by 2070, around 43% higher than Current Policy Scenario (CPS) and rising by roughly +124%, +42% and +43% across the three periods. Phosphorus (P) follows a similar growth pattern, reaching ~15 Mt by 2070 under NZS, again ~44% higher than CPS. These trends reflect strong LFP adoption in 4-wheelers through mid-century (~58%, then ~74%) and the continued role of lithium- and sodium-phosphate chemistries thereafter.

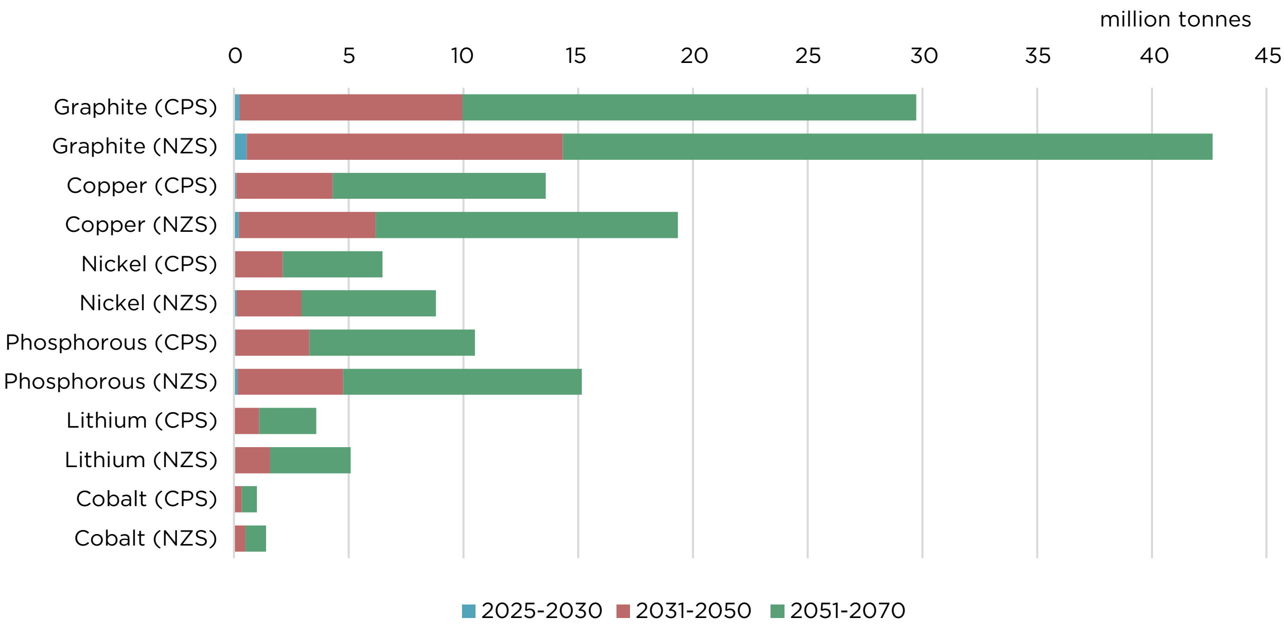


Figure 2.8: EV Batteries – Embedded Mineral Requirements

Nickel and cobalt show the largest NZS early uplift, about +97% and +101% respectively in 2030, before moderating to around +35% and +39% in 2051–70 as 4-wheelers further transition to LFP and then increasingly to ASSB (which reaches ~34% in late-century 4-wheelers). By 2070, cumulative nickel demand reaches ~8.8 Mt under NZS (~36% above CPS), while cumulative cobalt demand reaches ~1.4 Mt (~40% above CPS).

Lithium shows greater demand growth early under NZS +122% in 2025–30), moderating to +42% and +41% in subsequent periods, reflecting its presence across almost all major chemistries. By 2070, cumulative lithium demand reaches ~5 Mt under NZS, ~42% above CPS.

Copper demand associated with EV batteries is also significant, totalling over 19 Mt under NZS by 2070 about 42% higher than CPS owing to its widespread use in current collectors, electrical connections, and the broader EV architecture.

Overall, battery-related mineral demand is shaped by chemistry evolution, increasing battery size, and the pace of electrification across vehicle segments. Two- and three-wheelers dominate initial volumes, while four-wheelers and heavy-duty vehicles contribute the most mineral-intensive battery requirements after 2030. Under NZS, cumulative mineral demand for EV batteries is projected to be about 40% higher than CPS, driven by more rapid uptake and greater fleet-wide electrification.

2.2 CUMULATIVE DOMESTIC DEMAND FOR CETMS

Understanding how mineral needs accumulate over the next five decades is essential for anticipating supply gaps and investment priorities. This section synthesises projected cumulative demand for CETMs from 2025 to 2070 under Current Policy Scenario (CPS) and Net Zero Scenario (NZS). Under NZS, India requires an estimated ~169 Mt of CETMs, about 51% more than CPS (~112 Mt). Drawing on demand projections from solar, wind, batteries, electrolysers and EVs, the analysis examines temporal patterns, scenario differences and the relative contributions of each technology.

Top Demand Drivers

Copper and graphite emerge as the CETMs with the highest cumulative demand by 2070, at roughly 66 Mt and 46.4 Mt, respectively, under Net Zero Scenario. Copper's dominance reflects its widespread application across solar PV, wind turbines, EV batteries, EV motors, and electrolysers. Graphite demand arises almost entirely from battery anodes, with more than 95% sourced from EV and Battery Energy Storage Systems. Silicon follows at ~19 Mt, driven mainly by solar PV deployment. Phosphorus demand reaches ~16.6 Mt, reflecting its critical role in LFP batteries in both EVs and BESS.

Nickel also stands out at ~11 Mt due to its applications in EV batteries, BESS, wind turbines and electrolysers. Other high-volume CETMs include lithium at ~5.4 Mt, cobalt at ~1.4 Mt, and vanadium at ~0.7 Mt, all tied primarily to battery technologies.

Technology-Specific Mineral Dependencies

While many critical minerals are required across multiple Low-Carbon Technologies (LCTs), many display highly concentrated demand profiles tied to specific applications. A noteworthy subset of minerals, including neodymium, molybdenum, dysprosium, titanium and tin, also exhibit scale of demand above 0.1 Mt and 1 Mt.

- Wind energy and EVs are the exclusive drivers of demand for neodymium, praseodymium, dysprosium, and terbium (rare earth elements essential for permanent magnets in turbine generators and EV motors).
- Solar-exclusive minerals include gallium, tellurium, selenium, and germanium, many of which are essential for advanced PV technologies, exposing vulnerabilities in supply chains.
- Electrolyser-dominant minerals such as iridium, platinum, strontium, and gadolinium in contrast are low-volume, vital for green hydrogen production, and geopolitically sensitive due to supply concentration.
- A long-tail of minerals including strontium, gadolinium (REE), germanium, and yttrium has relatively low overall demand but may prove crucial for specialised applications and future innovations, warranting strategic attention.

Temporal Distribution

Demand for Critical Energy Transition Mineral (CETM) is heavily backloaded. Under Net Zero Scenario, only ~2% of cumulative demand occurs in 2025–2030, ~32% in 2030–2050, and ~66% in 2050–2070. This means that two-thirds of total CETM requirements materialise after 2050.

Some outliers deviate from the general pattern. Silicon, for example, reaches 4.7% of its total demand by 2030 and ~34% by 2050 due to early front-loaded PV deployment, after which demand slows as non-silicon PV shares rise. Minerals such as zirconium, germanium, and molybdenum show higher early-to-mid-century demand due to their roles in electrolysers and PV. Conversely, minerals such as vanadium, titanium, selenium, indium, gallium, tungsten, niobium, lanthanum, yttrium, strontium, cerium, and gadolinium accumulate more than 75% of their demand after 2050.

Technology-Wise Contribution

The technology-wise distribution of cumulative Critical Energy Transition Mineral (CETM) demand under Net Zero Scenario shows clear concentration patterns (see Figures 2.9a and 2.9b - graphs are split in two for readers ease):

- EV batteries dominate, accounting for ~55% of total demand, with substantial shares of lithium, phosphorous, cobalt, nickel, graphite, and copper.
- Solar technologies follow with ~30% of total demand, particularly for copper and silicon, and smaller volumes of tin, indium, tellurium, and selenium.
- Wind energy contributes ~6%, driven primarily by REEs and copper.
- Battery Energy Storage System (BESS) accounts for ~5%, driven by graphite, nickel, cobalt, vanadium, and copper.
- Electrolysers contribute only <1%, but still demand a diverse mix of CETMs including iridium, platinum, zirconium, and lanthanum.

- EV motors contribute ~3%, concentrated in Rare Earth Elements (REEs) (neodymium, dysprosium, praseodymium, terbium, and yttrium), alongside copper.

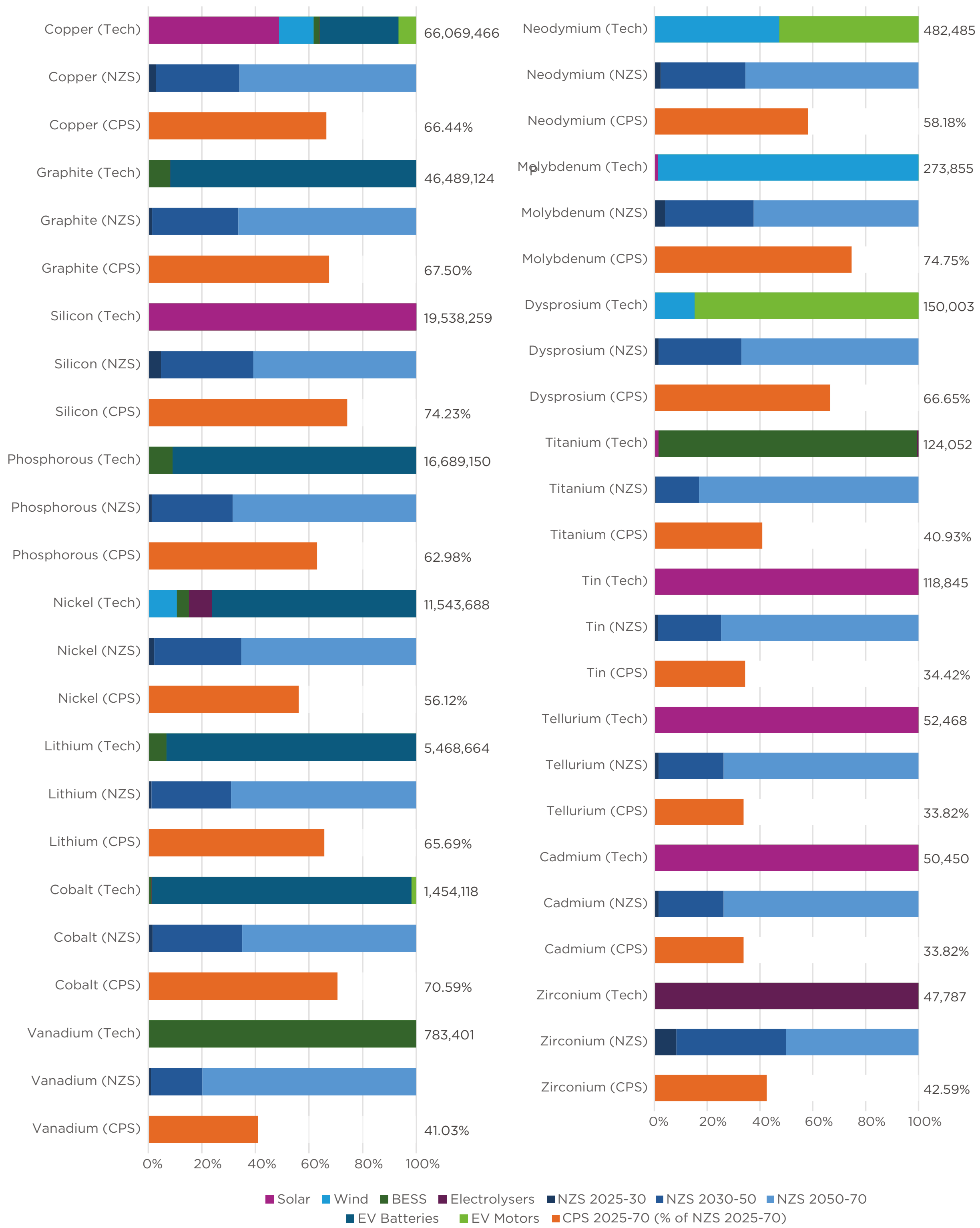


Figure 2.9a: Cumulative Mineral Demand in Current Policy Scenario (CPS) & Net Zero Scenario (NZS)

(Interpretation of graph - Bar 1: Share across different technologies under NZS; Bar 2: Share across different time horizons under NZS; Bar 3: Proportion in CPS relative to the NZS; Secondary y-axis: – Total demand under the NZS (Tonnes) and percentage in CPS relative to NZS)

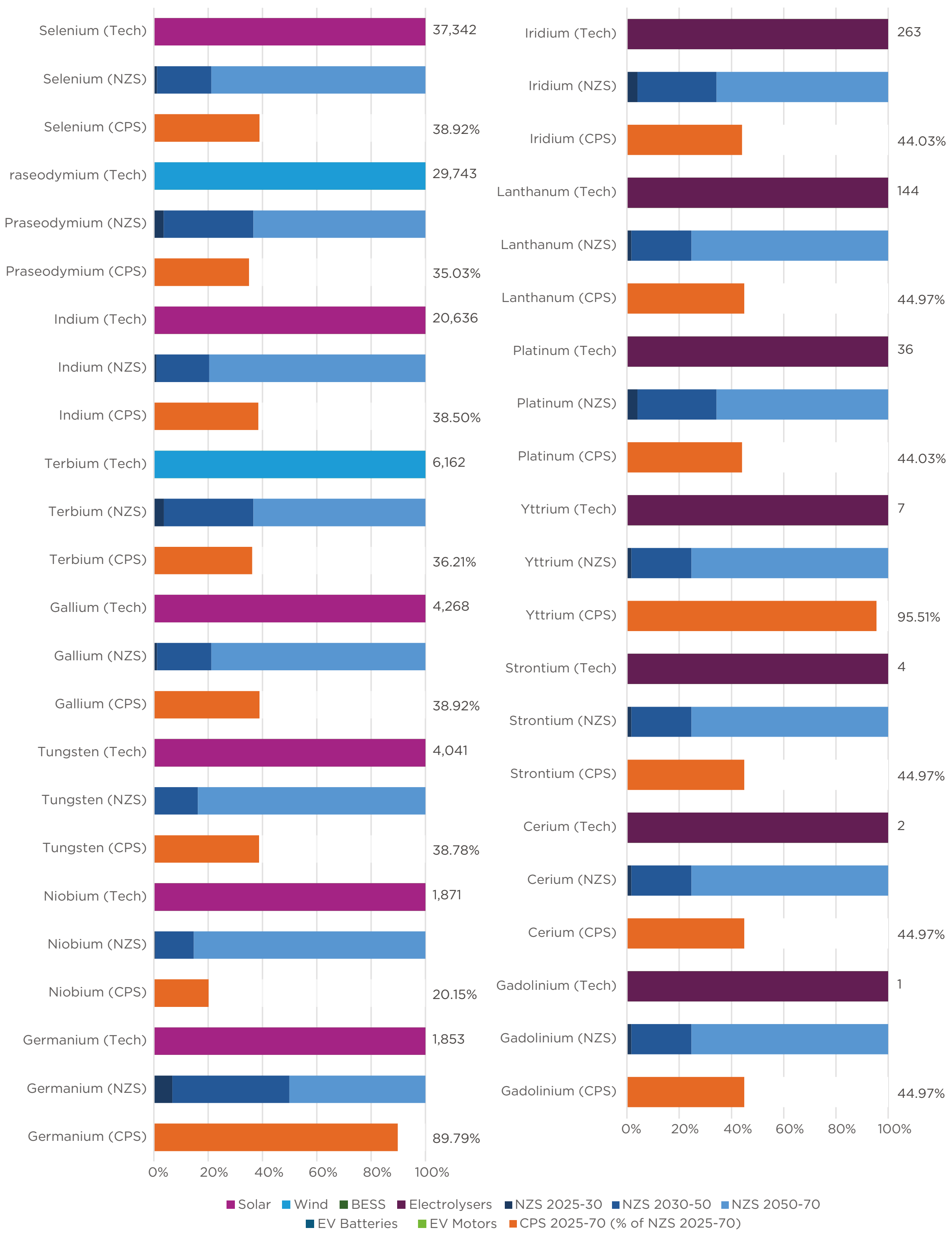


Figure 2.9b: Cumulative Mineral Demand in Current Policy Scenario (CPS) & Net Zero Scenario (NZS)

(Interpretation of graph - Bar 1: Share across different technologies under NZS; Bar 2: Share across different time horizons under NZS; Bar 3: Proportion in CPS relative to the NZS; Secondary y-axis: – Total demand under the NZS (Tonnes) and percentage in CPS relative to NZS)

The detailed information about Critical Energy Transition mineral requirement under Current Policy Scenario (CPS) and Net Zero Scenario (NZS) is provided in Annex E.

Mineral-diversity patterns matter for risk. Lower diversity (e.g., graphite–lithium–nickel for EVs and BESS; Nd–Pr–Dy–Tb for wind) heightens supply exposure, whereas higher diversity complicates procurement, standardisation and recycling. Among the LETs studied, mineral diversity varies by system class: among end-use systems, EVs draw on the fewest CETMs (~9 across batteries and traction motors); among grid infrastructure, BESS uses ~8, wind relies on ~8, solar (PV + CSP) spans ~16; and hydrogen electrolysers (AEL/PEMEL/SOEL) involve ~14.

Together, these trends highlight the breadth and depth of mineral dependencies across India's clean-energy transition and underscore the need for diversified, long-term supply strategies.

2.3 INDIA'S CETM DEMAND IN A GLOBAL CONTEXT (2050)

This section places India's projected Critical Energy Transition Mineral (CETM) demand in a global context. This provides a clearer picture of the country's role in international mineral value chains.

Understanding this comparison serves four strategic purposes:

1. It identifies Critical Energy Transition Minerals (CETMs) where India's projected demand could justify localisation of value chains, including mining, refining, and recycling.
2. It clarifies where India may, or may not, have the leverage to shape global prices, production volumes, or trade dynamics.
3. It informs procurement strategies for minerals with limited domestic demand, particularly where leveraging strategic international partnerships may be preferred.
4. The analysis also highlights the potential for Indian public and private entities to invest in global supply chains.

Even where domestic demand may not support full value chain development, overseas investments, aligned with global demand trends, could deliver strategic and commercial benefits. Instruments such as KABIL and India's participation in plurilateral platforms like the Minerals Security Partnership (MSP) can help operationalise this strategy.

Methodology

This assessment compares the projected CETM demand in 2050 with global demand projections published in the Global Demand Outlook (2025) of the International Energy Agency (IEA). Both datasets focus on mineral requirements for clean energy technologies such as batteries, solar PV, wind turbines, and electric vehicles in a Net Zero pathway.

Of the 37 CETMs tracked by the IEA and 31 tracked by this study, 27 minerals are common to both. IEA reports Platinum Group Elements (PGEs) as a single group "Platinum Group Metals (excluding iridium)", whereas this study treats iridium and platinum separately and therefore compares platinum demand with IEA's PGMs (excluding iridium) demand. Only phosphorous, cerium (used in nickel-metal hydride batteries), gadolinium and strontium (both used in solid-oxide electrolysers) fall outside the common list. All 27 common minerals were retained for comparison. Eventually, a small subset of thin-film PV-linked minerals (cadmium, indium, tellurium, tin, selenium, tungsten, and germanium), iridium and dysprosium were excluded due to their relatively low requirements and high sensitivity to technology pathway assumptions. The share of global demand was calculated as the ratio of India's 2050 demand to IEA's global projections for each mineral. These results are visualised in Figure 2.10.

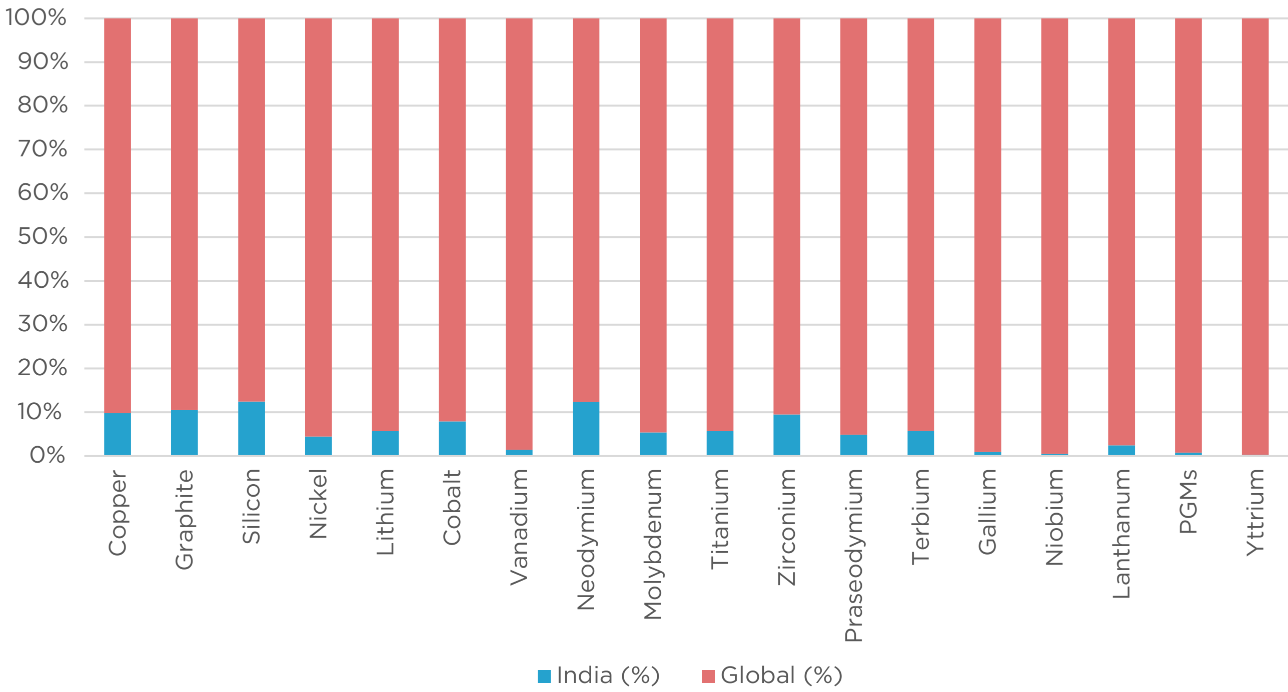


Figure 2.10: India's CETM Demand as Share of Global Demand in Net Zero Scenario (2050)

Analysis of Relative Shares

India's projected Critical Energy Transition Minerals demand in 2050 under NZS constitutes an average 9% of global demand. Three broad patterns emerge, driven by differences in technology mix, deployment scale, and material-intensity assumptions.

1. **Minerals with Mid-Tier Shares (10–15%)**: Three Critical Energy Transition Minerals fall in this range:
   - Silicon –12.5%
   - Neodymium –12.4%
   - Graphite –10.5%

These reflect India's strong build-out in PV (silicon), batteries (graphite), and sustained use of permanent magnets (Nd). Their elevated shares reinforce the importance of domestic processing and recycling strategies.

2. **Minerals with Low-to-Mid Relative Shares (3–10%)**: Nine Critical Energy Transition Minerals fall within this range
   - Copper – 9.8%
   - Zirconium – 9.5%
   - Cobalt – 8.0%

- Terbium – 5.8%
- Titanium – 5.7%
- Lithium – 5.7%
- Molybdenum – 5.4%
- Nickel – 4.5%
- Praseodymium – 4.9%

These support EV/BESS growth (Ni, Li, Co, Ti), wind/PV structures and alloys (Mo), REE magnets (Pr, Tb), and electrolysers (Zr). They warrant scalable domestic processing and recycling capacity without the concentration risks seen in the high-share group.

3. **Trace Demand Minerals (<3%)**: India's demand for the following Critical Energy Transition Minerals accounts for less than 3% of global totals:

- Lanthanum – 2.44%
- Vanadium – 1.5%
- Gallium – 0.95%
- PGMs – 0.82%
- Niobium – 0.54%
- Yttrium – 0.33%

These minerals are typically used in specialised applications, high-performance alloys and coatings in advanced electrolysers (Lanthanum, PGMs, Yttrium), battery storage (Vanadium), PV and Concentrated Solar Power (Gallium, Niobium) and motors in wind turbines (Yttrium). These are less prominent in India's current energy mix, but may grow in importance under future industrial decarbonisation scenarios and warrant close monitoring.

2.4 KEY TAKEAWAYS

This study identifies 31 of the 51 tracked elements (corresponds to 23 of the 30 critical minerals listed by the Ministry of Mines) as Critical Energy Transition Minerals essential for India's Net Zero pathway. The list spans bulk-use base metals, eight rare earth elements (lanthanum, cerium, neodymium, praseodymium, dysprosium, terbium, gadolinium, and yttrium), and two platinum group elements (platinum and iridium). Together, they highlight the diversity of materials needed to support the scale and diversity of India's low-carbon technology deployment.

Functional Categories of Mineral Demand

The projected mineral requirements reveal distinct functional clusters across clean energy technologies:

1. Bulk-use base metals such as copper and nickel underpin multiple technologies, EV batteries, motors, solar systems, and storage and form the structural backbone of the transition.

2. Storage-critical minerals like graphite, lithium, phosphorous, cobalt, and vanadium anchor battery chemistries. Their limited substitution potential and sourcing challenges must be addressed early to avoid downstream disruptions in EVs and grid-scale storage.
3. Rare earth elements, notably neodymium, praseodymium, dysprosium, terbium, and yttrium, are indispensable for high-performance permanent magnets in EV motors and wind turbines. These are low-volume but high-criticality materials, often tied to geographically concentrated supply chains, with limited alternatives.
4. PV-specific minerals present a dual challenge: while dominated by bulk silicon demand, they also depend on niche and high-risk minerals like gallium, tellurium, selenium, and germanium, often sourced from geopolitically sensitive regions.
5. Electrolyser-specific minerals like iridium, platinum, zirconium, and strontium, though low in volume, are crucial for green hydrogen production and are constrained by high cost and limited global availability.

Demand by Technology

Across low-carbon technologies, EVs generate the largest share of Critical Energy Transition Mineral (CETM) demand, accounting for ~55% of the total. Solar technologies contribute ~30%. Wind (~6%) and BESS (~5%) together represent ~11%, followed by EV motors (~3%). Electrolysers account for <1%.

These patterns underscore the distinct material footprints of each technology class. EV batteries and BESS drive high demand for graphite, lithium, nickel, phosphorous, cobalt, and vanadium, requiring targeted strategies to secure supply. EV motors and wind technologies depend heavily on neodymium, praseodymium, dysprosium, and terbium materials that must be prioritised for India’s domestic manufacturing ambitions. Solar technologies, while dominated by silicon, rely on strategic minerals such as gallium, germanium, and tellurium, exposing vulnerabilities in upstream supply chains. Electrolysers, although contributing a modest share, depend on scarce elements such as platinum, iridium, and select rare earths.

Temporal Distribution of Demand

A key finding is that over 66% of cumulative Critical Energy Transition Mineral (CETM) demand will materialise after 2050. This underscores both the urgency and the opportunity: early action to secure supply chains, investing in recycling, and strengthening domestic capability can yield long-term resilience and strategic advantage.

India in the Global Context

India’s Critical Energy Transition Mineral (CETM) demand in 2050 accounts for <~10% of global demand for most minerals, limiting its ability to influence global pricing, investment flows, and production decisions. Supply security will therefore depend on proactive strategies, including long-term offtake agreements, diversified international partnerships, and strengthened mineral diplomacy.

Yet the absolute volumes involved remain significant. Projected requirements of more than 20 Mt of copper and 14 Mt of graphite by 2050 justify substantial investment in domestic mining, processing, and recycling, even in the absence of global market leverage.

3

SUPPLY CHAIN RISKS

Supply Chain Risks

3

The criticality of minerals is generally estimated by gauging their economic importance and supply risks. Economic importance reflects the share of gross value-added in the manufacturing sector that could be disrupted if a mineral becomes unavailable. Supply risk captures the combined impact of geographic concentration in extraction and processing, and the quality of governance in major supplier countries. Higher concentration and weaker governance increase exposure to disruptions. Supply risk is further amplified when minerals lack viable substitutes, when a country has high import dependence, and when domestic recycling capacity is limited.

This section employs a multi-pronged methodology to assess supply chain risks associated with Critical Energy Transition Minerals (CETMs). First, it compares projected cumulative mineral demand (2025–2070) with India's known reserves, resource base, and current levels of import dependence to identify material-specific supply gaps. Second, domestic production and processing capacities are evaluated to assess the readiness of India's mineral value chain, including gaps in extraction technologies, refining infrastructure, and recycling capabilities. Third, trade exposure is analysed against geopolitical risks in key supplier countries to highlight high-risk materials and suppliers that warrant strategic attention. Finally, it reviews global critical mineral supply chains' weaknesses, drawing on secondary evidence from international trade publications, academic literature, industry reports, and government databases, focusing on trends over the past decade.

3.1 OVERVIEW OF CETM DEMAND, DOMESTIC RESOURCES AND RESERVES, AND IMPORT DEPENDENCE

Understanding India's Critical Energy Transition Mineral (CETM) supply landscape requires examining projected demand alongside domestic resource availability, reserve status, and current import dependence. Table 3.1 compares cumulative embedded mineral demand (2025–2070) with remaining resources, certified reserves, and import reliance for 23 priority CETMs, highlighting material-specific gaps, mismatches, and strategic strengths.

High Demand–High Import Dependence: Minerals such as nickel, lithium, cobalt, and Rare Earth Elements (REEs) show high cumulative demand, no reserves and near-complete import dependence (100%). These materials are essential for battery storage, electrolysers, and wind technologies, making supply security a critical concern and requiring urgent exploration and domestic processing efforts.

Gaps in Domestic Reserves Data: In several high-demand minerals (for example, cobalt, vanadium and lithium), resource estimates exist but reserves remain unestablished, creating long-term ambiguity around domestic supply potential. A number of moderate- and low-demand minerals (including tellurium, gallium, germanium and indium) also lack reserve data, underscoring the need for accelerated exploration and improved geological reporting.

Gaps in Processing and Refining Infrastructure: Some minerals, such as copper and graphite, have significant domestic resources and reserves yet show moderate import dependence. In silicon, overall import dependence is low, but India remains almost fully dependent on imported polysilicon for manufacturing crystalline silicon wafers used in solar PV. These mismatches suggest gaps in processing capacity, refining infrastructure and economic viability rather than geological endowment.

Trace and Niche Minerals: Some minerals (e.g., strontium, gallium, indium, tellurium, germanium) have very low projected demand but are critical to specialised applications in solar PV and electronics. With no reported reserves or resources, these minerals will likely need to be secured through strategic imports or as by-products of other mineral processes.

Table 3.1: Comparison of CETM Demand with Remaining Resources[4], Reserves[5] and Import Dependence[6]

	Minerals	Demand 2025-2070 (kt)	Resource[7] (kt)	Reserves[8] (kt)	Import Dependence[9] (%)
1	Copper	66,069	*14,96,979*	*1,63,891*	57
2	Graphite	46,489	2,03,060	8,563	28
3	Silicon	19,538	-	-	100
4	Phosphorous	16,689	2,80,377	30,876	85
5	Nickel	11,543	*1,89,000*	-	100
6	Lithium	5,468	-	-	100
7	Cobalt	1,454	*45,000*	-	100
8	Vanadium	783	*24,633*	-	46
9	REE	668	459	-	100
10	Molybdenum	273	*27,203*	-	100
11	Titanium	124	*4,11,108*	*15,998*	0
12	Tin	118	102	0.97	100
13	Tellurium	52	-	-	-
14	Cadmium	50.45	5.69	-	-

4 Resources refer to the overall presence of a mineral/material within the Earth's crust that may have potential value.

5 Reserves are the portion of the resources that are currently feasible to extract, considering existing legal permissions, available technology, and economic conditions.

6 '—' indicates that the necessary data for a complete assessment are not available.

7 (Committee on Identification of Critical Minerals, 2023)

8 (Committee on Identification of Critical Minerals, 2023)

9 (Chadha, R. et al., 2023)

	Minerals	Demand 2025-2070 (kt)	Resource[7] (kt)	Reserves[8] (kt)	Import Dependence[9] (%)
15	Zirconium	47.79	1,674	669	78
16	Selenium	37.34	-	-	100
17	Indium	20.64	-	-	100
18	Gallium	4.27	-	-	100
19	Tungsten	4.04	144	-	100
20	Niobium	1.87	-	-	100
21	Germanium	1.85	-	-	100
22	PGE	0.30	0.02	-	100
23	Strontium	0.004	-	-	100

This supply-demand snapshot illustrates the urgency of strengthening India's domestic Critical Energy Transition Mineral (CETM) ecosystem through expanded geological exploration, accelerated reserve certification, domestic mineral processing infrastructure, international sourcing partnerships, and expanded circular economy pathways. Without early, coordinated action, India risks future supply bottlenecks that could constrain its clean energy transition goals.

3.2 DOMESTIC CRITICAL MINERAL RESOURCES AND RESERVES

India has vast untapped geological potential and has identified resources for various critical minerals. For example, India has the world's eighth-largest resource of Rare Earth Elements (REEs). However, only a few companies currently mine and process REEs. A similar pattern exists for cobalt and nickel: despite sizeable resources, these have not been converted into mineable reserves, largely due to limited domestic expertise and slow industrial uptake of critical mineral projects.

Three structural factors underpin this underperformance:

1. Inefficient allocation of mineral resources and weak regulatory frameworks, which hinder timely exploration and development.
2. Limited financial resources and shortage of technical expertise to develop deep-seated mineral deposits, which are more complex and capital-intensive.
3. An auction-based allocation system that provides limited incentives for private sector participation in exploration and mining.

By addressing these systemic constraints, India can build capacity to develop domestic reserves of critical minerals, reducing long-term dependence on imports during a period of rapidly rising demand of critical energy transition minerals.

3.3 PROCESSING OF MINERALS IN INDIA

Indian industry has historically demonstrated strong capability in processing bulk minerals such as iron ore, zinc and copper. However, for many critical energy transition minerals, domestic processing capacity remains nonexistent. The key challenges include insufficient economies of scale, low investment in advanced processing technologies, difficulties in securing reliable raw material supplies (domestically and internationally), and weak domestic demand for many processed critical minerals. This lack of demand has discouraged investment in new facilities and hindered the development of an integrated domestic mineral value chain.

India's copper smelting capacity is rapidly expanding, with current installed capacity around 1.03 million tonnes per annum (MTPA). While the country possesses globally competitive smelting and refining assets (the world's second and third largest copper smelters and sixth largest copper refinery), the sector remains limited in terms of participants. Despite this global scale, many smelters operate below full capacity, and in some cases, domestic production has been constrained by regulatory and operational challenges. This has reduced domestic availability and increased reliance on imports, reflecting broader systemic bottlenecks in India's copper sector.

New copper processing capacities are emerging in India, including a major project in the Kutch region with a planned capacity of around 1 Mtpa, expected to be operational in two phases (2025 and 2029). These additions could significantly reduce import dependence for processed copper. However, long-term resilience will depend on a more competitive processing landscape, supported by greater private-sector participation, foreign investment, and the growth of medium-scale enterprises.

A similar situation exists for REE processing. India accounts for 1% of mined and 3% of processed neodymium globally (European Commission. Directorate General for Internal Market, Industry, Entrepreneurship and SMEs., 2023). Currently, only two public sector companies, Indian Rare Earths Limited (IREL) and Kerala Minerals and Metals Limited (KMML) mine and process beach sand monazite in India (Indian Bureau of Mines, 2024b). The private sector's lack of participation has kept India's REE processing potential underutilised. Although the 2023 amendments to the Mines and Minerals (Development and Regulation) Act opened certain REEs for auction, unlocking this potential will require substantial private investment supported by targeted government incentives for advanced processing technologies and the high upfront capital these facilities demand.

Secondary sources of critical minerals end-of-life technologies, e-waste and industrial scrap offer an emerging pathway to reduce dependence on mineral concentrates. Many start-ups are aiming to build domestic capability in battery recycling and materials extraction. For instance, Lohum, founded in 2018, can recycle 2 GWh of end-of-life batteries and reuse 300 MWh annually, and raised USD 54 million in 2024 to scale operations (*Lohum Raises USD 54 Million to Fuel Its Market Expansion–The Economic Times*, 2024). Similarly, Altmin, another new Indian company, has developed domestic lithium-ion cell chemistries and, with support from the International Advanced Research Centre for Powder Metallurgy and New Materials (ARCI), under the Union Ministry of Science and Technology, has established a pilot plant to produce cathode-active material in Hyderabad. These early initiatives illustrate India's growing capability to build secondary supply chains, though substantial scale-up will require continued government support.

While still in early stages, these initiatives demonstrate India's growing capability to build domestic mineral supply chains using secondary resources. Continued government support through funding, partnerships, and incentives will be essential to scale these efforts.

Mineral processing is inherently capital-intensive and carries technological and market risks. Projects are typically financed through a mix of vertical integration by downstream manufacturers, government support and commercial lending (*Financing the Energy Transition – Critical Minerals Processing*, 2023). Each carries limitations, underscoring the need for targeted incentives that attract early investment into critical energy transition mineral (CETM) processing and reduce risk for first movers.

3.4 IMPORT DEPENDENCE – DEEP DIVE OF FIVE CETMs

This section provides a focused analysis of five critical minerals—cobalt, copper, graphite, lithium, and nickel that are central to India's clean energy transition. For each mineral, it examines current import dependence, key supplier countries, market dynamics and price trends, and identifies strategic considerations for supply security.

Cobalt

Between April 2017 and December 2023, India imported cobalt oxide and hydroxide worth USD 61.5 million. In FY2023 alone, imports totalled 445 tonnes from South Africa, 152 tonnes from Belgium, 41 tonnes from China, 34 tonnes from Finland, and 33 tonnes from Tanzania.

Global supply is highly concentrated with 70% of cobalt mining occurring in the Democratic Republic of Congo (DRC), while 70% of refining takes place in China. India's import patterns align with global concentration point as key cobalt refining nations – Finland, Belgium and China – are also the largest exporters of cobalt oxide and hydroxide to India. Factors like EV demand and shifts to alternative battery chemistries also influence the cobalt market.

Copper

India's limited smelting capacity necessitates dependence on countries like Norway and Japan that have mineral extraction and processing capabilities. In FY2023, India imported 359.8 tonnes of copper oxides, with 179 tonnes from Norway, 35 tonnes from the US and 31.8 tonnes from China (Figure 3.1a).

Copper cathode imports in FY2022 totalled 204,951 tonnes, sourced mainly from Japan (172,515 tonnes), Tanzania (22,201 tonnes), the UAE (5,023 tonnes), Mozambique (1,985 tonnes) and Zambia (1,350 tonnes). Despite lacking domestic reserves, Japan leads in cathode exports due to its advanced technology and strong industrial base. In contrast, Congo and Zambia have established mining operations and significant copper reserves, with key refining operations such as the Mopani Copper Mines and the Konkola Copper Mines. Tanzania and Mozambique also leverage their proximity to ports to export cathodes (Figure 3.1b).

Global copper prices have fluctuated due to US-China trade tensions, a strong US dollar in 2018, and later supply disruptions arising from the pandemic and geopolitical events such as the Russia–Ukraine conflict. The shutdown of India's Vedanta smelter in 2018 turned India from a net exporter to a net importer. Despite refined copper production rising 16% between FY2022 and FY2023, imports increased by 180%, highlighting persistent supply gaps and strong demand from renewable energy, EVs and electronics (PTI, 2023).

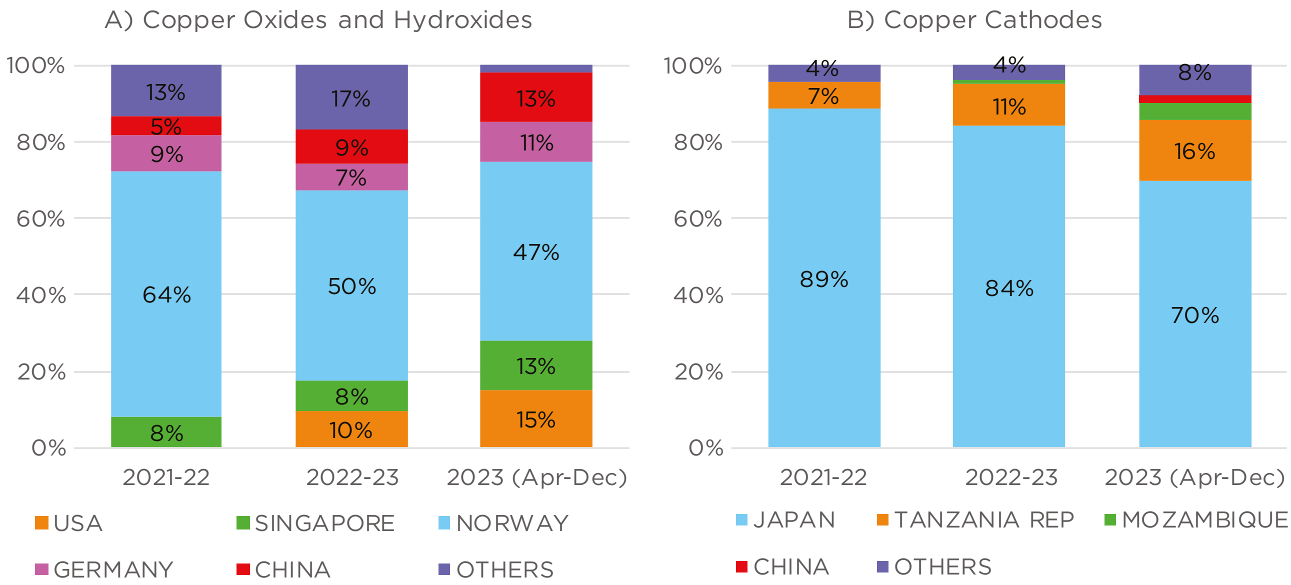


Figure 3.1: Import Dependence of (A) Copper Oxides and Hydroxides and (B) Copper Cathodes

Source: *UN Comtrade*

Graphite

India imports 60% of its graphite demand due to limited domestic production, despite being home to Graphite India, one of the world's largest synthetic graphite-producing companies. From April 2017 to December 2023, natural and synthetic graphite imports to India totalled USD 1.8 billion.

Natural graphite imports in FY2023 included 20,471 tonnes from China, 12,418 tonnes from Madagascar, 8,525 tonnes from Mozambique, 1,500 tonnes from Tanzania and 288 tonnes from Austria. Globally, Mozambique, Madagascar, Brazil, and Tanzania are major producers of natural graphite and present opportunities for South-South trade partnerships (Figure 3.2a).

The same year, India's synthetic graphite imports were dominated by China at 41,661 tonnes, followed by 1,316 tonnes from Germany, 812 tonnes from Malaysia, 660 tonnes from South Africa, and 451 tonnes from Japan. Some of the world's largest synthetic graphite producing companies are in China, USA, Japan and Germany. Since 2021, China has prioritised synthetic graphite production, which offers superior battery anode performance, and imposed export permits requirements for high- grade materials (Figure 3.2b).

China's export curbs, linked to national security concerns, coincide with US and Dutch restrictions on semiconductor-related exports to China. This opens up opportunities for India to position itself as a key trade partner for markets looking to diversify their graphite supply chain.

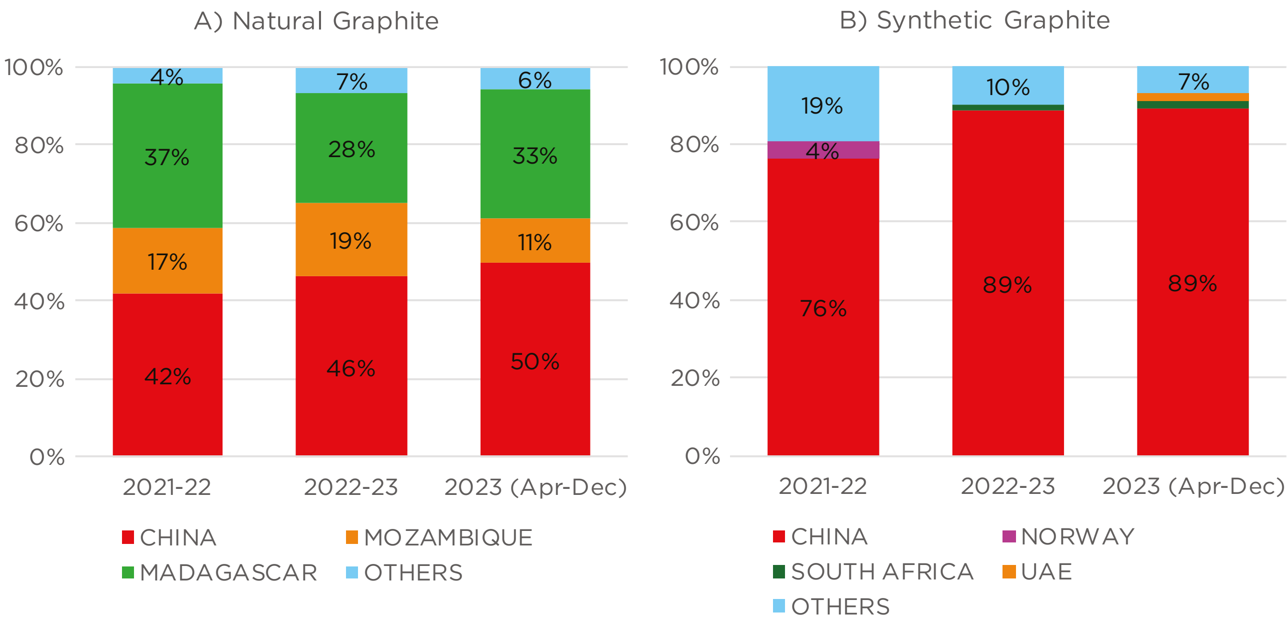


Figure 3.2: Import Dependence of (A) Natural Graphite and (B) Synthetic Graphite

Source: *UN Comtrade*

Lithium

India does not currently produce lithium and relies entirely on imports of lithium battery chemicals. Between April 2017 and December 2023, total imports of lithium compounds—including lithium-ion cells, lithium carbonate, and lithium oxides and hydroxides—amounted to USD 11.9 billion. However, an estimated 5.9 Mt of lithium resources were discovered in Jammu & Kashmir in February 2023 (ANI, 2023).

In FY2023, India imported lithium carbonate primarily from the Netherlands (400 tonnes), Belgium (227 tonnes), Ireland (200 tonnes), the US (75 tonnes) and Argentina (43 tonnes). Lithium oxides and hydroxides in FY2023 came mainly from Belgium (537 tonnes), followed by Russia (186 tonnes), the UAE (156 tonnes), Singapore (60 tonnes), and China (51 tonnes) (Figure 3.3).

Global lithium markets remain highly volatile due to the concentration of refining capacity (around 60% in China) as well as fluctuations in EV demand, pandemic-related disruptions and supply shocks.

India is gradually trying to diversify its import partners, and the Minerals Security Partnership (MSP) is expected to foster collaboration with other countries for lithium trade.

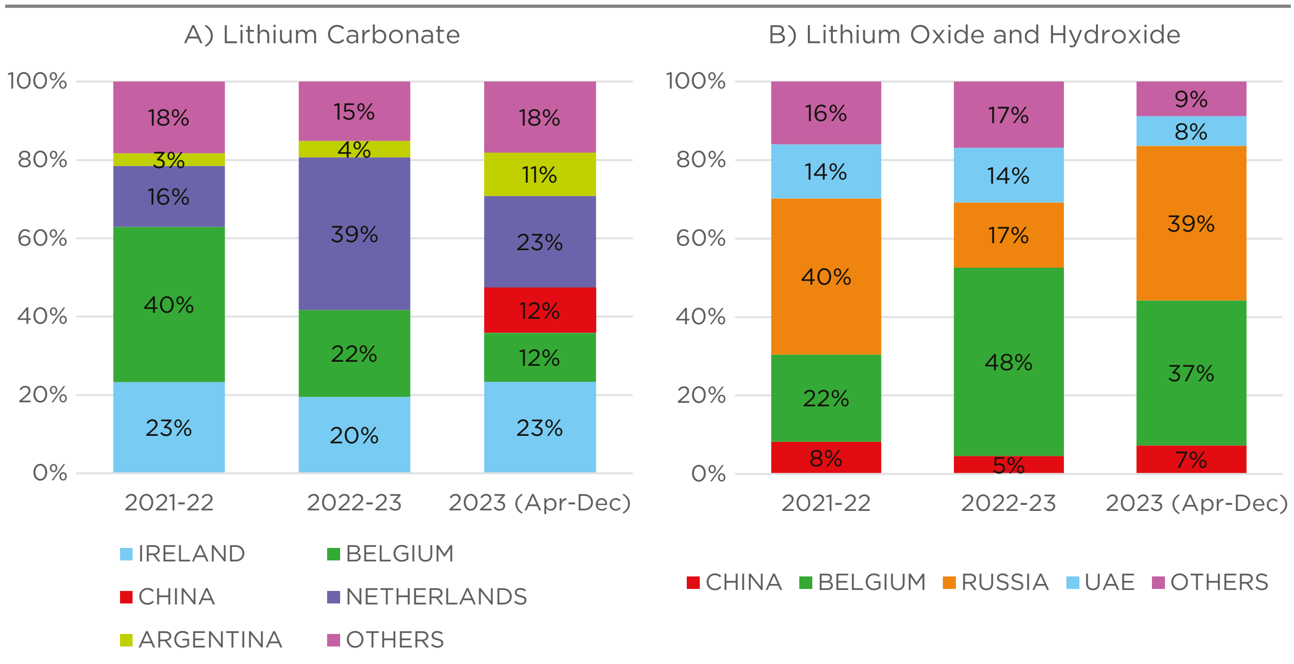


Figure 3.3: Import Dependence of (A) Lithium Carbonate and (B) Lithium Oxides and Hydroxides

Source: *UN Comtrade*

Nickel

Despite having an estimated 189 million tonnes of nickel reserves, India relies entirely on imports for renewable energy applications. Between April 2017 and December 2023, nickel compound imports totalled approximately USD 590 million.

India imports nickel and its compounds from China, Australia, the US, Finland, Sweden, the Philippines and South Africa. Australia has emerged as the dominant exporter due to the Australia-India Economic Cooperation and Trade Agreement signed in 2022. In FY2023, nickel oxides and hydroxides were primarily imported from Australia (1,760 tonnes), followed by Sweden (233 tonnes), China (142 tonnes), Belgium (58 tonnes) and Japan (42 tonnes). Nickel sulphate imports were heavily concentrated in Belgium (1,108 tonnes) and Japan (444 tonnes), with smaller quantities sourced from South Africa (121 tonnes), Singapore (9.6 tonnes) and China (6.6 tonnes) (Figure 3.4).

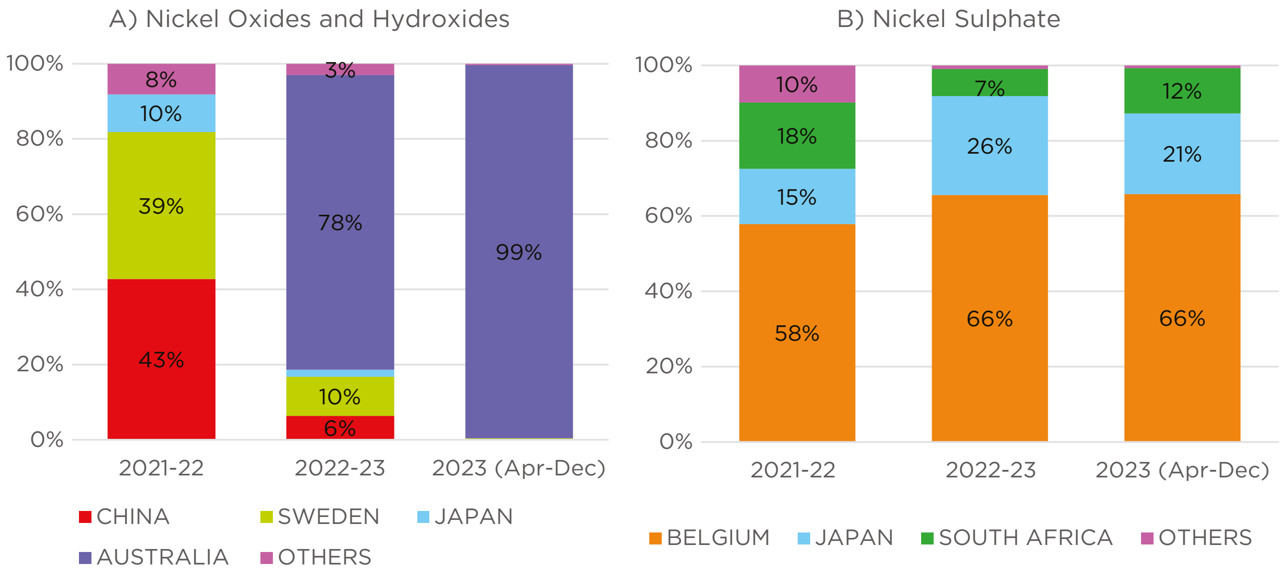


Figure 3.4: Import Dependence of (A) Nickel Oxides and Hydroxides and (B) Nickel Sulphate

Source: *UN Comtrade*

Belgium and Japan account for over 85% of India's nickel sulphate imports. These countries have well-developed metallurgical and refining industries, producing high-quality nickel sulphate that meets international standards. Belgium-headquartered company Umicore has made advancements in producing and supplying nickel sulphate.

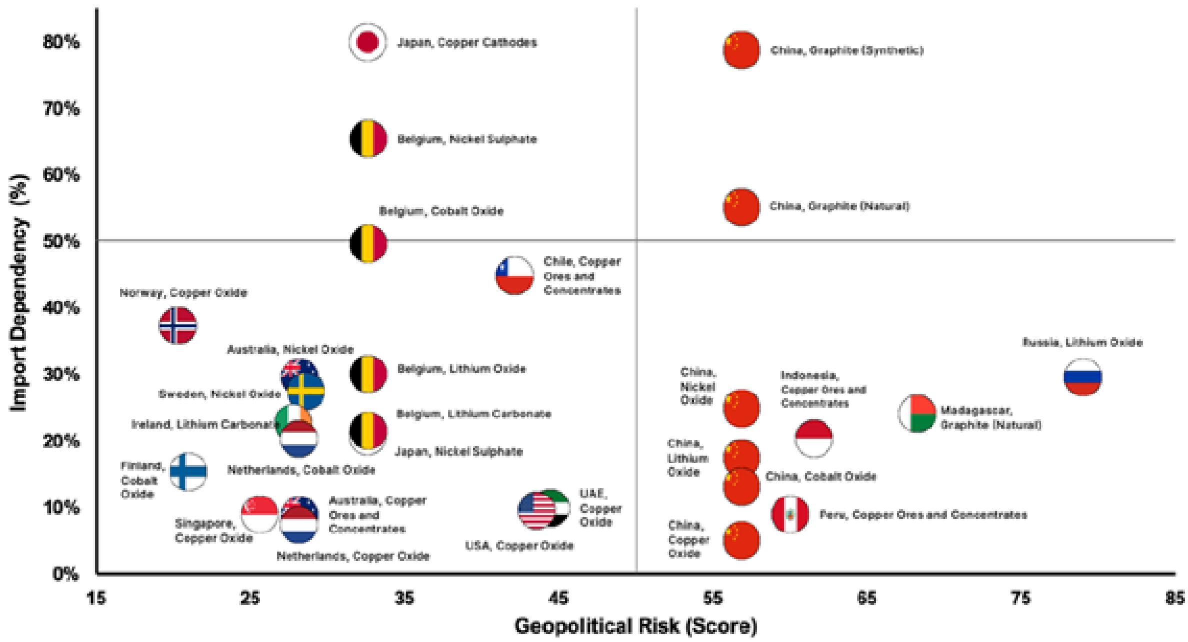
Nickel markets have experienced significant volatility due to pandemic disruptions, sanctions related to the Russia-Ukraine conflict. Key market drivers include demand from EV manufacturing and battery cathode production in China, while South Korea, Japan and the Philippines play pivotal roles in global partnerships. As battery demand increases, opportunities emerge for India to build domestic refining and processing capacity to reduce import dependence.

3.5 IMPORT DEPENDENCE AND GEOPOLITICAL RISKS

High import dependence, particularly from geopolitically sensitive regions, poses significant risks to supply-chain resilience. To inform strategic planning and policy responses, this section analyses India's import exposure for key critical minerals, combining trade flow data with country-level geopolitical risk assessments.

Figure 3.5 maps key CETMs, namely cobalt, lithium, nickel, graphite, copper, and their compounds, based on India's import dependency (Y-axis) and geopolitical risks associated with the source country (X-axis). Import dependence is calculated using Harmonised System (HS) Code-based trade flow data analysis, averaging 75% of total imports between FY2019 and FY2023 to stabilise trends. Geopolitical risk levels are derived from two global studies—the Fragile States Index (Fund for Peace, 2024) and Risk Map (Control Risks, 2024), which factor in social, political, economic, security, operational, and environmental risks, including geopolitical tensions, conflicts, cyber threats, corruption and climate impacts.

The graph also highlights critical vulnerabilities in India's mineral supply chains to geopolitical risks. Graphite (natural and synthetic) is the mineral that ranks highest because of a combination of high import dependence and high geopolitical risk with respect to China. The figure also illustrates high reliance on Japan for copper cathodes and Belgium for nickel sulphate. Although India shares a stable and friendly relationship with both these countries, the high single-country reliance for specific materials exposes the country to supply chain vulnerabilities in case of natural disasters, pandemics, infrastructure failures, or unforeseen circumstances.



Source: UN Comtrade, Control Risks, Fragile States Index, IEEFA

Figure 3.5: India's Import Dependency of Key Minerals vs. Geopolitical Risk

3.6 VULNERABILITIES OF THE GLOBAL CRITICAL MINERAL SUPPLY CHAINS

Bottlenecks in global supply chains can significantly constrain India's access to critical energy transition minerals. Disruptions—whether arising from policy shifts, geopolitical tensions, or market dynamics have a direct bearing on mineral availability, prices and security of supply. Regulatory actions and corporate strategies in major producing regions have further increased barriers to the free flow of critical minerals. Five key challenges stand out:

1. Foreign Ownership of Assets

Many new mining projects globally are owned by foreign companies that have secured mining rights through strategic investments. Critical minerals are often deep-seated and require large capital for mineral development. Hence, foreign investments have helped unlock production in resource-rich, but capital-poor regions. However, high levels of foreign control can limit domestic value addition in the host country, particularly by reinforcing the export of unprocessed minerals and the underdevelopment of downstream industries. Notably, Chinese public and private companies have been the largest investors in overseas mineral assets. Despite the country's limited domestic production of minerals such as lithium and cobalt, these overseas stakes provide steady access to mineral concentrates and reinforcing China's dominance in mineral processing (Leruth et al., 2022).

2. Export Restrictions

Export restrictions on CETMs have increased fivefold over the last decade (Przemyslaw Kowalski & Clarisse Legendre, 2023). Several countries use such restrictions to promote domestic processing and manufacturing industries. Indonesia and China, two of the largest CETM producers, have placed export restrictions on mineral concentrates to boost domestic mineral processing capacity. Others, such as Bolivia (2008) and Mexico (2017), nationalised lithium mining to increase state oversight. China's export controls have been particularly influential, including a 2010 restriction on Rare Earth Elements (REEs) to Japan and the 2024 restriction on antimony, gallium, and germanium to the United States. Such actions underscore the risk of reliance on single-country suppliers, particularly during periods of geopolitical tensions.

3. Supply Chain Contracts

Long-term mineral supply agreements, including offtake contracts, are widely used to secure access to critical minerals. These arrangements provide producers with financial certainty and buyers with a guaranteed supply. For example, China's CITIC Metal combined equity investments with an offtake agreement when acquiring a 26.5% stake in Peru's Las Bambas copper mine (MMG Limited, 2016). Similar strategies are used globally, including by OEMs such as Tesla, Mercedes-Benz, and BMW, which have entered upstream supply contracts for EV raw materials. While beneficial to participating firms, such agreements limit market access for late entrants and reduce liquidity in the spot market, restricting opportunities for new industries to procure minerals.

4. Price Fluctuations

Critical Energy Transition Minerals (CETMs) exhibit high price volatility driven by changes in demand, geopolitical events and structural shifts in the energy sector (International Energy Agency, 2024) which are essential for a range of clean energy technologies, have risen up the policy agenda in recent years due to increasing demand, volatile price movements, supply chain bottlenecks and geopolitical concerns. The dynamic nature of the market necessitates greater transparency and reliable information to facilitate informed decision-making, as underscored by the request from Group of Seven (G7. In 2023 alone, lithium prices fell by around 75%, while nickel, cobalt, manganese and graphite recorded declines of 30–45%. These swings create uncertainty for manufacturers who face rising input costs when prices increase and for miners, whose project viability declines sharply when prices fall. Reduced project returns make financing difficult, and several large mining operations in Australia slowed production in early 2024 due to depressed lithium prices (Angelica Garcia & Eri Silva, 2024). Price uncertainty is therefore a persistent structural challenge across CETM supply chains

5. Social and Environmental Vulnerabilities

Growing demand for Critical Energy Transition Minerals (CETMs) intensifies social and environmental pressures in major mining and processing regions. Mining operations in countries such as the Democratic Republic of Congo (DRC), Chile and Indonesia have been associated with deforestation, water stress, contamination and biodiversity loss. For instance, lithium extraction in Chile's Salar de Atacama consumes substantial amounts of water, exacerbating drought conditions and impacting Indigenous communities reliant on these water sources

2025). Similarly, nickel mining in Indonesia has contributed to deforestation and heavy-metal pollution, harming local ecosystems and communities (Sawal, 2022).

Social risks are similarly severe. Extraction in several regions is linked to human rights violations, including child labour, unsafe working conditions and displacement of Indigenous communities. Artisanal cobalt mining in the DRC has been particularly associated with hazardous work conditions and child labour (Cao et al., 2024)social and economic sustainability risks of cobalt mining, particularly artisanal and small-scale mining (ASM). In many cases, projects have proceeded without obtaining Free, Prior and Informed Consent (FPIC), leading to community conflict and social unrest. Addressing these vulnerabilities requires robust enforcement of environmental and labour standards, adoption of responsible mining and processing practices and sustained engagement with affected communities across the project lifecycle (UN Secretary General's Panel on Critical Energy Transition Minerals, 2024).

3.7 PROCUREMENT OF CETMS FOR DOMESTIC DEMAND

A stable supply of locally sourced raw materials can play a critical role in reducing India's import dependence. The government has introduced several Performance-Linked Incentive (PLI) schemes to promote domestic manufacturing of green technologies and related products. The solar PV module PLI, launched in 2021 with an initial outlay of INR 4,500 crore, aims to strengthen domestic capacity in the solar sector. Similarly, the PLI for the Automobile and Auto Component industry (INR 25,983 crore) and the PLI for Advanced Chemistry Cells (ACC) and battery storage (INR 18,100 crore) are designed to accelerate domestic production of EVs and battery technologies.

These initiatives have had a large budget outlay and have been effective in incentivising domestic manufacturers to increase their investments in green technologies. However, they have not been effective in growing the upstream sectors for mining and mineral processing in India. For PLI schemes in downstream manufacturing to meaningfully support upstream development, stronger domestic procurement requirements will be necessary. Alternatively, dedicated PLI-like mechanisms could be introduced specifically for mining, mineral processing and refining, attached to specific grades like for battery grade nickel, lithium, graphite etc., thereby strengthening the critical energy transition mineral value chain separately.

3.8 DISCUSSION OF FINDINGS

India's clean-energy transition faces significant risks arising from vulnerabilities in its mineral supply chains. Demand for Critical Energy Transition Minerals (CETMs) such as copper, lithium, cobalt, and nickel is projected to rise sharply, yet India remains heavily import-dependent due to limited reserves, underdeveloped processing capacity and low private-sector participation. Although the country has substantial geological resources, these remain largely untapped because of regulatory constraints, financial barriers and gaps in technical capability.

Geographical concentration of imports, especially from China, for several high-risk minerals, intensifies exposure to geopolitical disruptions. India needs to leverage differentiated strategies by mineral dependency quadrant, as outlined in the mineral dependency-risk matrix section.

Some specific strategies, based on the analysis includes:

i. **High dependency:** For natural/synthetic graphite, diversify toward Mozambique, Madagascar, Brazil, Tanzania, and explore cooperation with Minerals Security Partnership (MSP) members like Germany, Norway, and Canada.

ii. **High single-country reliance:** For copper cathodes and nickel sulphate, build domestic refining capacity in JV mode with Japanese partners (e.g., JX Nippon, Mitsubishi Materials), and explore alternative suppliers like the US.

iii. **Moderate dependency:** For lithium oxide and nickel oxide, build domestic refining capacity and seeking alternate import sources in South America, Australia, and Africa.

Global vulnerabilities such as export restrictions, long-term supply contracts that limit market access, and environmental, social and governance risks in major mining regions further compound supply insecurity. Addressing these risks will require sustained efforts to accelerate exploration and reserve certification, expand domestic processing and refining capacity, diversify international sourcing, and strengthen environmental safeguards and social-licence mechanisms across the entire value chain.

4

EXISTING POLICIES TO ENHANCE ACCESS TO CRITICAL MINERAL

Existing Policies to Enhance Access to Critical Mineral

4

India's growing demand for critical minerals has prompted a set of policy interventions to strengthen domestic exploration, production, and processing capabilities, Recognising the strategic importance of these minerals, the government has introduced reforms across the legislative, regulatory, and institutional landscape most notably through amendments to the Mines and Minerals (Development and Regulation) Act, 1957 (MMDR, 1957). This section reviews key policies and institutional mechanisms designed to enhance access to critical minerals, with a focus on improving mineral licensing, incentivising exploration, enabling transparent auctions, addressing post-lease challenges, and supporting international partnerships and trade strategies.

4.1 ALLOCATION OF MINERAL LICENSES

The Mines and Minerals (Development and Regulation) Act, 1957 was overhauled in 2015 to replace the *First Come First Serve (FCFS)*[10] system with competitive auctions for mineral concessions. The Act aimed to enhance transparency and reduce discretion. Further amendments in 2019, 2021, and 2023 streamlined regulations and introduced mechanisms like the District Mineral Foundation (DMF) to provide for the welfare of mining-affected communities and the National Mineral Exploration Trust (NMET) to encourage exploration.

From 2015 to 2024, 554 mineral blocks were successfully auctioned, but operationalisation has since lagged, with only 66 mines reaching the production state as of 9th August 2025. Several more are expected to commence production within the 2025-2026 financial year, with an ambitious target of 55 additional mines being operationalised in the next three quarters. However, an emerging concern from the auctions is that in certain cases, the winning bids exceeded 100% of the mineral's assessed value. Such aggressive bidding carries the risk of inflating downstream metal costs, which could impact overall sectoral competitiveness.

In 2023, critical and strategic minerals were added to the MMDR framework, and the government launched specific auctions to secure domestic supply chains for manufacturing advanced technologies, including low-carbon technologies. The first tranche of the critical mineral auctions was launched in November 2023. By July 2025, five auction tranches had been conducted, with 34 out of 55 unique blocks being successfully bid out (Table 4.1). With 15 blocks of these 34, graphite accounted for the largest share.

10 The FCFS system is the most commonly used mechanism to allocate mineral concessions globally and typically comes with safeguards in place to ensure that leases are granted fairly

Table 4.1: Results of Auctions for Critical Mineral Blocks

Summary	Tranche 1	Tranche 2	Tranche 3	Tranche 4	Tranche 5
Total Blocks	20	18	7	21	15
Fresh blocks	20	18	0	10	7
Reauctioned blocks	0	0	7	11	8
Mining Leases	4	1	0	1	1
Composite Licences	16	17	7	20	14
Preferred bidder announced	6	4	4	10	10
Fewer than 3 Technically Qualified Bidders (TQB)	12	9	3	7	2
No bids	2	5	0	4	3

As with the allocation of onshore mineral blocks, the Offshore Areas Mineral (Development and Regulation) Act, 2002, was amended to introduce auctions to allocate rights in offshore areas. India's exclusive maritime economic zone extends around 2 million km^2 and holds resources of construction and metallic minerals. The first tranche of 13 offshore mineral block was auctioned in November 2024 and consisted of lime mud, construction sand, and polymetallic nodules. While seabed mining provides a significant mineral inventory, its environmental impacts have not yet been fully understood.

4.2 INCENTIVISING EXPLORATION

Exploration is the first stage in the lifecycle of a mining project. It is a capital intensive and high-risk activity, demanding significant time, financial investment, technical equipment, and specialised skills. Globally, only around 1% of exploration projects fructify into an operational mine. This risk is often borne by small exploration focused companies–commonly called junior explorers–who aim to discover promising mineral assets and subsequently sell the rights to larger mining companies, using the proceeds to offset unsuccessful ventures.

Public institutions, like the Geological Survey of India (GSI), have historically conducted early-stage exploration, including baseline reconnaissance and regional geological mapping. Their primary role is to generate national-scale geoscientific datasets and improve transparency in subsurface information. These activities focus on broad coverage and data creation, rather than discovery-oriented exploration.

However, the increasing strategic importance of Critical Energy Transition Minerals (CETMs) highlights the limitations of an exploration ecosystem dominated by public agencies beyond baseline geoscience. Reconnaissance and early prospecting for CETMs, especially deep-seated or by-product-driven mineralisation, require iterative field investigation, rapid progression from regional signals to prospect-scale testing, and risk-tolerant capital. These attributes are difficult to sustain within institutions whose mandates prioritise broad geographic coverage, standardised survey programmes, and non-commercial objectives.

Following the transition to the auction-based allocation regime in 2015, a 'non-exclusive reconnaissance permit' was introduced to facilitate exploration. However, uptake was limited as the permit neither provided exploration companies with the right to mine nor to transfer the rights of the discovered assets.

To further support exploration, National Mineral Exploration Trust (NMET) was established, funded by a 2% royalty contribution from mining companies. The 2021 amendments enabled Notified Exploration Agencies (NEA) accredited by QCI-NABET to receive NMET funding. As of January 2024, the NMET sanctioned INR 2,695 crore to 471 exploration-related projects. However, only around 2% of the funding was allocated to private explorers, with the rest going to public sector companies. Of the 471 projects, 244 have been completed, while the remaining are ongoing. Most are at the G3 or G4 stages of exploration (i.e., early stages of exploration). Around 30% of the projects focus on critical minerals, while the remaining target bulk minerals like iron ore, coal, and bauxite.

In 2023, further amendments to the MMDR Act introduced a new concession–the Exploration Licenses (ELs), to promote the exploration of deep-seated and critical minerals. ELs, awarded through auctions, may be based on an area suggested by any interested party. A key concern is that exploration companies will receive revenue for their work only after a successfully discovered resource is auctioned and developed, an outcome that takes years to materialise, if at all (Chadha et al., 2023). Additionally, they are only entitled to a share of the final auction premium, the value of which remains unknown at exploration. Unlike in other jurisdictions, EL in India does not grant the exploration company a right to mine, weakening the incentive for private participation.

Since its introduction in 2023, several states unsuccessfully attempted to auction Exploration Licenses (ELs). Subsequently, in late 2024, the centre took on the role of issuing EL auctions. Of the 13 blocks auctioned under Tranche-1 in March 2025 (encompassing 10 states for 8 mineral commodities), only 7 were successfully concluded. These outcomes underline the persistence of discovery-stage constraints and the limited appetite for exploration under current risk-reward structures.

International experience suggests that effective exploration ecosystems clearly differentiate between foundational geoscience and risk-bearing discovery activity. Public agencies focus on high-quality baseline surveys, modern geophysical datasets, and open-access geoscience platforms. Private explorers operating under regulatory oversight and environmental and social safeguards, and undertake reconnaissance-to-prospecting activities that convert geological information into discoveries. These private explorers are typically incentivised by the ability to internalise discovery upside through transferable exploration rights, time-bound progression to subsequent licence stages, and clear pathways to monetise successful discoveries through asset sales, partnerships, or downstream development. Such sequencing strengthens the entire exploration-to-mining pipeline and improves auction outcomes by ensuring that allocated blocks are supported by credible geological intelligence, thereby reducing non-participation and speculative bidding (S Vijay Kumar, 2019).

Incentivising the exploration of critical energy transition minerals requires recalibrating the balance between public and private roles at the early stages of the exploration lifecycle. Public institutions such as GSI should continue to anchor national geoscience programmes and data systems. Reconnaissance and prospecting activities should increasingly enable private participation through transparent, time-bound licensing frameworks that better align discovery incentives with downstream allocation mechanisms.

4.3 ACCESSING CREDIBLE EXPLORATION DATA

Ministry of Mines in 2023 launched the National Geoscience Data Portal (NGDR) to foster innovation in exploration. NGDR is a comprehensive online platform for accessing, sharing, and analysing geospatial information across the nation.

However, India's critical mineral exploration challenge is also one of data quality and usability, not just data volume. While substantial geological surveys and mapping have been undertaken by the Geological Survey of India (GSI), and is scientifically credible, much of this information is not generated, classified, or disclosed in formats that enable investors to make bankable project decisions.

Experts and industry highlight (Aggam Walia, 2024; A Vijay Kumar, 2019) that India's reporting still leans on legacy United Nations Framework Classification for Resources (UNFC) style classifications and heterogeneous reporting standards, which do not consistently incorporate economic viability, confidence levels, and competent-person sign-off. These elements are required by reporting codes such as Committee for Mineral Reserves International Reporting Standards (CRIRSCO) or Joint Ore Reserve Committee (JORC) developed by Australia, or the proposed Indian Mineral Industry Code (IMIC) (*NACRI – Mining Engineers' Association of India*, 2022) developed by Indian experts.

This weak alignment with investor-oriented reporting frameworks reduces confidence in stated resources and reserve estimates, leading private and foreign investors to discount or re-do state-generated geological work before committing capital.

4.4 POST-LEASE CLEARANCES

Before commencing mining operations, leaseholders must obtain four primary clearances: Forest Clearance (FC), Environmental Clearance (EC), Wildlife Clearance (WLC), and Consent to Operate (CTO). While EC and CTO are mandatory for all projects, FC and WLC apply only when forest and wildlife are involved. These clearances are issued by authorities at various governance levels and are regulated by the Ministry of Environment, Forests, and Climate Change (MOEFCC). Often, these clearances face delays and backlogs despite a statutory 420-day deadline. For instance, it took over five years for the Ghoraburhani-Sagasahi iron ore mine in Sundargarh, Odisha to operationalise in 2021. Until 2023, it was the only virgin mine to have operationalised in Odisha among the 48 blocks successfully auctioned out in 2016.

A study of Jharkhand, Karnataka, and Odisha found that the greatest delays occurred at the Environmental Clearance (EC) and the Forest Clearance (FC) stages, with Odisha recording the highest number of pending applications beyond the statutory period (Bansal, K. & Kapoor, I., 2022). Streamlining these processes is essential to reduce investor uncertainty. It is as important to have high and strictly enforced standards to issue clearance, as it is to ensure that application processes are concluded within the prescribed timeline.

4.5 NATIONAL CRITICAL MINERAL MISSION

In January 2025, the Union Cabinet approved the National Critical Mineral Mission (NCMM) with a total outlay of INR 34,300 crore to strengthen India's critical mineral supply chain and support exploration, processing and value-chain development. It has a direct expenditure of INR 16,300 crore from 2024–25 to 2030–31, including a budgetary support of INR 2,600 crore, and aligned expenditure from PSUs at INR 18,000 crore (Ministry of Mines, 2025). The mission aims to increase mineral sector efficiencies through integration and collaboration between various government bodies and other stakeholders under one mission. Its focus is to increase domestic production and recycling of minerals, along with facilitating the acquisition of critical mineral assets abroad. The mission will facilitate trade, research, and technological advancement in the mineral sector by developing strong financial incentives for greater participation from the private sector.

The National Critical Mineral Mission (NCMM) is a necessary policy initiative that has the potential to help shape the future of India's critical mineral landscape. However, some challenges may directly impact the outcomes of the mission. Vulnerabilities in global supply chains due to restrictions on mineral exports have increased the barriers for highly import-dependent countries to access mineral concentrates. New entrants also have to content with the dominance of Chinese players in the global critical mineral supply chains, which is underpinned by their equity stakes in operational mines and long-term offtake agreements with mine owners. Securing India's critical mineral supply chains would require the use of other policy tools, such as trade and fiscal policies, to support the NCMM in achieving its desired objective.

4.6 PUBLIC SECTOR UNDERTAKINGS (PSUS) IN INDIA'S CRITICAL MINERALS STRATEGY

PSUs continue to play an important role in India's mineral sector, particularly in large-scale mining, mineral processing, and overseas asset acquisition. In recent years, several PSUs have either been assigned mandates or have independently initiated activities related to critical minerals, reflecting the growing strategic importance of these materials for India's energy transition and industrial competitiveness.

Examples include Coal India Limited's engagement in lithium exploration and overseas critical mineral initiatives (Shivam Prakash, 2025) NMDC's established technical and financial capacity in large-scale mining and stated interest in diversification beyond iron ore (www.ETAuto.com); and Indian Rare Earths Limited's specialised capabilities in rare earth mining, separation, and processing. Collectively, these entities represent significant public-sector capability relevant to the exploration, mining, and processing of Critical Energy Transition Minerals (CETMs).

Table 4.2: Recent PSU Activity on CETMs

PSU	Administrative Ministry	CETM-relevant activity
Coal India	Ministry of Coal	Lithium exploration (Argentina), critical minerals JV discussions, diversification mandate
NMDC	Ministry of Steel	Geological exploration capability, iron-ore core, stated interest in diversification and critical minerals
IREL	Atomic Energy	REE mining, separation, processing; technical monopoly in certain REE streams
KABIL	Ministry of Mines	Overseas asset acquisition mandate

At present, however, these capabilities are distributed across multiple administrative ministries (see table 4.2), reflecting historical sectoral mandates rather than a unified critical minerals strategy, resulting in institutional fragmentation and mandate misalignment across the critical minerals ecosystem. While statutory responsibility for critical and strategic minerals increasingly rests with the Ministry of Mines under the MMDR framework, operational capabilities relevant to CETMs remain institutionally fragmented.

As CETMs transition from niche inputs to system-critical materials underpinning clean energy technologies, advanced manufacturing, and industrial policy, this fragmentation creates coordination and execution risks. This can materialise in practice through delayed decision-making, duplication of exploratory or feasibility efforts across agencies, and weak accountability for outcomes along the exploration-to-mining pipeline. Dispersed administrative control can slow decision-making, dilute accountability for exploration and mining outcomes, and limit the ability to deploy public sector capacity in a mission-oriented manner aligned with national priorities.

The emerging policy challenge is therefore not the absence of public sector capability, but the effective alignment and mobilisation of these capabilities within the mining policy ecosystem. Addressing this challenge is central to strengthening domestic exploration and mining outcomes for CETMs and ensuring that public sector assets contribute coherently to India's long-term critical minerals strategy.

4.7 INTERNATIONAL STRATEGIES

Recognising that several critical minerals essential for the energy transition either are not found in India or are present only in limited or non-viable quantities, the Government of India has taken proactive steps to secure overseas supplies through the following measures:

1. **Established Khanij Bidesh India Limited (KABIL)**: A joint venture public sector company with the mandate to identify and acquire overseas critical mineral assets. It has signed an agreement for lithium exploration and mining in Argentina (India Signs Agreement for Lithium Exploration & Mining Project in Argentina).
2. **Elimination of Import Duties on Critical Minerals**: In the 2024–25 Union Budget, India fully exempted 25 critical minerals from customs duties. This includes lithium, cobalt, copper, and REEs, and several types of waste material containing these minerals (Law, 2025).
3. **Deepened International Ties around Minerals:** India has significantly strengthened international partnerships to secure reliable and diversified sources of critical minerals. It is an active participant in the Quadrilateral Security Dialogue (QUAD) and the broader Minerals Security Partnership (MSP), both of which aim to build resilient, transparent, and sustainable mineral supply chains. Bilateral collaborations have also advanced, including the India-Australia Critical Minerals Investment Partnership targeting joint investments in five lithium and cobalt projects (PIB, 2023), and a 2024 India-U.S. Memorandum of Understanding (MoU) focused on cooperation in exploration, processing, and recycling of key minerals (PIB, 2024).

4. **NCMM's international initiatives:**

   Stockpile Programme: A joint initiative between central PSUs or with private companies shall be institutionalised to develop a National Critical Mineral Stockpile Programme to guard against supply disruptions and aid mineral supply for domestic utilisation. To develop the National Critical Minerals Stockpile/Reserves, the government has allocated INR 500 crore during the Mission period for this purpose.

   Exploration: In addition, the Mission will spend INR 1,600 crore up to FY2031, to support critical minerals exploration activities outside India. To encourage the participation of Indian public (Central & State) and private sector companies in the acquisition of assets abroad, the government has plans to incentivise mining and set up evacuation infrastructure with financial outlay of INR 4,000 crore under the NCMM. In the private sector, some Indian companies have invested in mines in Africa, signalling growing interest in business-led global resource partnerships.

Critical Role of Khanij Bidesh India Limited (KABIL)

KABIL has a central responsibility in India's strategy to secure long-term, diversified sources of CETMs and reduce reliance on a concentrated global supply chain. Its mandate places it at the forefront of India's international engagements on critical-minerals, making it a key instrument for translating strategic objectives into tangible overseas partnerships and investments.

Currently, KABIL's activities are concentrated in early-stage international engagements, including memoranda of understanding and preliminary project assessments, and initial collaborations. These foundation efforts are essential steps in building India's presence in global critical mineral markets, though the scale of ongoing activity is relatively limited compared with the breadth of responsibilities it holds. Its current bandwidth, particularly in areas such as project development, risk assessment, and operational follow-through, is still evolving.

KABIL can draw valuable lessons from the Indian overseas public sector enterprises in other sectors, such as energy, which have developed strong in-house capabilities in geological evaluation, project finance, host-government engagement, and asset operations across diverse international contexts. Leveraging such experience can help KABIL progressively strengthen its institutional depth, execution capacity and project development expertise.

This is essential for reducing import risk and translating India's international critical minerals strategy from intent to delivery.

4.8 MINERAL MARKETS

The MMDR Amendment Act, 2025, incorporates a provision to empower the Central Government to promote the development of markets, including trading of minerals, their concentrates or processed forms (including metals) through mineral exchanges. The Government could nominate a authority to register and regulate mineral exchanges and prescribe rules to regulate various aspects and activities of such exchanges and related matters.

Efficient trading exchanges will help both mining companies and end-users of minerals to better determine and predict prices, aiding in budgeting and planning, stabilising markets, and absorbing shocks and disruptions. Enhanced trade also stimulates storage, transport, and logistics facilities. The mineral trading exchanges will also help determine fair market prices based on supply and demand dynamics. This may further help state governments in realising fair revenue share.

4.9 DISCUSSION OF FINDINGS

India has undertaken significant legislative and institutional reforms to enhance access to critical minerals. The transition to auction-based mineral allocation and the creation of mechanisms like District Mineral Foundation (DMF) and National Mineral Exploration Trust (NMET) have increased transparency and funding for exploration. Internationally, India has adopted a proactive approach through initiatives like Khanij Bidesh India Limited (KABIL), tariff reductions, strategic partnerships under Quadrilateral Security Dialogue (QUAD) and Minerals Security Partnership (MSP). The launch of the National Critical Mineral Mission (NCMM) in early 2025 further consolidates these efforts under a unified institutional framework, with dedicated funding to drive domestic exploration, recycling, and overseas asset acquisition.

Despite this progress, persistent operational and structural constraints continue to limit outcomes on the ground. Actual mine operationalisation remains slow, and exploration continues to be dominated by public agencies, with limited private participation due to unresolved commercial risks. High royalty and tax burdens, coupled with procedural delays in post-lease clearances, further deter investment. As a result, while the policy architecture reflects a strategic pivot towards supply security and global integration, realising its full potential will require parallel domestic reforms that streamline approvals, de-risk private exploration, and enable sustained, long-term investment across the value chain.

Long and uncertain pathways from exploration to production

India's current exploration and licensing framework relies heavily on auction-based allocation even at early stages, where geological confidence is low and competitive interest is limited. In such contexts, auction-based allocation can inadvertently delay exploration and mine development, resulting in no realised economic value.

International experience across major mining jurisdictions demonstrates that early-stage exploration for critical and strategic minerals is most effectively driven by specialised junior explorers operating under predictable, low-friction licensing regimes. Competitive allocation mechanisms are introduced only once geological confidence and project viability are established. This staged approach, followed in Australia, Canada, Latin America and Africa, combines non-auctioned access for early discovery with competitive allocation once resources are delineated and commercial interest is demonstrably high (uncommon in critical minerals).

While auctions are effective instruments once geological confidence and competition are established, undiscovered or undeveloped resources generate no royalty, tax or downstream economic activity. Earlier discovery and production enable sustained public revenues over the life of the resource through royalties, corporate taxation, GST from processing, employment generation and reduced import dependence, often exceeding one-time auction receipts. From a public-finance perspective, enabling discovery and development is therefore a prerequisite for meaningful revenue realisation when it comes to critical minerals. Moreover, in the context of strategic and critical minerals, the acute supply vulnerability, national security relevance, and time-sensitive industrial policy objectives, the state may prioritise speed and certainty over price discovery, subject to adequate safeguards.

Persistent geological uncertainty and exploration risk

Geological uncertainty remains elevated even in areas that have been surveyed, and that without more credible, standardised and accessible data, reforms to licensing, auctions, or exploration incentives alone will not substantially lower riskadjusted cost of capital for private and foreign explorers.

5

ECOSYSTEM REQUIREMENTS FOR CIRCULAR ECONOMY SOLUTIONS

Ecosystem Requirements for Circular Economy Solutions

5

With the domestic primary supply of Critical Energy Transition Minerals (CETMs) remaining limited and heavily import-dependent, India would be exposed to vulnerabilities arising from geopolitical risks, supply disruptions, and price volatility. In this context, circular-economy pathways offer an essential complementary supply stream by enabling the recovery, reuse, and recycling of critical materials from end-of-life products and industrial waste.

Circular approaches not only enhance resource efficiency and reduce environmental impact but also strengthen self-reliance and industrial resilience. By recovering CETMs from used batteries, electronics, renewable energy infrastructure, and industrial by-products, India can significantly supplement its primary supply and reduce overall material footprint.

This chapter presents an analytical assessment of the role circularity can play in supporting India's critical energy transition mineral needs. It estimates the volume of e-waste and other secondary sources available for material recovery across different sectors and technologies. Using a bottom-up forecasting approach based on sales data, asset lifecycles, and failure rate modelling, the analysis projects e-waste generation through 2047. In addition, a Technology Assessment Framework (TAF) evaluates recycling technologies against technical, economic, and environmental criteria to identify the most viable pathways for scaling circular-economy practices in India.

5.1 CURRENT LANDSCAPE OF CIRCULAR ECONOMY POLICIES

Governments worldwide are increasingly adopting circular economy strategies to address the rising demand for critical minerals, with e-waste management emerging as a central focus. In India, the regulatory framework for e-waste has evolved through successive versions of the E-waste (Management) Rules, first introduced in 2011 and revised in 2016, 2018, and 2022. The latest set of rules, effective from April 2023, further strengthens the Extended Producer Responsibility (EPR) system by placing clear obligations on manufacturers, producers, refurbishers, and recyclers for the end-of-life management of their products.

The National Policy on Electronics (NPE) 2019 outlines protocols for implementing EPR requirements and promoting sustainable growth in the electronics sector. The Battery Waste Management Rules (BWMR) 2022 establish a dedicated framework for the sustainable management and recycling of battery waste, emphasising EPR and setting mandatory recycling targets. Additionally, the Ministry of MSME, is implementing the Scheme for Promotion and Investment in the Circular Economy for Micro and Small Enterprises (MSE-SPICE) to promote circular economy initiatives including e-waste recycling—within the MSME ecosystem.

Taken together, these policy measures aim to create a more structured, traceable, and environmentally sustainable e-waste processing ecosystem in India.

5.2 ESTIMATING E-WASTE AVAILABLE FOR RECYCLING

The study applies a five-step methodology (detailed in Annex B) to estimate e-waste available for recycling and the associated recovery of Critical Energy Transition Minerals (CETMs) through 2047. It begins with compiling e-waste generation data from 10 states for the base year 2022, followed by forecasting future waste volumes using historical sales trends, product-lifespan profiles and adoption trajectories. The analysis then projects e-waste recoverable in 2047 under both existing policy targets (60–80%) and an reform scenario with an 85% processing rate. These projected waste streams are linked to recoverable material volumes by applying material-intensity factors, covering both critical minerals (e.g., lithium, cobalt) and non-critical metals (e.g., iron, aluminium). Finally, a 95% recovery efficiency is assumed to reflect high-performance recycling systems.

Between FY 2017–18 and FY 2021–22, e-waste generation in India more than doubled—from 708,445 tonnes to 1,601,155 tonnes (PIB, 2023). While formal-sector processing increased from 9.8% to 32.9% over the same period, this expansion remains far below both policy targets and the rate of growth in e-waste generation. The widening gap between generation and formal recovery highlights persistent structural constraints in India's collection and processing ecosystem and underscores the urgency of strengthening both upstream aggregation systems and downstream treatment capacity.

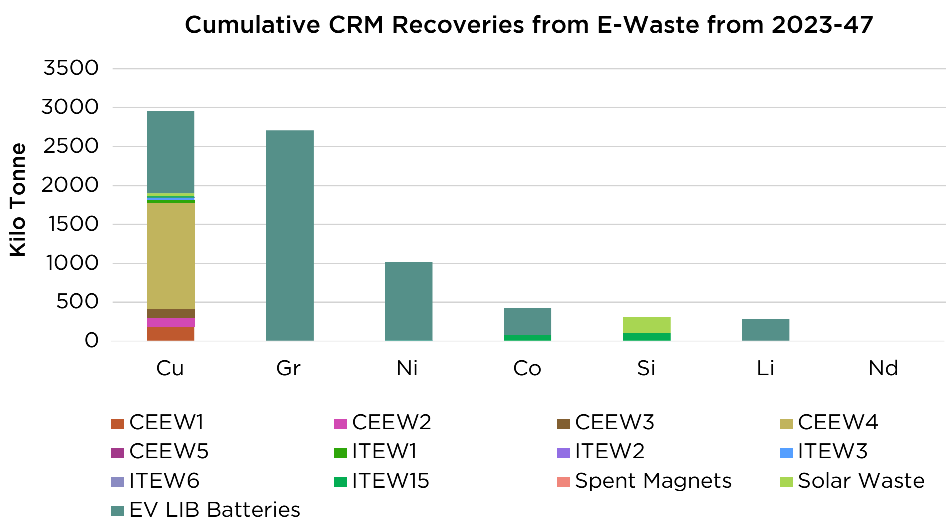


Figure 5.1: Cumulative CETM Recoveries from E-Waste Between 2025 and 2047 in Current Policy Scenario

**CEEW - Consumer Electrical and Electronics Waste, categories are explained in Annex Table B.1*

Figure 5.1 presents cumulative recoverable Critical Energy Transition Mineral (CETM) volumes from the modelled e-waste streams between 2025 and 2047. Copper shows the largest recovery potential, driven by its widespread presence across conventional consumer and industrial electronics such as refrigerators, washing machines, laptops and printers. Graphite is the next-largest recovery stream, with a vast majority of recoveries coming from end-of-life EV lithium-ion batteries underscoring the strategic importance of battery recycling for domestic supply security.

Other high-value battery minerals nickel, lithium and cobalt also exhibit substantial recoverable volumes, principally sourced from EV battery waste. Silicon recoveries are moderate and concentrated in end-of-life solar PV modules, highlighting the growing relevance of photovoltaic waste management. Neodymium is recovered in smaller absolute quantities but is notable because it is sourced almost exclusively from spent permanent magnets used in EV motors and wind turbines.

Collectively, these trends indicate a structural shift in India's secondary resource base: recoverable Critical Energy Transition Minerals (CETMs) will increasingly originate from clean-energy technology waste rather than from traditional electronics. This shift requires dedicated collection channels, reverse-logistics systems, and specialised processing facilities tailored to battery packs, PV modules and magnet-containing assemblies. Under the reform scenario (immediate adoption of an 85% processing target), recoveries for the modelled minerals increase by 13.25% (Annex I).

5.3 IDENTIFYING OPTIMAL E-WASTE RECYCLING TECHNOLOGY

To identify the most suitable recycling pathways for the modelled waste streams, the study applied a Technology Assessment Framework (TAF) that evaluated three processing routes namely pyrometallurgy, hydrometallurgy (acid leaching) and hydrometallurgy (bioleaching) against technical, economic and environmental (TEE) criteria. A fuzzy-TOPSIS ranking method, informed by expert judgement and sensitivity testing (details in Annex B) was used to assess each technology's closeness to an ideal solution.

Hydrometallurgy (bioleaching) emerged as the top-ranked technology on environmental and economic criteria because of its low capital costs and minimal environmental impact. Hydrometallurgy (acid-leaching) ranked highest on the technical criterion due to its maturity, higher recovery efficiency, and wider applicability. Pyrometallurgy, although technically mature, received the lowest rank across all TEE criteria, making it the least optimal technology for e-waste recycling.

These findings highlight the potential of hydrometallurgical approaches, especially bioleaching, as promising solutions for scaling environmentally sound and cost-effective e-waste recycling in India.

5.4 EXTENT OF CETM DEMAND THAT CAN BE MET BY CIRCULARITY

Figure 5.2 below illustrates the share of India's Critical Energy Transition Mineral demand in 2025-2047 that can potentially be met through recycling e-waste and end-of-life products generated during the same period. Cobalt shows the most promise in potential recovery from recycling, its share rises from around 30% in 2030 to almost 100% by 2040. This is largely due to the high volume of cobalt-rich batteries reaching their end of life with a simultaneous shift toward lower-cobalt and cobalt-free alternatives in future, reducing overall cobalt demand in the economy. Nickel follows a similar but more gradual trajectory, due to its continued requirement in various technologies.

Graphite, copper, and lithium all show steady increases, reaching around 15-25% by 2047, reflecting growing recycling volumes as battery and electronics waste accumulates. In contrast, recycling contributes to only a fraction of the new demand for silicon and neodymium.

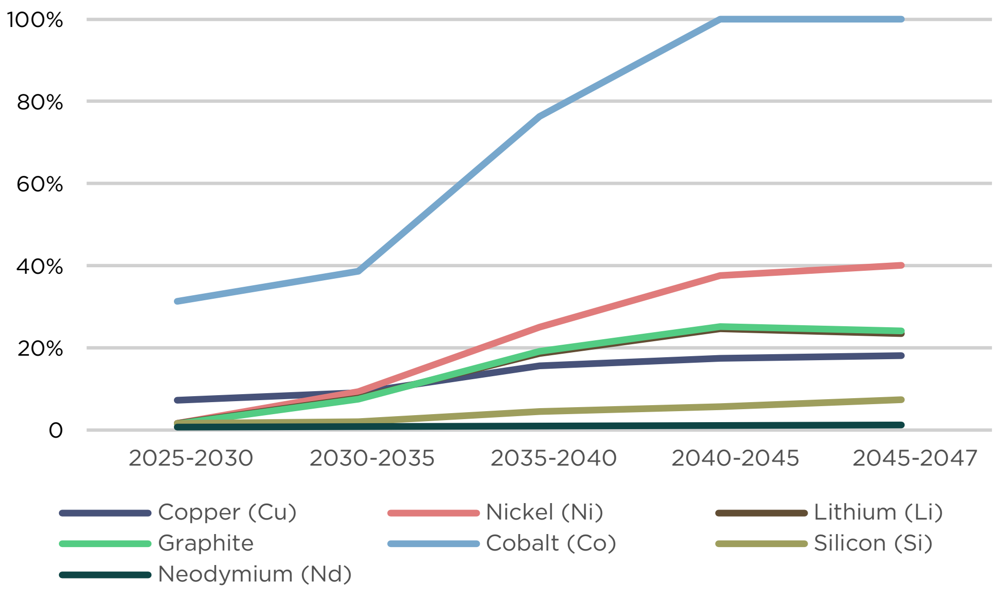


Figure 5.2: Share of CETM Demand fulfilled by Recycled Minerals Between 2025 and 2047 Current Policy Scenario

As deployment of low-carbon technologies picks up at mid-century, we see the limited ability of recycling to meet demand. These trends show that recycling can partly succeed in meeting the needs for select minerals. For most Critical Energy Transition Minerals (CETMs), it may supplement but will not replace primary supply, highlighting the need for parallel investments in mining, processing, waste import, and material efficiency strategies.

5.5 ALTERNATIVE SOURCES OF MINERALS

While consumer electronics remain a key focus for mineral recovery, there is significant untapped potential in alternate sources, particularly manufacturing waste from sectors such as automotive, battery production, renewable energy, and mining tailing. Industrial scrap, spent catalysts, and by-products like slag and sludge often contain high concentrations of Critical Raw Materials (CRMs) such as lithium, nickel, cobalt, rare earth elements, and precious metals. These sources are typically more centralised and compositionally consistent than post-consumer waste, making them more accessible and cost-effective for recovery. Tapping into these streams can reduce dependence on primary mining, enhance resource security, and contribute to India's clean energy and circular economy goals.

To unlock this potential, policies must incentivise industries to accurately report, segregate, and direct valuable manufacturing waste into formal recycling systems. With the right regulatory and infrastructural support, India can not only strengthen its domestic supply chains for strategic minerals but also enhance sustainable resource recovery.

5.6 DISCUSSION OF FINDINGS

Despite several systemic limitations, e-waste and battery recycling show considerable potential, as yet untapped, to contribute to India's Critical Energy Transition Mineral (CETM) security. Notably, recycling can only partially meet the demand for battery-related minerals. For many other CETMs such as silicon and rare earths like neodymium, the contribution remains marginal.

While scaling up formal recycling systems can help close material loops for select minerals, to realise the full potential of circular economy pathways in India, it must be complemented by i) parallel efforts to improve collection efficiency; ii) investment in advanced recovery technologies; and iii) strengthened regulatory enforcement.

In conclusion, the effectiveness of circular economy as a source must also be viewed through the lens of India's manufacturing trajectory. Even if Indian manufacturers deploy only 20–30% of the low-carbon technologies, the projected levels of material recovery may be adequate to meet much of the domestic demand for key battery minerals. However, if India's manufacturing footprint expands significantly, the recycling alone will not suffice. In such a case, the country would need to increase primary mineral procurement and actively explore the import of high-value end-of-life products and battery scrap from other regions as an additional feedstock.

6

R&D REQUIREMENTS FOR CRITICAL MINERAL PROCESSING AND RECYCLING

R&D Requirements for Critical Mineral Processing and Recycling

6

Research and Development (R&D) is a cornerstone of India's Critical Energy Transition Mineral (CETM) strategy. As global demand for these minerals surge, India must develop the capacity to not only secure raw materials but also process, refine, and recycle them domestically. At present, much of the global value in Critical Energy Transition Minerals (CETMs) lies not in the extraction stage, but in the downstream processing and technology-intensive stages. These are dominated by a handful of countries, exposing India to significant supply and pricing risks. Bridging this gap demands a robust, mission-oriented R&D agenda that will play a critical role in:

1. Improving resource efficiency, enabling extraction from low-grade or unconventional ores.
2. Reducing environmental impact by promoting cleaner, less energy-intensive processes.
3. Unlocking value from secondary sources, through advanced recycling and recovery technologies.

This chapter reviews India's current capabilities in critical mineral processing and recycling, examines the existing policy support for CETM related R&D, and provides an overview of global research trends that could inform the direction of future domestic efforts.

6.1 TECHNOLOGIES FOR MINERAL PROCESSING AND RECYCLING

India's domestic R&D ecosystem led by institutions such as Council of Scientific and Industrial Research (CSIR) laboratories, Indian Institutes of Technology (IITs), and select private firms has made notable strides in developing processing and recycling technologies for several CETMs. However, the maturity of these technologies varies significantly across the mineral spectrum. The following section presents a comparative analysis using data compiled for 18 CETMs (Table 6.1) with details of the data shared in Annex H.

Table 6.1: Summary of Minerals Analysed for Processing and Recycling Technology and R&D Readiness

Type of Use	Minerals Mapped	# of Minerals
Battery Materials	Li, Co, Ni, V, Graphite	5
Rare Earths & Magnetics	Nd, Pr, Tb, Y, Sc	5
Electronics/Semiconductors	Ga, Ge, In, Te, Se	5
Alloying & Structural	Ti, Nb, Ta	3

Based on the comparative analysis, the following classification emerges:

Mature Process

In various Critical Energy Transition Minerals (CETMs), India has developed technological capabilities assessed to be at par with international best practices, with successful pilot-scale demonstrations or commercial operations already established.

Lithium, cobalt, nickel, graphite, vanadium, tungsten, and titanium[11] represent clear opportunities for industrial scaling, commercialisation support, and policy incentives, including PLI schemes. Similarly, in recycling, India has developed mature technologies with strong potential to support a domestic circular economy for critical minerals (lithium, cobalt, nickel, graphite, vanadium, tungsten, and titanium) particularly in sectors such as batteries, motors, and e-waste recycling.

Pilot/Partial Process

At the same time, several processes remain at a pilot or pre-commercial stage, often limited to beneficiation or intermediate purification, lacking the capability to produce high-purity end-products. This is true for primary processing (neodymium, praseodymium, titanium-metal, niobium, tantalum, germanium, tellurium, yttrium, and selenium) and recycling (indium, niobium, tantalum, and gallium), where promising lab-scale innovations require scale-up, validation, and industrial integration to match global benchmarks. These technologies are ideal candidates for translational R&D support through public–private consortia, as well as targeted international collaborations. Investment in such initiatives would help bridge the gap between innovation and deployment.

Finally, there are critical minerals for which India currently lacks any meaningful domestic processing capability—whether at the research, pilot, or commercial scale (terbium, gallium, indium, and scandium). This is also true for certain recyclable feedstocks (germanium, scandium, tellurium, and selenium), where the absence of suitable processes, infrastructure, or access to proprietary technologies results in complete import dependence. These require urgent attention from India's Critical Energy Transition Mineral ecosystem through mission-mode R&D programmes, technology access agreements, or global partnerships, particularly for by-product recovery and high-purity separation.

6.2 R&D-SUPPORTIVE POLICIES IN PROCESSING AND RECYCLING OF CRITICAL MINERALS

Under its Science and Technology (S&T) Programme, the Ministry of Mines provides funding to academic institutions, universities, national institutes, and R&D organisations recognised by the Department of Scientific and Industrial Research, startups, and MSMEs to implement R&D projects. This programme aims to promote applied research in geosciences, mineral exploration, mining, mineral processing, optimum utilisation, and conservation of mineral resources for national benefit.

In 2023, the programme's scope was expanded with the introduction of the "Promotion of Research and Innovation in Startups and MSMEs in Mining, Mineral Processing, Metallurgy and

11 Ti processes currently terminate at TiO_2 concentrate; full metal-level capabilities are absent.

Recycling Sector" (S&T-PRISM). The S&T Programme now has two key components:

1. **R&D:** Funds are allocated to academic institutions, universities, national institutes, and R&D institutions recognised by the DSIR for undertaking R&D projects.
2. **S&T-PRISM:** Funds are allocated to ensure timely availability of seed support to deserving startups.

A total of 22 projects related to critical minerals from academic institutions, universities, national institutes, and R&D institutions have been sanctioned under the R&D component during 2024-25. The same year, six projects from startups and MSMEs have been sanctioned under the S&T-PRISM component, totalling 28 sanctioned critical mineral-related projects.

The Ministry of Electronics and Information Technology (MeitY) plays a pivotal role in advancing cost-effective technological solutions, skill development, and capacity building to manage e-waste across the country. As part of its initiatives, MeitY has established India's first Centre of Excellence (CoE) for e-waste management at C-MET, Hyderabad.

This CoE serves as a hub for providing affordable recycling technologies, fostering start-up creation, offering incubation facilities, and conducting skill development programmes. The recycling technologies developed at this centre cater to:

1. Printed Circuit Board
2. Lithium-ion Battery
3. Rare Earth Permanent Magnets
4. Fluorescent Lamp Phosphors
5. PV Solar Cells

The CoE has successfully transferred these advanced technologies to approximately 30 industries, promoting sustainable e-waste management and supporting the country's circular economy goals.

These efforts aim to bridge the gap between innovation and commercialisation and are integral to building a self-reliant, resilient supply chain for critical minerals essential to India's clean energy future.

6.3 GLOBAL DEVELOPMENTS IN MINERAL PROCESSING AND RECYCLING

Traditional mineral processing has largely focused on optimising established technologies rather than inventing new ones. Processing costs, technological requirements, and operational complexity are strongly influenced by feedstock characteristics, particularly ore grade and impurity levels. Lower-grade ores demand more intensive treatment, while ore composition determines the choice of metallurgical routes. Recycling presents comparable complexities as the type, quality, and composition of end-of-life materials shape the design and efficiency of recovery processes.

Most current operations rely on proven pyrometallurgical and hydrometallurgical techniques, where precise control of temperature, pressure, and chemical conditions is critical for high recovery and process stability. Although incremental improvements to these methods have delivered gains in efficiency and cost performance, evolving supply-chain dynamics and sustainability constraints are reshaping global R&D priorities. Conventional processes are often energy-intensive, generate substantial emissions, have large chemical footprints, and offer limited flexibility in handling low-grade or complex feedstocks. These methods also face challenges in economically recovering trace elements and in scaling for decentralised applications, which are increasingly critical as Critical Energy Transition Mineral supply chains become more complex and globally dispersed.

In response, global R&D is pivoting toward next-generation processing and recycling technologies that offer greater efficiency, selectivity, and sustainability. Direct lithium extraction, for instance, enables targeted recovery from low-concentration brines and clays without energy-intensive evaporation (Amir Razmjou, 2024). In recycling, direct recycling of lithium-ion batteries retains material structure, reducing the number of processing steps, while closed-loop battery recycling aims to minimise both waste and chemical inputs (Neumann et al., 2022).

Renewables-powered electrometallurgical and solvent-free extraction processes are also being explored globally to significantly cut down on reagent use, carbon and energy intensity. Importantly, advanced electrowinning and electrorefining techniques are being developed to enable the recovery of high-purity metals from complex, low-concentration solutions, such as those found in urban mining and recycling of electronics and batteries. These methods offer precise control over metal purity and are more adaptable to variable feedstocks (Rai et al., 2021). Complementing this, ion-selective membrane technologies are emerging as powerful tools for targeted metal separation, allowing for the efficient recovery of specific elements while reducing cross-contamination and chemical waste (Wang et al., 2023).

Together, these innovations present a strategic opportunity for India to leapfrog legacy infrastructure, build decentralised and low-footprint processing systems, and align its CETM roadmap with global frontiers in sustainable materials recovery.

6.4 DISCUSSION OF FINDINGS

India has made measurable progress in developing R&D capabilities for Critical Energy Transition Mineral (CETM) processing and recycling, particularly for materials such as lithium, cobalt, nickel, and graphite. However, the maturity of technologies varies significantly across the CETM spectrum. While several processes are at par with global standards and ready for industrial scaling, others remain in the pilot stage or are entirely absent, especially for niche elements such as scandium, tellurium, and gallium used in high-tech products. India's recycling capabilities, though promising, also show uneven readiness across different materials. As global innovation shifts toward cleaner, modular, and more selective technologies, India's R&D agenda must evolve accordingly. Addressing the identified gaps through targeted investments, translational infrastructure, and international collaboration will be critical to achieving self-reliance and sustainability in CETM supply chains.

7

POLICY SUGGESTIONS

Policy Suggestions

7

This chapter translates the strategic insights from the preceding chapters into a focused set of policy actions to strengthen India's Critical Energy Transition Mineral ecosystem. A coherent critical minerals strategy requires clarity on the principles that shape these policy choices. These guiding principles translate India's critical mineral ecosystem challenges into a structured logic for action. They clarify the direction of reform, guide sequencing across different supply pathways and time horizons, and surface the cross-cutting enablers required for a resilient CETM ecosystem. Together, they provide the organising logic for the intervention pillars that follow and ensure that suggestions remain anchored in system-wide strategic priorities.

7.1 GUIDING PRINCIPLES FOR POLICY ACTION

Principle 1: Enable private sector leadership across the value chain

Public institutions will continue to play a catalytic and coordinating role, but scaling CETM supply chains ultimately depends on sustained private investment, operational leadership, and technology adoption. Policy frameworks should therefore prioritise predictability in regulation, streamlined approvals, risk-sharing mechanisms, and fiscal alignment that enable competitive private participation across exploration, refining, recycling and international sourcing.

Principle 2: Align interventions with differentiated timelines across supply pathways

Primary mining, secondary recovery, refining, and overseas sourcing operate on fundamentally different timelines and risk profiles. Policy design must recognise these differences by accelerating near-term capacity creation where feasible (such as recycling and processing), while sustaining long-term horizon support for exploration and mine development. Sequencing interventions in line with these structural timelines is essential to avoid policy misalignment and investor uncertainty.

Principle 3: Diversify risk through strategic and mutually beneficial international partnerships

Given high concentration in global CETM supply chains, India must actively diversify access through partnerships that go beyond transactional imports. International engagement should prioritise co-investment, long-term offtake, technology collaboration and "value-chain stack" arrangements that embed India within resilient, shared supply networks, rather than isolated or opportunistic sourcing relationships.

Principle 4: Treat environmental and social performance as a core supply-security requirement

Weak environmental and social safeguards increase project risk, undermine social licence to operate, and can disrupt supply chains through litigation, delays, and community opposition. Fast-tracking approvals should therefore not dilute standards. Policy approaches should instead reinforce robust standards, safeguards, traceability, transparency, and independent verification as essential enablers of long-term supply security and global market access.

Principle 5: Prioritise mission-oriented innovation and leap-frog technologies

India should avoid locking itself into late-stage replication of existing technologies and processes. Innovation policy should instead prioritise mission-driven R&D, structured pilot-to-commercial pathways, and next-generation technologies that reduce cost, environmental footprint, and strategic dependence. This approach positions India to build competitive capability aligned with future technology transitions, rather than remaining dependent on incumbent process routes.

Principle 6: Strengthen institutional capacity, data systems, and centre-state coordination

Effective critical minerals governance depends on strong institutions, reliable data, and coordinated decision-making across various levels of government. Policies should be guided by integrated mineral flow data, shared analytical baselines, and clearly defined centre-state roles. Strengthening these institutional foundations is essential to ensure that demand signals, supply-side interventions, and industrial development remain aligned and adaptive over time.

The suggestions that follows operationalises these principles into a set of policy actions. They are organised into five thematic pillars and can be read as a coherent package based on:

i. Domestic mining measures that accelerate discovery-to-production without eroding legitimacy

ii. Technology actions that close readiness and scale-up gaps

iii. International strategies to manage concentration and market risk

iv. Interventions to unlock midstream and circularity capacity

v. Governance measures that institutionalise strategy, risk assessment, calibration, and delivery accountability.

Each pillar specifies discrete actions and their core implementation parameters, while avoiding duplication of existing schemes or mandates. The pillars are intended to function as a coherent package, with each addressing a distinct constraint and reinforcing the others through sequencing rather than overlap.

7.2 SUGGESTIONS

Pillar-1: Strengthen domestic exploration and mining

Domestic exploration and mining remain necessary components of India's Critical Energy Transition Mineral supply base, notwithstanding long development timelines and geological uncertainty. This pillar focuses on modernising exploration access, improving the credibility and usability of geological information, aligning public sector capabilities, and strengthening permitting coordination while preserving environmental and social accountability.

a. Rebalance exploration access and licensing pathways

Conditional First-Come, First-Served (FCFS) access may be introduced for early-stage exploration of priority critical minerals. It should also be linked to mandatory data disclosure, time-bound milestones, and rights-based progression to mining leases upon successful discovery. Further, clear thresholds should be defined for the transition from FCFS to auction after attaining a sector-level maturity.

b. Make private-sector participation the default for early-stage exploration

Adopt private-sector award as the default pathway for exploration licences for critical minerals, using conditional First-Come, First-Served (FCFS) mechanisms (preferred over auction) appropriate to geological uncertainty and till market matures.

c. Improve geological knowledge and data credibility

Mandate Committee for Mineral Reserves International Reporting Standards (CRIRSCO)-aligned reporting through Indian Mineral Industry Code (IMIC) and embed decision-grade geological disclosure into statutory and regulatory processes, including licence conversion and development approvals.

d. Align public sector mining capabilities with critical minerals priorities

Review and realign the mandates, asset deployment, investment priorities, and administrative control of public sector mining and processing enterprises (e.g., National Mineral Development Corporation, Coal India, Indian Rare Earths Limited) to ensure consistency with national critical minerals objectives.

e. Preserve environmental and social accountability in project approvals

Retain public consultation as a targeted risk-screening mechanism, restrict expedited approvals to compliant proponents, and mandate independent audits for fast-tracked projects.

f. Improve permitting coordination for critical mineral projects through a dedicated coordination committee

Coordinated permitting guidance for Critical Energy Transition Mineral (CETM) projects should be issued to improve sequencing and enable parallel processing across approvals, with establishing single-point coordination mechanisms without altering statutory decision-making authority.

A Chief Secretary-chaired coordination committee may be constituted to resolve inter-departmental bottlenecks and monitor applications through digital permitting dashboards tracking status, dependencies and decision timelines.

Pillar-2: Build domestic innovation and technology capability for critical raw materials

India's long-term critical raw materials supply resilience depends on the ability to develop, adapt, and deploy processing, separation, refining, and recycling technologies domestically. This pillar focuses on organising R&D around deployment outcomes, strengthening pilot-to-commercial pathways, and structuring international technology engagement to support domestic absorption rather than persistent dependence.

a. Establish a mission-oriented R&D framework for critical raw materials

A mission-oriented R&D framework should be established, focusing on priority minerals, materials, precursors, and processing technologies identified through national risk assessments. Funding can be shifted from fragmented, project-based approach toward outcome-oriented missions linked to deployment needs in refining, recycling, and associated manufacturing.

b. Create pilot-to-commercialisation pathways for priority technologies

Shared pilot and demonstration infrastructure are needed for priority processing, refining, and recycling technologies, with transparent access rules for start-ups, MSMEs, and private firms. VGF and other risk-sharing instruments should be provided for first-of-a-kind deployments, including concessional finance, guarantees, and time-bound performance-linked support tied to recovery, purity, and environmental benchmarks.

c. Enable structured international technology co-development and absorption

Structure bilateral and plurilateral technology co-development arrangements or programmes covering joint pilots, shared IP generation, and researcher mobility in priority Critical Raw Material (CRM) technologies. Domestic capability-building requirements (such as local engineering development, workforce training, and phased localisation) can be embedded within international technology partnerships and incentive frameworks.

Public support should prioritise technologies with demonstrable pathways to domestic absorption and scale, avoiding open-ended dependence on licensed or proprietary processes.

Pillar-3: Diversify international supply sources and reduce import risk

India's dependence on a narrow set of countries and firms for critical minerals exposes clean-energy and manufacturing value chains to geopolitical and market risks. This pillar reduces vulnerability through risk-differentiated partnerships, shared value-chain arrangements and coordinated overseas facilitation.

a. Diversify overseas mineral access through risk-differentiated partnerships

Critical minerals need to be classified by concentration and geopolitical exposure, and their risk profile can be translated into differentiated engagement strategies.

b. *Embed India in resilient global value-chain arrangements*

Minerals suitable for value-chain stack partnerships, such as lithium, cobalt, nickel, and rare earth materials, should be identified for pilot shared processing and refining hubs through bilateral and plurilateral frameworks.

c. *De-risk overseas access through aggregation and facilitation*

Project preparation support should be established, alongside aggregate demand for equity and offtake, and coordinate overseas engagement through a single-window facilitation platform.

d. *Strengthen KABIL for overseas Critical Energy Transition Mineral (CETM) execution*

KABIL's execution capacity requires strengthening through calibrated capitalisation, targeted lateral recruitment in international mining and project finance, and prioritised overseas CETM project pipeline. For this, partnerships with overseas-facing PSUs and public financial institutions can leverage their due diligence, negotiation, and asset operation expertise while retaining KABIL's focused CETM mandate.

e. *Reduce market risk through improved price discovery and hedging*

Facilitate access to relevant global mineral exchanges and develop India-linked instruments where required, integrating market signals into sourcing and stockpiling decisions.

Pillar-4: Scale circularity and refining

India's Critical Energy Transition Mineral (CETM) supply constraints are concentrated in midstream refining and recycling capacity rather than in downstream manufacturing alone. This pillar operationalises the midstream and circularity constraints identified in Chapter 5 by focusing on economic viability, feedstock access, and technology availability for refining and advanced recycling, while maintaining environmental and social compliance.

a. *Make refining and advanced recycling economically viable*

A coordinated package of incentives combining capital support, output-linked incentives, and tax rationalisation is required for Critical Energy Transition Mineral refining and advanced recycling facilities. First-of-a-kind and scale-up projects should be prioritised to produce high-purity materials relevant to downstream manufacturing. National Critical Mineral Mission (NCMM)-linked processing cluster support can also be extended to advanced recycling hubs, enabling land access, shared infrastructure, and anchor-firm-led cluster models. Verification of Extended Producer Responsibility (EPR) compliance and third-party audits need to be strengthened to ensure that fiscal and financial incentives accrue only to authorised and compliant refining and recycling operators.

b. *Secure access to critical refining and recycling technologies*

Facilitate access to priority refining and recycling technologies through bilateral and multilateral cooperation frameworks, with clearly defined capability-building requirements linked to domestic absorption and operation.

c. Unlock reliable secondary feedstock for Critical Energy Transition Mineral (CETMs)

Waste-management and import regulations need amendment to permit authorised refining and recycling entities to import traceable, high-value CETM-bearing scrap and end-of-life products under strict environmental standards. Further, protocols can be issued for authorised access to mine tailings and legacy waste for CETM recovery. For this, one-time national potential assessment can be undertaken for tailings relevant to critical minerals.

Pillar-5: Institutional architecture for national critical raw materials governance

The actions in this section establish enabling conditions for Pillars 1-4. They are intended to support coherent, whole-of-government implementation rather than operate as a standalone thematic pillar.

The preceding synthesis highlights that India's critical minerals challenge increasingly reflects system-level governance gaps rather than deficiencies in individual policy instruments. As the scope of concern expands from Critical Energy Transition Minerals to a broader set defined better as Critical Raw Materials, including specific grades of outputs, intermediate materials, processing reagents, specialised equipment and enabling technologies, the need for durable, cross-cutting governance functions becomes more pronounced.

While execution responsibility is appropriately distributed across line ministries and mission-mode programmes such as National Critical Mineral Mission (NCMM), effective Critical Raw Material governance requires institutional functions that operate across mandates and time horizons. In particular, the synthesis identifies four persistent gaps: fragmented scope-setting, reactive risk assessment, limited calibration of policy and market instruments, and the absence of differentiated stewardship for system-critical projects.

The Institutional Architecture set out below is designed to address these gaps by separating strategy from execution, strengthening system-level intelligence and prioritisation, and enabling timely escalation and coordination, without duplicating existing authorities or displacing line-ministry accountability.

a. Establish a National Critical Raw Material (CRM) analytical unit for strategy and system-level risk assessment: Constitute a CRM analytical unit responsible for:

- i. Setting strategic scope across CRMs beyond a mineral-only or mining-centric lens;
- ii. Maintaining the Net Zero Technology and Materials Roadmap as a living, regularly updated framework. This report provides the initial consolidated roadmap and analytical foundation, which should be periodically updated as technologies, deployment pathways, and material intensity data evolve.
- iii. Undertaking periodic, system-level risk assessments spanning domestic and international supply, primary and secondary sources, and enabling inputs such as technologies and equipment; and
- iv. Developing and periodically updating a National Critical Raw Materials Strategy.

Design Safeguard: The analytical unit should not execute programmes, own budgets, coordinate approvals, or assume line-ministry functions. Its role is limited to strategy, prioritisation, risk assessment, and structured escalation.

b. Develop a National Critical Raw Materials Strategy on a recurring basis. The Strategy should:

i. Consolidate demand signals (including outputs from the Net Zero Technology & Materials Roadmap);

ii. Integrate supply-risk assessments across minerals, materials, and enabling technologies; Risk & Early-Warning Assessment to include indicators such as import concentration, processing bottlenecks, technology chokepoints, geopolitical exposure and environmental or social risk flags.

iii. Identify priority raw materials, value chains, and strategic CRM projects; and

iv. Define sequencing, calibration, and escalation logic across ministries and states.

Scope Clarity: The strategy should guide missions and policies, not replace them. It should remain adaptive, analytical, and strategic rather than evolving into a programme or scheme.

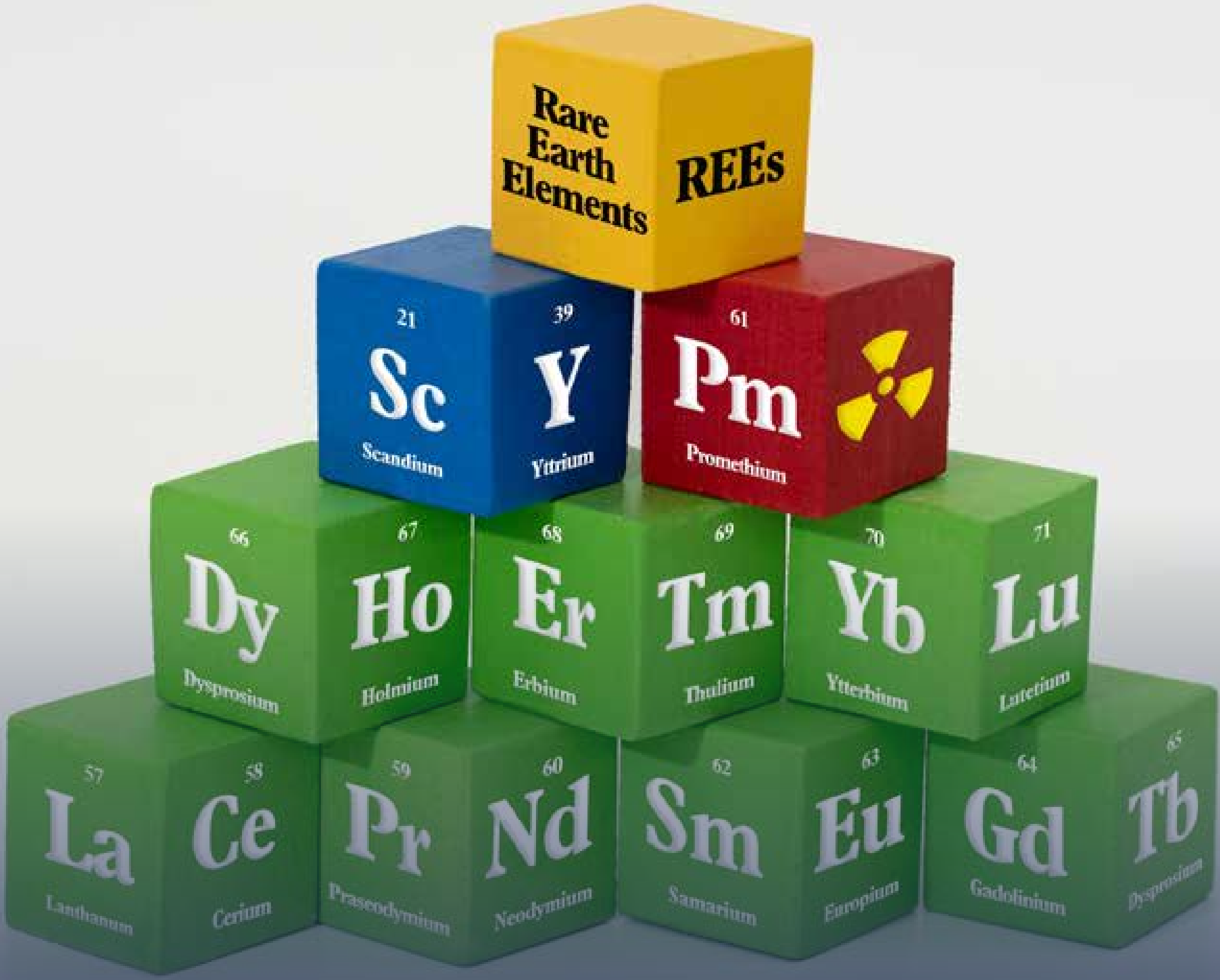
c. Enable strategic project designation, stewardship, and delivery coordination: Constitute an Inter-Ministerial Committee (IMC) to:

i. Develop coordinated guidance to periodically review the performance of existing policy and market instruments, such as stockpiling frameworks, offtake arrangements, incentive structures, and approval timelines against strategic objectives and evolving risk profiles. The IMC will also review the role played by the analytical unit and suggest improvements.

ii. IMC may co-opt state government units wherever applicable to resolve inter-departmental bottlenecks and monitor progress, supported by digital permitting dashboards tracking application status, dependencies, and decision timelines.

iii. Identify a limited set of strategic critical raw materials projects across mining, processing, recycling, technology demonstration, and overseas sourcing whose outcomes have system-wide implications for supply security, market confidence, or downstream industrial viability.

iv. Apply differentiated treatment to designated strategic projects, including priority handling, coordinated sequencing of approvals, targeted access to incentives and finance, and active inter-agency bottleneck resolution, without diluting statutory environmental or social safeguards.


Rare Earth Elements
REEs
21 Sc Scandium
39 Y Yttrium
61 Pm Promethium
66 Dy Dysprosium
67 Ho Holmium
68 Er Erbium
69 Tm Thulium
70 Yb Ytterbium
71 Lu Lutetium
57 La Lanthanum
58 Ce Cerium
59 Pr Praseodymium
60 Nd Neodymium
62 Sm Samarium
63 Eu Europium
64 Gd Gadolinium
65 Tb

ANNEXURES

ANNEX A LIST OF CRITICAL MINERALS AND CETM

Table A.1: List of Critical Minerals and CETM

No.	Mineral / Element	Group	CETM (WG4)	MMDR Part D
1	Cadmium	Element	☑	☑
2	Cobalt	Element	☑	☑
3	Gallium	Element	☑	☑
4	Graphite	Element	☑	☑
5	Indium	Element	☑	☑
6	Lithium	Element	☑	☑
7	Molybdenum	Element	☑	☑
8	Nickel	Element	☑	☑
9	Niobium	Element	☑	☑
10	Selenium	Element	☑	☑
11	Tellurium	Element	☑	☑
12	Tin	Element	☑	☑
13	Titanium	Element	☑	☑
14	Tungsten	Element	☑	☑
15	Vanadium	Element	☑	☑
16	Zirconium	Element	☑	☑
17	Copper	Element	☑	☒
18	Germanium	Element	☑	☒
19	Silicon	Element	☑	☒
20	Strontium	Element	☑	☒
21.1	Iridium	PGE	☑	☑
21.2	Platinum	PGE	☑	☑
21.3	Osmium	PGE	☒	☑
21.4	Palladium	PGE	☒	☑
21.5	Rhodium	PGE	☒	☑
21.6	Ruthenium	PGE	☒	☑

No.	Mineral / Element	Group	CETsM (WG4)	MMDR Part D
22.1	Cerium	REE (Light)	☑	☑
22.2	Lanthanum	REE (Light)	☑	☑
22.3	Neodymium	REE (Light)	☑	☑
22.4	Praseodymium	REE (Light)	☑	☑
22.5	Europium	REE (Light)	☒	☑
22.6	Promethium	REE (Light)	☒	☑
22.7	Samarium	REE (Light)	☒	☑
22.8	Dysprosium	REE (Heavy)	☑	☑
22.9	Gadolinium	REE (Heavy)	☑	☑
22.10	Terbium	REE (Heavy)	☑	☑
22.11	Yttrium	REE-like (Heavy)	☑	☑
22.12	Erbium	REE (Heavy)	☒	☑
22.13	Holmium	REE (Heavy)	☒	☑
22.14	Lutetium	REE (Heavy)	☒	☑
22.15	Thulium	REE (Heavy)	☒	☑
22.16	Ytterbium	REE (Heavy)	☒	☑
22.17	Scandium	REE-like (Light)	☒	☑
23	Phosphates	Element	☑	☑
24	Beryllium	Element	☒	☑
25	Potash (Glauconite)	Element	☒	☑
26	Rhenium	Element	☒	☑
27	Tantalum	Element	☒	☑
28	Antimony	Element	☒	☒
29	Bismuth	Element	☒	☒
30	Hafnium	Element	☒	☒

ANNEX B METHODOLOGIES IN DETAIL

CETM demand assessment for Renewable Energy and Green Hydrogen

1. **Technology Variants and Market Share Projections:** Technology variants are specific subtypes or configurations within a broader low-carbon technology category. For example, EV batteries include multiple battery chemistries such as LFP, Lithium Nickel Manganese Cobalt Oxide (NMC532, NMC811), and the newly commercialised Sodium Ion battery have been considered among others. The future market shares of these technology variants were projected primarily from existing studies and expert literature.

   Given the limited availability of precise market share data, especially for emerging technologies, a heuristic approach was adopted. Market shares were projected based on the Technology Readiness Level (TRL), efficiency, and End-of-Life (EOL) characteristics of each technology variant.

   Variants with high maturity levels (TRL 8–9) are expected to experience gradual reductions in market share due to competition from emerging technologies. Conversely, variants with less mature technology (TRL 4–7) are expected to gain share as technological advancements improve their commercial viability. Annex D lists the market share of all technology variants considered in this study. For EOL assumptions, clean energy technologies that retire at least 20 years after their commercialisation has been included.

2. **Estimating Mineral Intensity:** Mineral intensities for each technology variant were sourced from comprehensive industry studies and relevant literature. For renewable power-generation technologies like Solar PV, CSP, and wind, mineral intensity is expressed in tonnes per gigawatt (t/GW), consistent with their rated power-generating capacities. For BESS, mineral intensity is expressed in tonnes per gigawatt hour (t/GWh) aligning with their energy storage capacities. Electrolyser capacities were estimated using projected Green Hydrogen production data provided by NITI Aayog, coupled with efficiency data for different electrolyser variants, expressed in t/GW.

3. **Calculating Cumulative Embedded Mineral Demand:** The cumulative mineral demand for each technology variant was calculated by combining the annual projected installed capacity required of each low-carbon technology, evolving market shares of the technology variants, and mineral intensities of each variant.

   The following equation explains the cumulative embedded mineral content for a specific mineral in a technology variant:

$$C_{(m,v)}(t) = \sum_{y=2025}^{t} \left[I_y \times S_{(v,y)} \times M_{(m,v)} \right]$$

$C_{(m,v)}(t)$ = Cumulative embedded mineral content of mineral m in technology variant v by end year t.

m = one of the 30 critical minerals

I_Y = Total annual installations (e.g., MW capacity, number of EVs, etc.) of the low-carbon technology category (e.g., Solar PV, Wind, etc.) in year y.

y = start year for annual critical mineral calculation beginning with 2025, ending in year t (2030, 2047 and 2070)

$S_{(v,y)}$ = Market share (%) (0–1) of the specific technology variant v within the low-carbon technology category in year y.

$m_{(m,v)}$ = Embedded mineral intensity (e.g., kg mineral per MW installed or per unit) of mineral m in technology variant v.

Key assumptions:

- Mineral intensity per technology variant remains constant over time.
- Variations in cumulative mineral content are driven entirely by:
  - Annual installations of technology category (changing over time as energy demand increases)
  - Market share variation of the technology variant (changing over time as more efficient technology variants mature and commercialise)

Methodology for recovery of CETM from E-waste

This study estimates the volume of e-waste available for recycling and the potential recovery of CETMs based on data from the state annual reports. Data on e-waste generation was collected from 10 states with 2022 as the base year. In instances where 2022 data was unavailable, data from adjacent years was used. The types of e-waste analysed include Consumer Electrical and Electronics Waste (CEEW) and Information Technology and Telecommunication Equipment Waste (ITEW).

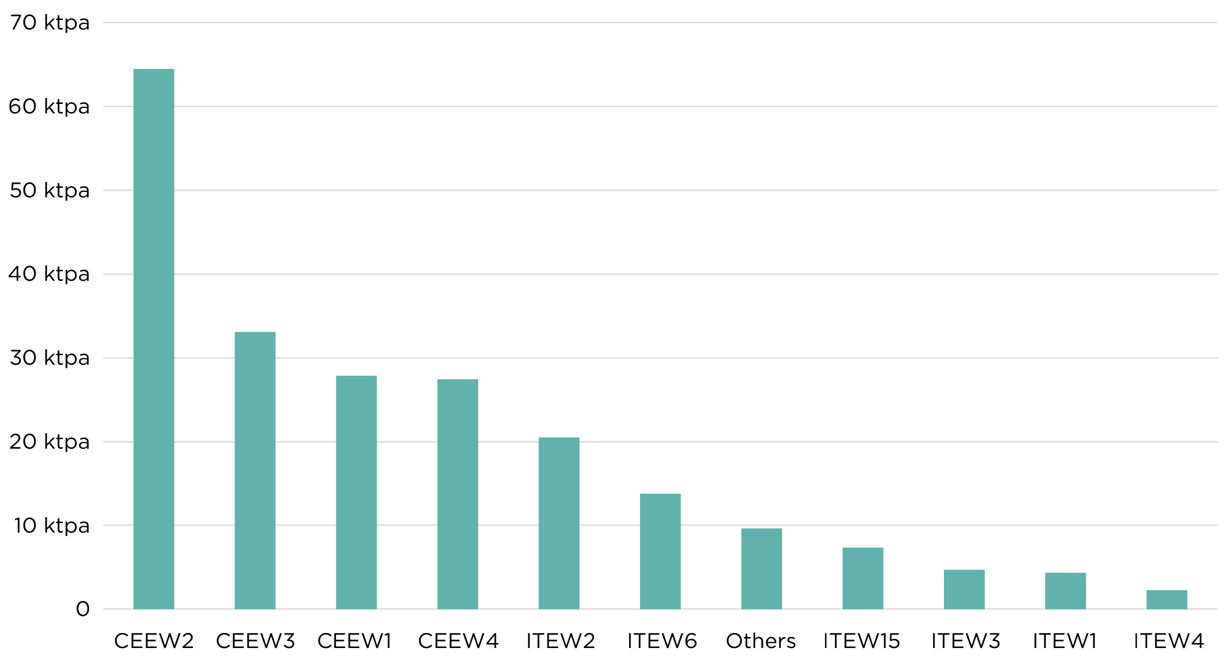


Figure A.1: E-waste Generated (ktpa) by Waste Types across India for the Year 2021-22

Figure A.1 presents the quantity of e-waste generated in kilo tonnes per annum (ktpa) across different categories in 2022. The e-waste forecasting methodology combined historical sales data (2011–2023), product lifespan assumptions, and second-life usage to estimate future e-waste volumes. For conventional electronics, the TNPCB (TNPCB, 2021) method using composite growth indices was applied (Annex B). E-waste generation was modelled using a two-parameter Weibull distribution[12] to estimate end-of-life timelines.

Table B.1: E-waste Categories Analysed

E-waste categories	
CEEW1	Television Sets
CEEW2	Refrigerator
CEEW3	Washing Machine
CEEW4	Air-Conditioners Excluding Centralized Air Conditioning Plants
CEEW5	Fluorescent and other Mercury containing Lamps
ITEW1	Centralized Data Processing: Mainframe
ITEW2	Personal Computing: Personal Computers
ITEW3	Personal Computing: Laptop Computers
ITEW4	Personal Computing: Notebook Computers
ITEW6	Printers including Cartridges
ITEW15	Cellular Telephones: Feature Phones
Lithium-ion batteries	
Solar PV panels	
Spent Magnets	

After e-waste forecasting, three steps were undertaken to estimate the recoverable material, particularly CETMs:

1. **Estimating E-waste processed:** Two distinct scenarios were modelled to reflect varying levels of policy ambition and infrastructure development; Current Policy Scenario: Aligns with the official processing targets set forth in India's policies for different e-waste categories and EV batteries. Reform Scenario (RS): Assumes enhanced efforts and infrastructure, aiming for an 85% processing rate for consumer durables. For spent magnets, processing rates were 25% in BS and 40% in AS, and for solar PV panel processing, rates were 70% in BS scenario and 90% in AS.

12 The Weibull distribution is a continuous probability distribution commonly used in probability theory and statistics. It's versatile model and can be used for a wide range of scenarios, especially related to time-to-failure or time between events. This makes it a valuable tool for analysing reliability data, predicting failures, and understanding the life characteristics of products or systems. It is characterised by two parameters: shape parameter (β): determines the distribution's form or the rate at which failures occur over time, and scale parameter (η): represents the lifespan, influencing the spread of the data.

Table B.2: E-waste processed projections

Year	Current Policy Scenario	Reform Scenario
2023-2024	60%	85%
2024-2025	60%	85%
2025-2026	70%	85%
2026-2027	70%	85%
2027-2028	80%	85%
2028-2029	80%	85%
2029 onwards	80%	85%

2. **Calculating material content in processed waste:** To estimate the total material content recoverable from processed waste, the e-waste processed was multiplied by material intensities values for each product type. Materials extracted from e-waste were categorised into two categories:

Critical Energy Transition Minerals	Non-Critical Materials
Cobalt, Copper, Graphite, Lithium, Nickel, Silicon, Platinum, Palladium and Neodymium	Iron, Aluminium, Lead, Gold, Silver, Zinc, Manganese, Plastics and Glass

3. **Computing recoveries:** A 95% recovery rate was assumed for minerals and metals embedded in processed waste. This accounts for high-performance recycling systems capable of extracting nearly all recoverable material from each waste stream.

Technology Assessment Framework (TAF) for Recycling Technology

A Technology Assessment Framework (TAF) supports decision making by helping stakeholders, such as government agencies, companies, and investors-evaluate and adopt appropriate technologies (Anjali Singh & Thirumalai N C, 2023). This is especially relevant in the context of India's formal e-waste recycling industries that are still at a nascent stage. A well-structured TAF can guide the selection of the right recycling technology based on the waste type and contextual priorities.

In this study, a technology assessment was carried out to identify the most efficient and scalable recycling technology for e-waste. The assessment evaluated three technologies—pyrometallurgy, hydrometallurgy (acid-leaching), and hydrometallurgy (bioleaching)—using a technical, economic, and environmental (TEE) framework.

To undertake this evaluation, the study applied the Fuzzy Technique for Order Preference by Similarity to Ideal Solution (Fuzzy-TOPSIS) method, which enables systematic comparison of alternatives under conditions of uncertainty (Choudhary & Shankar, 2012). Expert assessments of each technology were collected on a 1–5 scale—Very Low (VL), Low (L), Average (A), High (H), and Very High (VH)—and converted into triangular fuzzy numbers. This fuzzification allows the model to incorporate variability and judgement more realistically than crisp scoring.

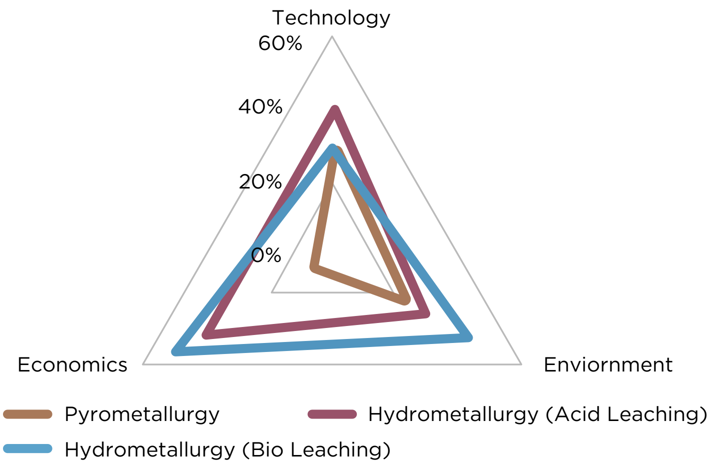


Figure B.1: Typical Representation of Results from TAF

The Fuzzy-TOPSIS approach maps experts ranking with triangular fuzzy numbers to determine the relevance of one criterion over another. A fuzzified decision matrix is prepared and the fuzzy-(TOPSIS) is applied on the fuzzified decision matrix under each criterion considered in this study.

Under the Fuzzy-TOPSIS approach, expert scores are translated into a weighted decision matrix, and each technology's performance is assessed relative to a positive ideal solution (best performance across all criteria) and a negative ideal solution (worst performance across all criteria). Final selection is determined using thze closeness coefficient, which measures how far an option is from the negative ideal and how close it is to the positive one. A higher coefficient indicates a better overall ranking.

This study also incorporates a modified aggregation method in which criterion weights are derived from the distances between fuzzy numbers—an approach that prevents zero-weight distortions and ensures that each TEE dimension is meaningfully represented in the final ranking.

The procedure of Fuzzy-TOPSIS starts from the construction of an evaluation matrix X = [Xij], where Xij denotes the valuation of the ith alternative with respect to jth criterion. It can be summarised as follows:

Step 1: Calculation of normalised decision matrix *Z* = [*zij*]

$$Z_{ij}=X_{ij} \,/\, \sqrt{\left(\sum_{i=1}^{n} X_{ij}^{2}\right)},\ j=1,\ \ldots,\ m,\ i=1,\ \ldots,\ n. \qquad \text{...(1)}$$

Step 2: Calculation of the weighted normalised decision matrix *V* = [*vij*]

$$Vij = Zij\ (\cdot)\ Wj,\ j=1,\ \ldots,\ m,\ i = 1,\ \ldots,\ n. \qquad \text{...(2)}$$

Step 3: Determination of the fuzzy positive and negative ideal solution *A+* and *A−*

$$A+ = \{V+1, \ldots, V+m\} = \left(\max_{i} V_{ij} \mid j \in B\right), \left(\min_{i} V_{ij} \mid j \in C\right) \qquad \text{...(3)}$$

$$A- = \{V-1, \ldots, V-m\} = \left(\max_{i} V_{ij} \mid j \in B\right), \left(\min_{i} V_{ij} \mid j \in C\right) \qquad \text{...(4)}$$

where B is for benefit criteria and C is for cost criteria.

Step 4: Calculation of the distance of each alternative from the positive ideal solution and negative ideal solution

$$d_i^+ = \sqrt{\sum_{j=1_m} \left(V_{ij} - V_j^+\right)}, \; i = 1,\; 2,\; 3\ldots\ldots\ldots, n, \qquad \ldots(5)$$

$$d_i^- = \sqrt{\sum_{j=1_m} \left(V_{ij} - V_j^-\right)}, \; i = 1,\; 2,\; 3\ldots\ldots\ldots, n, \qquad \ldots(6)$$

Step 5: Calculation of the relative closeness to the ideal solutions

$$CCi = \frac{d_i^-}{\left(d_i^- + d_i^+\right)}, \; i = 1,\; 2,\; 3,\ldots\ldots\ldots \;, n. \qquad \ldots(7)$$

Step 6: (ranking of alternatives): The closer the CC*i* is to one the higher the priority of the *i*th alternative technology.

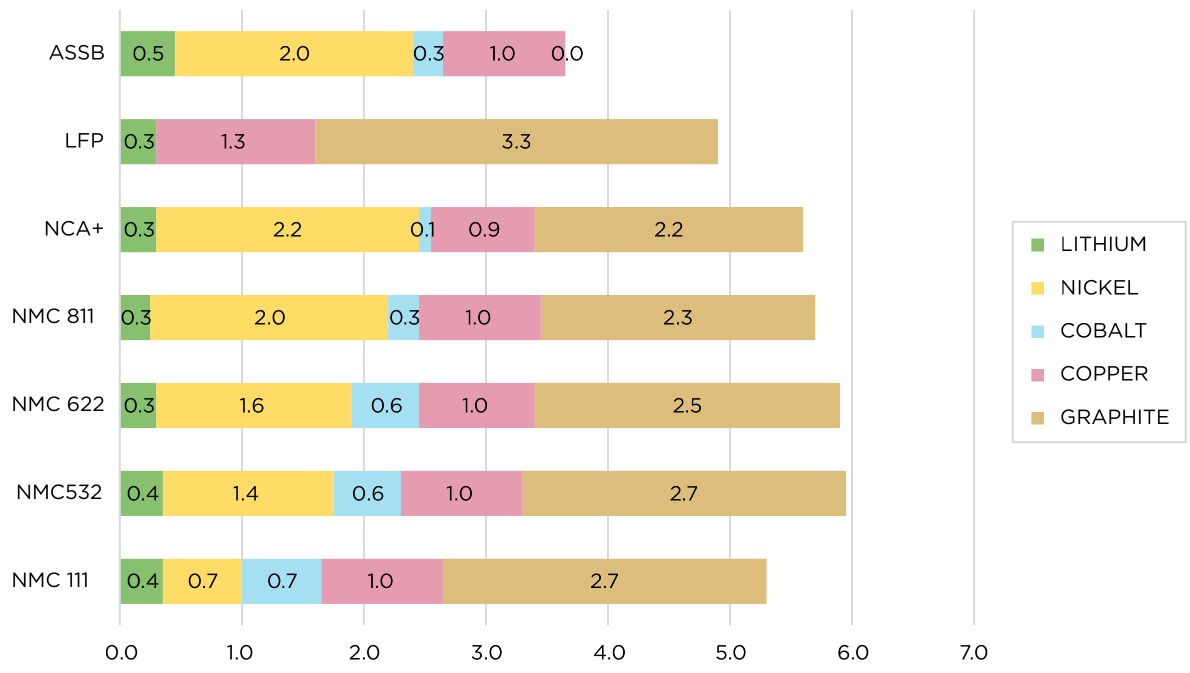


Figure B.2: Material Requirements across Battery Chemistry (kg/kWh).

CETM Demand Assessment for EV – batteries and motors

The study applies a bottom-up techno-economic modelling approach that incorporates forecasts of EV sales, component-specific technology trends, and material intensity estimates derived from peer-reviewed studies, reports, and industry or stakeholder consultations. The model estimates the embedded mineral demand of India's EV market from 2025 to 2070, disaggregated by vehicle segment, technology type, and scenario pathway.

Vehicle Sale Projections

EV sales projections for 2025 to 2070 were obtained from NITI Aayog's integrated energy sector models.

Technology Mapping

Each vehicle category was mapped to its corresponding technology components, including batteries and motors. The average battery capacity assumed for each segment is given in Figure B.3.

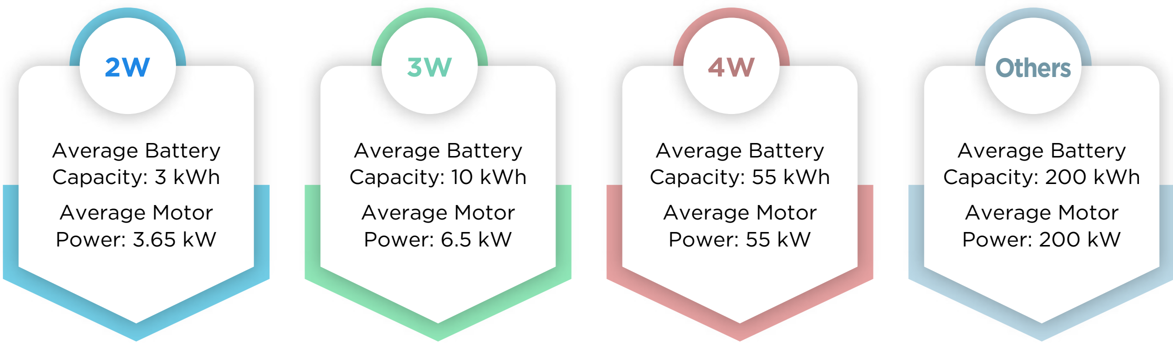


Figure B.3: Average Battery Capacity and Motor Power for Each Vehicle Segment

Battery-chemistry distribution was modelled dynamically using historical trends and forward-looking assessments from the IEA, drawing on both global and India-specific energy-transition scenarios. The base-case IEA scenario employed in this study reflects a continued shift away from cobalt-rich chemistries (such as NMC 111) toward higher-nickel variants (NMC 532, NMC 622, NMC 811) and increased adoption of LFP batteries, particularly in heavy trucks and entry-level passenger vehicles where cost and safety considerations dominate (International Energy Agency, 2021). The scenario also assumes that ASSBs begin commercial entry around 2030 and scale gradually after 2040 in premium and heavy-duty vehicles as improvements in energy density and performance mature.

The model considered seven key chemistries: Lithium, Nickel, Manganese, Cobalt Oxide (NMC)-111, 532, 622, and 811; LFP, and ASSB. Mineral intensity values were sourced from a combination of academic research, life-cycle assessments (LCA) studies, and private communications with industry experts and stakeholders. The intensity values (kg/kWh) for each chemistry and component are summarised in the accompanying graphs.

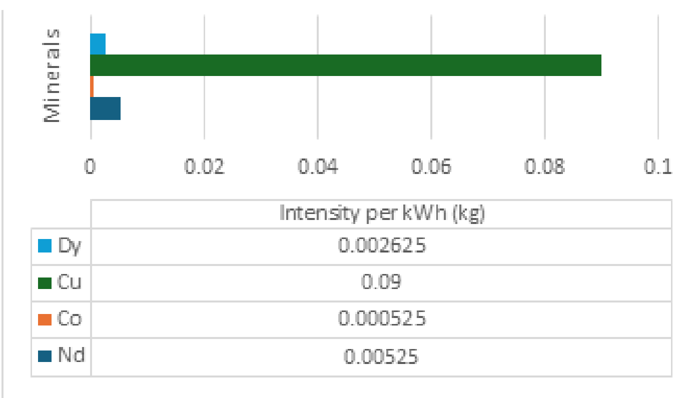


Figure B.4: Mineral Requirement for PMSM Motors

The analysis also assumes that permanent-magnet synchronous motors (PMSMs) account for roughly 93% of EV traction motors, reflecting their global dominance due to high efficiency and cross-segment applicability (Adamas Intelligence, 2020; *Global PMSM Market Share Continues to Rise Despite Soaring Rare Earth Prices, 2021*). In the Indian context, current mineral-demand projections assume that material intensities for batteries and motors remain largely static over time, with only marginal improvements. Material-substitution rates remain difficult to model given limited data and rapidly evolving technology pathways. As domestic R&D expands and technological choices diversify, future assessments may incorporate dynamic intensity and substitution parameters where credible data becomes available.

Mineral Demand Estimation Framework

Embedded demand for each critical mineral across EV segments was calculated using a bottom-up, component-level accounting method. Technology-specific material intensities were combined with projected vehicle sales and technology-share trajectories using the following formulation.

$$\mathbf{M}_{i,w,y} = \mathbf{S}_{w,y} \times \mathbf{C}_{w} \times \mathbf{T}_{i,w,y} \times \mathbf{I}_{i,w}$$

Where:

$M_{i,w,y}$ = Embedded mineral '*i*' (in kg) demand for vehicle type '*w*' in a year '*y*'

$S_{w,y}$ = Forecasted vehicle sales of vehicle type '*w*' in year '*y*'

C_{w} = Average vehicle component capacity for vehicle type '*w*' (e.g., battery in kWh and traction motors in kW)

$T_{i,w,y}$ = Market share of the technology using mineral '*i*' within vehicle type '*w*' in year 'y' (e.g., motor type or battery chemistry)

$I_{i,w}$ = Material intensity of mineral 'i' per unit of the vehicle component (in kg/kWh or kg/kW) for vehicle type 'w'.

Outputs were aggregated per year for each mineral to estimate the cumulative demand up to 2047 and 2070. The approach was kept similar to that of the other global demand forecasts such as the IEA (International Energy Agency, 2024)which are essential for a range of clean energy technologies, have risen up the policy agenda in recent years due to increasing demand, volatile price movements, supply chain bottlenecks and geopolitical concerns. The dynamic nature of the market necessitates greater transparency and reliable information to facilitate informed decision-making, as underscored by the request from Group of Seven (G7.

ANNEX C MATERIAL INTENSITY

Table C.1: Mineral Intensities (in t/GW) of Solar PV Technologies

Solar PV Technology	Nickel (Ni)	Tin (Sn)	Copper (Cu)	Silicon (Si)	Indium (In)	Gallium (Ga)	Selenium (Se)	Cadmium (Cd)	Tellurium (Te)	Molybdenum (Mo)	Tungsten (W)	Graphite	Titanium (Ti)	Lithium (Li)	Germanium (Ge)
Crystalline Silicon															
Monocrystalline Silicon (mono-Si) PV			4450	3000											
Polycrystalline Silicon (poly-Si) PV			4450	3000											
Heterojunction Silicon (HJT) PV			4600	4000											
Thin film solar cell															
Copper Indium Gallium Selenide (CIGS) Thin-Film PV		6	4622		15	4	35								
Amorphous Silicon (a-Si) Thin-Film PV			4600	150											48
Cadmium Telluride (CdTe)		103.3	4600					50	52						
Perovskite															
perovskite/ silicon tandem	0.132	0.456	0		2.259					0	0	0	0.972	0	
Perovskite APT	3.223	12.509	2.987		4.707					3.427	6.417	143.733	1.944	0.0024	

Source: *Rajesh Chadha & Ganesh Sivamani, 2024; Wagner et al., 2024; Prabhu et al., 2021*

Table C.2: Mineral Intensities (in t/GW) of Solar CSP Technologies

Solar CSP Technology	Categories	Copper (Cu)	Molybdenum (Mo)	Nickel (Ni)	Titanium (Ti)	Vanadium (V)	Niobium (Nb)
Parabolic troughs	Linear concentrating systems	3200	200	940	25	1.9	0
Solar power towers	Point Focus	1400	56	1800	0	1.7	140

Source: *Pihl et al., 2012*

Table C.3: Mineral Intensities (in t/GW) of Onshore & Offshore Wind Technologies

Wind Technology	Category	Wind turbine types	Copper (Cu)	Dysprosium (Dy)	Molybdenum (Mo)	Neodymium (Nd)	Nickel (Ni)	Praseodymium (Pr)	Terbium (Tb)	Yttrium (Y)
Onshore										
GB-HS-PMSG (GB HS PMG)	Gearbox	Gearbox High Speed Permanent Magnet Synchronous Generator	1150	7	110	70	490	4	1	
GB-DFIG	Gearbox	Gearbox Doubly-Fed Induction Generator	1900	3	110	18	490	0	0	
GB-SCIG	Gearbox	Gearbox-Squirrel Cage Induction Generator	1000	4.7	110	34	490	0	0	
DD-EESG	Direct Drive	Direct Drive Electrically Excited Synchronous Generator	6200	0	110	0	490	0	0	
DD-PMSG	Direct Drive	Direct Drive Permanent Magnet Synchronous Generator	4600	21	110	210	490	35	7	
Offshore										
DD-EESG	Direct Drive	Direct Drive Electrically Excited Synchronous Generator	1150	7	110	70	490	4	1	
DD-PMSG	Direct Drive	Direct Drive Permanent Magnet Synchronous Generator	1900	3	110	18	490	0	0	
DD-HTS	Direct Drive	Direct Drive High temperature semiconductor	1000	4.7	110	34	490	0	0	0.3
GB-MS PMG	Gearbox	Gearbox Medium Speed Permanent Magnet Synchronous Generator	6200	0	110	0	490	0	0	

Source: *European Commission. Joint Research Centre., 2020*

Table C.4: Mineral Intensities (in t/GWh) of BESS Technologies

BESS Technology	Battery Type	Graphite	Lithium (Li)	Cobalt (Co)	Nickel (Ni)	Copper (Cu)	Vanadium (V)	Titanium (Ti)	Phosphorous
Prussian Blue Analogues ($Na_2Fe[Fe(CN)_6]$)	**(PBA)**				580				
Lead-Acid	**Pb-A**								
NASICON ($Na_3V_2(PO_4)_3$	**NVP**						598		545
Vanadium Redox Flow Battery	**VRFB**					21	3400		
Lithium Nickel Manganese Cobalt	**NMC 523**	883	117	183	467				
Lithium Titanate	**LTO**		54					469	
Lithium Iron Phosphate	**LFP**	1100	87	0	0	433			387
Sodium Iron Phosphate ($NaFePO_4$)	**NFP**								457
Lithium Nickel Manganese Cobalt	**LNMC-811**	750	83	83	650	333			
Layered Sodium Manganese Oxide ($NaMnO_2$)	**NaMO2**								
Sodium Nickel Manganese Cobalt	**NaNMC**			83	650				
Lithium Nickel Manganese Cobalt	**LNMC-622**	883	100	183	533	317			
Sodium-Nickel Chloride	**NaNiCl2**				1500				
Polysulfide Bromide	**PSB**								

BESS Technology	Battery Type	Graphite	Lithium (Li)	Cobalt (Co)	Nickel (Ni)	Copper (Cu)	Vanadium (V)	Titanium (Ti)	Phosphorous
Lithium Manganese Oxide	**LMO**		97	0	0	0			
Solid-State Batteries	**ESS**		200						
Lithium Nickel cobalt aluminium Oxide	**NCA**	733	100	33	717	283			
Sodium-Sulphur	**NaS**								
Lithium-Sulphur Batteries	**Li-S**		200						
Zinc-Bromine	**ZnBr**								

Source: *(IEA, 2023)*

Table C.5: Mineral Intensities (in t/GW) of Electrolysers for Hydrogen

Technology	Copper (Cu)	Zirconium (Zr)	Nickel (Ni)	Graphite	Cobalt (Co)	Iridium (Ir)	Platinum (Pt)	Silicon (Si)	Titanium (Ti)	Lanthanum (La)	Strontium (Sr)	Gadolinium (Gd)	Cerium (Ce)	Yttrium (Y)
Alkaline Electrolysers (AEL)	533.33	245	5066.67	114.67	8									
Proton Exchange Membrane Electrolysers (PEMEL)	0.53			1.7		1.4	0.19	1.05	0.61					
Solid Oxide Electrolysis (SOEL)	14.149	0.90761	1.791					14.149	6.5084	1.2882	0.038128	0.0053167	0.01895	0.062563

Source: (Teixeira et al., 2024)(IEA, 2021)(Koj et al., 2017)

Table C.6: Mineral Intensities (in kg/vehicle) for EV Battery Technology

Vehicle Type	Category	Lithium	Nickel	Cobalt	Copper	Graphite	Phosphorous
2 WHEELERS	NMC 111	0.4	0.7	0.7	1.0	2.7	0.0
	NMC532	0.4	1.4	0.6	1.0	2.7	0.0
	NMC 622	0.3	1.6	0.6	1.0	2.5	0.0
	NMC 811	0.3	2.0	0.3	1.0	2.3	0.0
	NCA+	0.3	2.2	0.1	0.9	2.2	0.0
	LFP	0.3	0.0	0.0	1.3	3.3	1.3
	ASSB	0.5	2.0	0.3	1.0	0.0	0.0
3 WHEELERS	NMC 111	1.2	2.2	2.2	3.3	8.8	0.0
	NMC 532	1.2	4.7	1.8	3.3	8.8	0.0
	NMC 622	1.0	5.3	1.8	3.2	8.3	0.0
	NMC 811	0.8	6.5	0.8	3.3	7.5	0.0
	NCA+	1.0	7.2	0.3	2.8	7.3	0.0
	LFP	1.0	0.0	0.0	4.3	11.0	4.5
	ASSB	1.5	6.5	0.8	3.3	0.0	0.0
4 WHEELERS	NMC 111	6.4	11.9	11.9	18.3	48.5	0.0
	NMC 532	6.4	25.7	10.1	18.3	48.6	0.0
	NMC 622	5.5	29.3	10.1	17.4	45.8	0.0
	NMC 811	4.6	35.8	4.6	18.3	41.3	0.0
	NCA+	5.5	39.4	1.8	15.6	40.3	0.0
	LFP	5.5	0.0	0.0	23.8	60.5	24.5
	ASSB	8.3	35.8	4.6	18.3	0.0	0.0
OTHERS	NMC 111	23.3	43.3	43.3	66.7	176.7	0.0
	NMC532	23.3	93.3	36.7	66.7	176.7	0.0
	NMC 622	20.0	106.7	36.7	63.3	166.7	0.0
	NMC 811	16.7	130.0	16.7	66.7	150.0	0.0
	NCA+	20.0	143.3	6.7	56.7	146.7	0.0
	LFP	20.0	0.0	0.0	86.7	220.0	89.2
	ASSB	30.0	130.0	16.7	66.7	0.0	0.0

Source: *Bhutada, 2022*

Table C.7: Mineral Intensities (in kg/kW) of Motors for EVs

Cobalt	Copper	Dysprosium	Neodymium
0.000525	0.09	0.002625	0.00525

Source: *(Elwert et al., 2016)(Luke Gear & Dr Richard Collins, 2020)*

ANNEX D MARKET SHARE OF EACH LOW-CARBON TECHNOLOGY

Market share of each sub-technology in Solar PV, Solar CSP, Onshore Wind, Offshore Wind, BESS, and Electrolysers, respectively (cumulative for 5-year periods starting 2025).

The updated version of NITI Aayog's IESS and the TIMES Model provides new capacity addition values for Solar as a combined category. From the combined solar category, the separate new capacity values for Solar PV and CSP are estimated by taking their share in total capacity from the older version of IESS 2047 (V3.0). The resulting disaggregated values are presented in Tables E.1 and E.2.

Table D.1: Market Share of Sub-Technologies in Solar PV

Year	2030	2035	2040	2045	2050	2055	2060	2065	2070
Solar PV Technology (under Current Policy Scenario)									
Monocrystalline Silicon (mono-Si) PV	52%	49%	45%	42%	40%	38%	36%	34%	32%
Polycrystalline Silicon (poly-Si) PV	27%	25%	22%	20%	19%	18%	17%	17%	17%
Heterojunction Silicon (HJT) PV	10%	12%	14%	15%	17%	18%	19%	19%	19%
Copper Indium Gallium Selenide (CIGS) Thin-Film PV	3%	4%	5%	6%	7%	8%	9%	11%	12%
Amorphous Silicon (a-Si) Thin-Film PV	2%	2%	1%	1%	1%	1%	1%	0%	0%
Cadmium Telluride (CdTe)	5%	6%	7%	7%	7%	7%	8%	8%	8%
Perovskite/silicon tandem	0%	2%	4%	5%	6%	6%	7%	7%	8%
Perovskite APT	0%	0%	3%	4%	5%	5%	5%	5%	5%
Solar PV Technology (under Net Zero Scenario)									
Monocrystalline Silicon (mono-Si) PV	50%	45%	40%	35%	32%	28%	26%	25%	24%
Polycrystalline Silicon (poly-Si) PV	28%	24%	19%	15%	12%	10%	8%	7%	5%
Heterojunction Silicon (HJT) PV	10%	13%	15%	17%	18%	19%	20%	20%	20%
Copper Indium Gallium Selenide (CIGS) Thin-Film PV	5%	6%	7%	9%	11%	13%	14%	15%	16%

Year	2030	2035	2040	2045	2050	2055	2060	2065	2070
Amorphous Silicon (a-Si) Thin-Film PV	1%	1%	1%	1%	1%	1%	0%	0%	0%
Cadmium Telluride (CdTe)	6%	7%	9%	11%	12%	13%	13%	13%	13%
Perovskite/silicon tandem	0%	4%	5%	7%	8%	9%	10%	11%	11%
Perovskite APT	0%	0%	4%	5%	6%	7%	8%	10%	11%

Table D.2: Market Share of Sub-Technologies in Solar CSP

Year	2030	2035	2040	2045	2050	2055	2060	2065	2070
Solar CSP (under Current Policy Scenario)									
Parabolic troughs	94%	91%	89%	87%	86%	84%	82%	81%	80%
Solar power towers	6%	9%	11%	13%	14%	16%	18%	19%	20%
Solar CSP (under Net Zero Scenario)									
Parabolic troughs	75%	55%	45%	35%	30%	25%	22%	21%	20%
Solar power towers	25%	45%	55%	65%	70%	75%	78%	79%	80%

Table D.3: Market Share of Sub-Technologies in Onshore and Offshore Wind

Year	2030	2035	2040	2045	2050	2055	2060	2065	2070
Onshore Wind (under Current Policy Scenario)									
GB-HS-PMSG (GB HS PMG)	37%	39%	40%	41%	41%	42%	43%	44%	45%
GB-DFIG	22%	19%	15%	13%	11%	10%	8%	7%	5%
GB-SCIG	1%	1%	1%	1%	1%	1%	1%	1%	1%
DD-EESG	32%	33%	34%	35%	35%	36%	36%	37%	37%
DD-PMSG	8%	9%	10%	11%	11%	11%	12%	12%	12%
Onshore Wind (under Net Zero Scenario)									
GB-HS-PMSG (GB HS PMG)	43%	44%	45%	45%	45%	45%	45%	45%	45%
GB-DFIG	7%	5%	3%	1%	0%	0%	0%	0%	0%
GB-SCIG	1%	0%	0%	0%	0%	0%	0%	0%	0%
DD-EESG	24%	25%	26%	27%	27%	27%	27%	28%	28%
DD-PMSG	25%	26%	26%	27%	28%	27%	27%	28%	28%
Offshore Wind (under Current Policy Scenario)									
GB-SCIG	57%	56%	54%	52%	50%	48%	45%	45%	45%
DD-PMSG	31%	30%	29%	27%	26%	25%	25%	24%	24%

Year	2030	2035	2040	2045	2050	2055	2060	2065	2070
DD-HTS	0%	2%	5%	8%	11%	14%	17%	18%	17%
GB-MS PMG	12%	12%	12%	13%	13%	13%	13%	13%	14%
Offshore Wind (under Net Zero Scenario)									
GB-SCIG	5%	5%	5%	4%	4%	3%	3%	3%	3%
DD-PMSG	82%	84%	85%	86%	87%	88%	88%	88%	88%
DD-HTS	0%	0%	0%	0%	0%	0%	0%	0%	0%
GB-MS PMG	12%	11%	11%	10%	10%	9%	9%	9%	9%

Table D.4: Market Share of Sub-Technologies in BESS

Year	2030	2035	2040	2045	2050	2055	2060	2065	2070
BESS (same market share under Current Policy Scenario and Net Zero Scenario)									
Lithium Iron Phosphate	86.0%	80.0%	75.2%	70.3%	65.8%	61.2%	56.5%	51.4%	46.1%
NMC 523	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
NMC 811	1.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
NMC 622	1.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Lithium Titanate	0.9%	1.5%	2.1%	2.7%	3.3%	3.9%	4.5%	5.1%	5.7%
Lithium Manganese Oxide	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Lithium Nickel cobalt aluminium Oxide	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Sodium Iron Phosphate ($NaFePO_4$)	1.0%	2.0%	2.3%	2.6%	3.0%	3.3%	3.7%	4.1%	4.4%
Prussian Blue Analogues ($Na_2Fe[Fe(CN)_6]$)	1.0%	2.0%	2.3%	2.6%	3.0%	3.3%	3.7%	4.1%	4.4%
NASICON ($Na_3V_2(PO_4)_3$	1.0%	2.0%	2.3%	2.6%	3.0%	3.3%	3.7%	4.1%	4.4%
Layered Sodium Manganese Oxide ($NaMnO_2$)	1.0%	2.0%	2.3%	2.6%	3.0%	3.3%	3.7%	4.1%	4.4%
Sodium Nickel Manganese Cobalt	1.0%	2.0%	2.3%	2.6%	3.0%	3.3%	3.7%	4.1%	4.4%
Sodium-Nickel Chloride	1.0%	1.5%	2.0%	2.4%	2.6%	2.8%	3.0%	3.2%	3.4%
Sodium-Sulphur	1.0%	1.4%	1.8%	2.2%	2.4%	2.6%	2.8%	3.0%	3.2%
Vanadium Redox Flow Battery	1.5%	1.8%	2.1%	2.4%	2.7%	3.0%	3.3%	3.6%	4.0%
Polysulfide Bromide	0.8%	1.2%	1.6%	2.0%	2.4%	2.8%	3.2%	3.6%	4.0%

Year	2030	2035	2040	2045	2050	2055	2060	2065	2070
Zinc-Bromine	0.8%	1.2%	1.6%	2.0%	2.4%	2.8%	3.2%	3.6%	4.0%
Solid-State Batteries	0.2%	0.4%	0.6%	1.0%	1.4%	1.8%	2.2%	2.6%	4.0%
Lithium-Sulphur Batteries	0.0%	1.0%	1.4%	1.8%	2.2%	2.6%	3.0%	3.4%	3.8%
Lead-Acid	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table D.5: Market Share of Sub-Technologies in Electrolysers

Year	2030	2035	2040	2045	2050	2055	2060	2065	2070
Electrolysers (same market share under Current Policy Scenario and Net Zero Scenario)									
alkaline electrolysers (AEL)	65%	60%	55%	50%	45%	40%	35%	30%	25%
proton exchange membrane electrolysers (PEMEL)	25%	27%	28%	29%	30%	31%	32%	33%	34%
solid oxide electrolysis (SOEL)	10%	13%	17%	21%	25%	29%	33%	37%	41%

Table D.6: Market Share of Sub-Technologies in EV Batteries

Vehicle Category	Battery Type	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050	2050-2055	2055-2060	2060-2065	2065-2070
2Ws	NMC 111	3%	2%	0%	0%	0%	0%	0%	0%	0%
	NMC 532	8%	4%	0%	0%	0%	0%	0%	0%	0%
	NMC 622	11%	8%	6%	6%	6%	5%	5%	5%	2%
	NMC 811	63%	65%	67%	67%	67%	67%	67%	67%	67%
	NCA+	6%	4%	2%	2%	2%	2%	2%	2%	2%
	LFP	8%	10%	11%	11%	11%	11%	11%	11%	15%
	ASSB	0%	7%	14%	14%	14%	14%	14%	14%	14%
3Ws	NMC 111	3%	2%	0%	0%	0%	0%	0%	0%	0%
	NMC 532	8%	4%	0%	0%	0%	0%	0%	0%	0%
	NMC 622	11%	8%	6%	6%	6%	5%	5%	5%	2%
	NMC 811	63%	65%	67%	67%	67%	67%	67%	67%	67%
	NCA+	6%	4%	2%	2%	2%	2%	2%	2%	2%
	LFP	8%	10%	11%	11%	11%	11%	11%	11%	15%
	ASSB	0%	7%	14%	14%	14%	14%	14%	14%	14%

Vehicle Category	Battery Type	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050	2050-2055	2055-2060	2060-2065	2065-2070
4Ws	NMC 111	2%	0%	0%	0%	0%	0%	0%	0%	0%
	NMC 532	5%	3%	2%	0%	0%	0%	0%	0%	0%
	NMC 622	7%	4%	2%	1%	0%	0%	0%	0%	0%
	NMC 811	22%	23%	21%	18%	14%	11%	8%	5%	3%
	NCA+	6%	4%	2%	2%	0%	0%	0%	0%	0%
	LFP	58%	64%	68%	71%	74%	73%	70%	67%	63%
	ASSB	0%	2%	5%	8%	12%	16%	22%	28%	34%
OTHERS	NMC 111	0%	0%	0%	0%	0%	0%	0%	0%	0%
	NMC 532	0%	0%	0%	0%	0%	0%	0%	0%	0%
	NMC 622	10%	10%	10%	10%	10%	8%	8%	8%	5%
	NMC 811	0%	0%	0%	0%	0%	0%	0%	0%	0%
	NCA+	0%	0%	0%	0%	0%	0%	0%	0%	0%
	LFP	90%	85%	80%	80%	80%	80%	80%	80%	80%
	ASSB	0%	5%	10%	10%	10%	12%	12%	12%	15%

ANNEX E DEMAND FOR CRITICAL ENERGY TRANSITION MINERALS

Table E.1: Demand for Critical Energy Transition Minerals at Different Time Horizons

Name	Current Policy Scenario (Tonnes)			Net Zero Scenario (Tonnes)		
	2025-2030	2031-2050	2051-2070	2025-2030	2031-2050	2051-2070
Copper	1447931	13917166	28532628	1882424	20623186	43563856
Graphite	279372	10237656	20862674	700016	14955111	30833997
Silicon	858502	4794167	8851178	924808	6738516	11874935
Phosphorous	80274	3409639	7668264	214298	5044803	11430049
Nickel	133218	2585554	5307677	253940	3758838	7530909
Lithium	27118	1119950	2601999	66305	1624768	3777590
Cobalt	11574	336336	660669	23598	478156	926934
Vanadium	1756	65802	253890	8274	149672	625455
Neodymium	4441	90600	185657	11689	154897	315898
Molybdemum	7230	71045	126440	11298	91786	170771
Titanium	150	8985	41642	635	20347	103070
Dysprosium	954	31410	67497	2363	47152	100488
Tin	1330	11160	28417	1706	28318	88821
Tellurium	709	5789	13476	1047	14965	42618
Cadmium	622	4850	11588	788	12435	37227

Name	Current Policy Scenario (Tonnes)			Net Zero Scenario (Tonnes)		
	2025-2030	2031-2050	2051-2070	2025-2030	2031-2050	2051-2070
Selenium	260	2898	11377	460	7452	29430
Zirconium	2001	6930	11420	4001	19867	23919
Praseodymium	330	3624	6583	1092	9802	18849
Indium	117	1648	6296	208	4104	16587
Tungsten	0	315	1252	0	656	3385
Gallium	30	331	1300	53	852	3363
Niobium	4	56	318	10	265	1596
Germanium	241	804	618	126	798	928
Lanthanum	1.2	11	52	2	33	108
Platinum	0.7	4	11	1	11	23
Yttrium	0.1	1.2	5.4	0.1	1.6	5.3
Strontium	0.0	0.3	1.5	0.1	1.0	3.2
Cerium	0.0	0.2	0.8	0.0	0.5	1.6
Gadolinium	0.0	0.0	0.2	0.0	0.1	0.4

ANNEX F GROWTH RATES FOR DIFFERENT E-WASTE CATEGORIES

Table F.1: Growth Rates for Different E-waste Categories

		CAGR (2018-2023)	Deploy-ment: Household	Deploy-ment: Organisa-tional	CGI (H)[13]	CGI (P&I)[14]	CGI (O)[15]	Weighted Average	Average Growth
CEEW1	TV Sets	2%	70%	30%	1.05		1.04	1.046	3.55%
CEEW2	Refrigerator	3%	100%		1.05			1.050	3.88%
CEEW3	Washing Machine	6%	100%		1.05			1.050	5.62%

13 composite growth index (Households) =

$$\left(1+\frac{\text{Percapita Income growth rate}}{100}\times\frac{\text{Internet Penetration}}{100}\right)\times\left(1+\frac{\text{Household Growth rate}}{100}\right)$$

14 composite growth index (Personal and Industrial) =

$$\left(1+\frac{\text{Percapita Income growth rate}}{100}\times\frac{\text{Internet Penetration}}{100}\times\frac{\text{cellphone growth rate}}{100}\right)\times\left(1+\frac{\text{Population Growth rate}}{100}\right)$$

15 composite growth index (Organisational) =

$$\left(1+\frac{\text{Percapita Income growth rate}}{100}\times\frac{\text{Internet Penetration}}{100}\right)\times\left(1+\frac{\text{Population Growth rate}}{100}\times\frac{\text{share of manufacturing and services to GDP}}{100}\right)$$

		CAGR (2018-2023)	Deploy-ment: Household	Deploy-ment: Organisa-tional	CGI (H)[13]	CGI (P&I)[14]	CGI (O)[15]	Weighted Average	Average Growth
CEEW4	AC	11%	60%	40%	1.050		1.04	1.045	7.66%
CEEW5	Fluorescent and other Mercury containing lamps	5%	70%	30%	1.050		1.04	1.046	4.76%
ITEW1	Centralised Data Processing: Mainframe	8%		100%			1.04	1.037	5.64%
ITEW2	Personal Computers	-4%	70%	30%	1.050		1.04	1.046	0.22%
ITEW3	Laptops	5%	70%	30%	1.050		1.04	1.046	4.69%
ITEW6	Printers	2%	30%	70%	1.050		1.04	1.041	2.94%
ITEW15	Cellular Phones	5%				1.19		1.185	11.93%

ANNEX G SHAPE, SCALE AND WEIGHTS PARAMETERS USED FOR THE E-WASTE PROJECTION

Table G.1: Shape, Scale and Weights Parameters used for the E-waste Projection

Code	Waste Type	E-waste life (yrs)	E-waste weight (kg)	Shape Parameter
CEEW1	TV Sets	9	13.2	3.75
CEEW2	Refrigerator	10	34	4
CEEW3	Washing Machine	9	67	4
CEEW4	AC	10	47	5
CEEW5	Fluorescent and other Mercury containing lamps	5	0.2	3.2
ITEW1	Centralised Data Processing: Mainframe	10	35	3.5
ITEW2	Personal Computers	5	7.5	3.5
ITEW3	Laptops	5	2.63	3.2
ITEW6	Printers	10	6.5	3.8
ITEW15	Cellular Phones	3	0.2	2.8
NA1	Spent Magnets: Wind Turbines	25	450	2
NA2	Solar PV panels	25	9	2.5
NA3	EV LIB Batteries	10	45	4

ANNEX H TECHNOLOGICAL CAPABILITIES IN PROCESSING CETMS FROM PRIMARY AND SECONDARY SOURCES

Table H.1: Mapping of India's Technological Capabilities in Processing CETMs

Type of Use	Minerals
Battery Materials	Li, Co, Ni, V, Graphite
Rare Earths & Magnetics	Nd, Pr, Tb, Y, Sc
Electronics/Semiconductors	Ga, Ge, In, Te, Se
Alloying & Structural	Ti, Nb, Ta

Primary Source

Metal	Resource	Availability	Process of India	Merits/ demerits	Non-Indian Process	Merit/ Demerits	Technology Assessment of Indian process
Li	Spodumene, Lepidolite, Zinnwaldite	Yes, in Karnataka, Jharkhand, Rajasthan	Yes, CSIR-NML and CSIR-IMMT	Beneficiation gives 4.5% Li_2O 98% pure Li product by acid process	Acid Process in ABC, China	Operational with higher Li content 99% LiOH/ LCE	At Par
Co	Cobalt ore	Yes, Odisha, Jharkhand	Yes 2ktpy by NICOMET, CUNCOLIM, RUBAMIN, HZL	Hydrometallurgy and Solvent Extraction	Acid Process in China	99% Co salts	At Par
Ni	Nickel	Yes, Odisha, Jharkhand	EMEW at HCL 5,400 MTPA by NICOMET	Hydrometallurgy with Acid	Acid Process in China, US, Australia	99% Ni Salts	At Par
Nd, Pr	REE Ore, Monazite	Yes, in Gujarat and Beach sand	Yes	99% extraction in solution Purification uncompleted	Alkali-Acid Process in China	99% salts	Not at Par
Tb,Y	REE Ore	No	No	No	Acid Process in China	High Pure oxide salt	NA
Ti	Titanate and Titaniferous magnetite	No	Yes, CSIR-NML and CSIR-IMMT	TiO_2 concentrate	Kroll Process	High Pure TiO_2, $TiCl_4$ and Ti Metal	Not at Par
Graphite	Graphite Mines	Yes, in Odisha, Jharkhand, Tamil Nadu	Yes, CSIR-NML and CSIR-NIIST	Column beneficiation TRL-9 Process	Beneficiation	High pure graphite	At Par

Metal	Resource	Availability	Process of India	Merits/ demerits	Non-Indian Process	Merit/ Demerits	Technology Assessment of Indian process
V	Vanadite	Yes, in Karnataka, North East	Yes, CSIR-NML	AMV, and Fe-V	Alkali Roasting process in CSIRO	High Pure Sodium Vanadate	At Par
W	Zinnwaldite	Yes, in Rajasthan	Yes, CSIR-NML	Granite beneficiation WO3 from concentrate	Alkali roasting in Poland	90% MOH	At Par
Ga	NIL	NIL	NA	NA	Alkali processing in China	Ga salt and metal	NA
Ge	Sphalerite	Yes, in Rajasthan	No	NA	Acid leaching in Brazil, China	>90% extraction in solution GeCl4 product tested	NA
In	NIL	NA	NA	NA	Acid Process in C	ITO 99%	NA
Nb Ta	Cassiterite (Sn)	Yes, in Karnataka, Jharkhand, MP	Yes, CSIR-NML and BARC	52% Fe- Nb concentrate Nb, Ta, Sn salts	HF leaching	4N pure salts	No
Sc	NA	NA	NA	NA	Acid Process in ABC, China	90% pure salts and misch oxides	NA
Te, Se	Copper Ores	Yes, in Jharkhand, Rajasthan	NA	NA	Alkali Process in China	Oxide Salts	NA

Secondary Sources

Metal	Resource	Availability	Process of India	Merits/ demerits	Non-Indian Process	Merit/ Demerits	Technology Assessment of Indian process
Li, Co, Ni	LIBs	1.2billiontpa	Acid leaching	Patented at NML Applies on all 7 LIB Chemistries 99% pure salts •85% solvent/ chemical recycling	Yes, Glencore, Li Cycle, Toxco, etc.	Focusses on LCO, NMC High pure salts with fluid recycling	At Par
Nd, Pr	Magnets	–	Acid leaching	Patented at NML 99% pure salts	Yes, Boliden, Umicore	High Pure salts	At Par
Tb, Y	Phosphors	173mtpa	Acid leaching	Patented at NML 99% pure salts Eu, Y salts are derivatives	Yes, Boliden, Umicore	High Pure salts	At Par
Ti	Red Mud	19mtpa	Acid leaching	80% purity of oxide	Yes, Greek Rud Mud Consortium	High Pure Ti oxide	At Par
Graphite	LIBs	1.2billiontpa	Acid leaching	Patented at NML 90% pure graphite/graphene	Yes, Glencore, Li Cycle, Toxco, etc.	High Pure graphite flakes	At Par
V	Spent catalyst, Coal Slag, Bayer's Sludge	–	Varies with Feed	Patented at NML High Pure vanadium salts on TRL-9	Yes, AVX	High Pure oxides and metals	At Par
W	Tool Scrap and Die Scrap	—-	Acid leaching	Patented at NML YTO, APT, Co-salt	Yes, BOLIDEN	Yellow Tungsten Oxide (WO_3)	At Par
Ga	Red Mud and Bayer's Liquor	19mtpa	Solvent Extraction	Patented at NML 4N pure metal	No	NA	–
Ge	Zinc wastes	6mtpa	NA	NA	Boliden	Makes Ge Product	NA
In	LCD screens	700tpa	Acid leaching	Flowsheets with NML, IITR	Boliden	Indium Tin Oxide	Yes
Nb, Ta	Tin Slag, WEEE capacitors	1.2billiontpa	Acid/ Alkali leaching	High Nb, Ta recovery	NIL	NA	
Sc	Red Mud	19.68mtpa	Acid Leaching	90% recovery	RUSAL	>90% pure salts	No
Te, Se	Copper Slimes	700 mtpa	Alkali Process	99% Pure Se and Te metal Powder with Cu regenerated	—-	——	NA

ANNEX I CUMULATIVE RECOVERIES FROM E-WASTE UNTIL 2047 (REFORM SCENARIO)

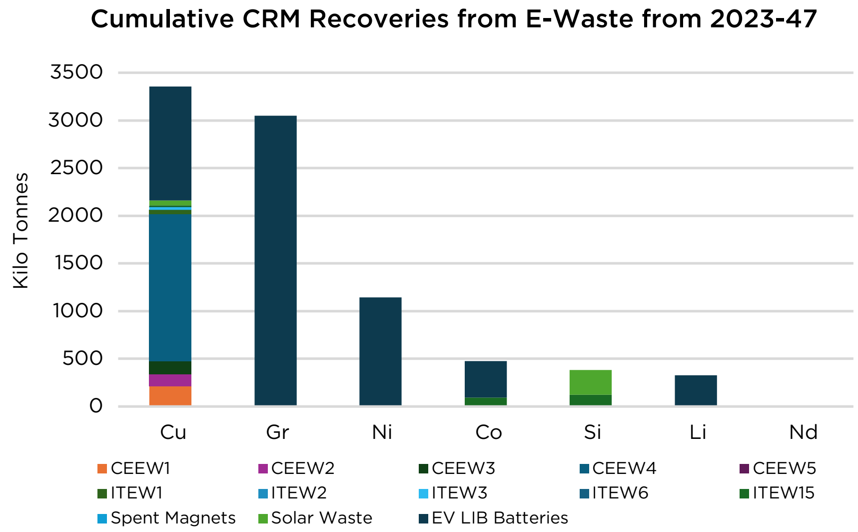


Figure I.1: Cumulative CETM Recoveries from E-waste Between 2025 and 2047 (Reform Scenario)

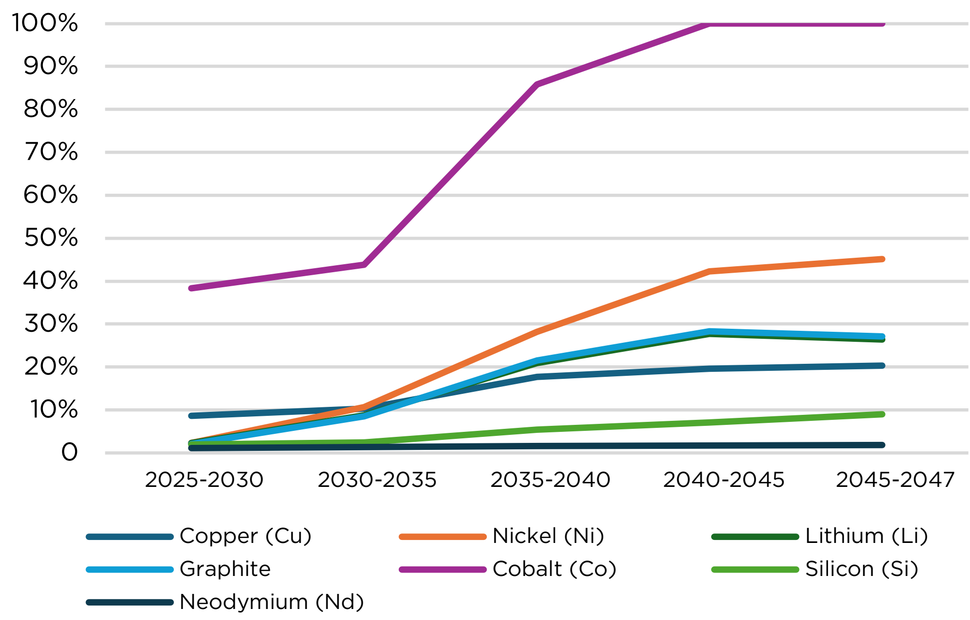


Figure I.2: Share of Mineral Demand fulfilled by Recycled Minerals Between 2025 and 2047 (Reform Scenario)

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