Resource Reality

Mapping India's Critical Mineral Needs for Clean Energy Success

With India's ambitious eye on Net-Zero 2070, the demand for clean energy is seeing a surge. The newer technologies based on renewable energy has put stress on the demand for critical minerals like copper, lithium, cobalt, nickel, graphite, among others. In this article, **Animesh Ghosh** and **Soumit Pandey** estimate India's critical mineral demands in the years to come.

The global transition towards renewable energy has significantly increased the demand for critical minerals (CM), like copper, lithium, cobalt, nickel, graphite[1], and rare earth elements. These minerals are essential for manufacturing materials of clean energy (CE) technologies, including solar panels, wind turbines, battery energy storage systems, and electric vehicles[2,3]. As the adoption of these technologies accelerates, the demand for CM is projected to rise substantially in the coming decades, raising concerns about supply and sustainability[4,5]. As a fast-developing economy, India is actively participating in this energy transition but has increasingly relied on imports to meet the demand for these essential materials[6,7]. Despite India's ample domestic resources, low and ineffective domestic production has hindered the establishment of a self-reliant supply chain, making imports indispensable. This dependency exposes India to significant geopolitical risks, including supply disruptions and price volatility arising from global competition and monopolistic control by mineral-rich nations[8]. As the global energy transition accelerates, these risks will likely intensify, further threatening India's CE aspirations and necessitating a robust and strategic approach to critical mineral management.

To address these challenges, India needs to develop a comprehensive strategy to secure the supply of critical minerals (CM) required for its clean energy (CE) transition. Possible

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approaches include diversifying import sources[9], investing in domestic exploration and mining[10], and developing recycling and circular economy solutions[11] to reduce reliance on primary resource extraction. Government initiatives like Viksit Bharat and Vocal for Local aim to strengthen domestic critical mineral exploration and supply chains, which are vital for achieving net-zero emissions by 2070. The 2024 budget underscores self-reliance, while India's membership in the minerals security partnership ensures global supply security. While the Ministry of Mines has identified 30 CM aligned with CE goals, reliance on imports and uncertainties in global supply persist. A coordinated strategy involving industry, government, and research institutions is essential to achieving a sustainable and resilient energy future.

Importing CM Key to India's CE Transition

To address ongoing concerns, importing CM is essential for India's CE transition. However, growing global demand and supply chain challenges require a strategic approach to ensure energy security and sustainability[12][13]. This necessitates focusing on domestic exploration, international partnerships, and circular economy solutions to address supply-demand imbalances[14]. It is crucial to assess the need for CM in significant milestone years: 2030 (short-term, aiming for 50 per cent of energy requirements from renewable sources), 2047 (mid-term, marking the 100th anniversary of India's independence under the Viksit Bharat initiative), and 2070 (long-term, targeting net-zero carbon emissions). Evaluating scenarios such as business-as-usual, deterministic, and heroic can provide valuable insights into the potential effects of these policies.

The ACPET team examined CE sub-technologies in generation and storage to assess import dependencies, domestic production capabilities, and strategies to enhance value chains. Unlike prior studies, this research linked critical mineral demand to sub-technologies with technology readiness levels (TRLs) above four, incorporating market share projections. It analysed three scenarios and identified the minerals required for solar (PV & CSP), wind (onshore and offshore), and battery energy storage systems (BESS). The study also explored recovery potential from end-of-life products and proposed policies for sustainable, effective technology adoption.

IESS 4.0 as the Basis of Study

The study's approach consisted of four key elements. Firstly, it is based on NITI Aayog's IESS 4.0 framework, which considers three scenarios: business-as-usual (Trajectory 2 of IESS), deterministic (Trajectory 3 of IESS), and heroic (Trajectory 4 of IESS). Secondly, the technology selection incorporated technology readiness levels (TRL) 4-9 and accounted for variations in market share. Thirdly, capacity projections analysed cumulative installed capacity, plant retirement capacity patterns, and technology-specific deployment scenarios. Lastly, the literature review provided specific insights into mineral requirements, including material intensity mapping, recovery rates,

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uniform circularity considerations, and yearly variations.

The methodology involved a three-step process. First, it evaluated CE technologies across various renewable energy segments (solar, wind, and BESS). Secondly, it estimated the total cumulative demand for CM required by each segment. Finally, it calculated the actual total requirement for CM, factoring in the effects of recovery of CM and circularity. This approach provided a comprehensive overview of the mineral needs for India's energy transition.

In the solar segment, both photovoltaic (PV) and concentrated solar power (CSP) technologies were analysed. The PV analysis incorporated eight sub-technologies that considered different cell architectures and manufacturing processes. At the same time, the CSP assessment covered two sub-technological variants based on thermal storage and power generation mechanisms. For wind energy, the research framework was structured to analyse both onshore and offshore installations. The onshore wind assessment included five sub-technologies focusing on different turbine configurations and generation capacities. Offshore wind analysis encompassed four sub-technologies, considering fixed and floating foundations besides varying power ratings. The most extensive battery storage analysis examined six fundamental chemistries: lithium, vanadium, sodium, lead, nickel, and bromine. This segment investigated 20 sub-technologies, accounting for different electrode materials, electrolyte compositions, and cell designs. Comprehensive categorization enabled a detailed assessment of material intensity and technological evolution pathways for each sub segment.

Copper-Critical Mineral with Highest Cumulative Demand

Although this study evaluates cumulative requirements and CM recovery across all three scenarios, the deterministic scenario was emphasized more. This aligns closely with India's realistic path towards achieving net-zero emissions and sustainability goals, representing a feasible and actionable

approach within the nation's context. Within this framework, our analysis reveals significant implications for the cumulative requirements of five prominent CMs—copper, nickel, cobalt, graphite, and lithium—that are integral to India's renewable energy transition by 2070. These materials are crucial in advancing CE technologies, underscoring the importance of addressing supply vulnerabilities and recovery potential.

Copper exhibits the highest cumulative demand in the deterministic scenario. Demand for copper is projected to increase ~18 times by 2070 to reach net-zero, compared to ~394 kilotonnes (KT) in 2023. This substantial increase reflects copper's critical role in electrical conductivity and thermal management across renewable technologies. Demand for nickel is projected to increase ~156 times by 2070 to reach net-zero, compared to ~14 KT in 2023. Graphite's requirements show aggressive growth due to the increasing market share of next-generation Perovskite Solar PV and BESS applications. Demand for graphite is projected to increase ~148 times by 2070 to reach net-zero, as compared to negligible demand in 2023. Finally, cobalt and lithium show significant cumulative demand by 2070 due to the increasing market share of various BESS applications. Demand for cobalt and lithium is forecasted to rise approximately ~104 times and ~148 times by 2070, respectively, compared to the negligible levels recorded in 2023.

The findings highlight significant supply vulnerabilities. Despite substantial domestic copper reserves (163.89 MT)[15] and graphite reserves (8.56 MT)[15], current imports of 2,097.82 KT[15] and 108.76 KT[15] indicate infrastructure, cost-effective technology, policy support, and processing capacity limitations. More critically, nickel, lithium, and cobalt show complete import dependence, with zero active domestic reserves and current imports of 158.41 KT[15], 1679.29 KT[15], and 1,484 tonnes[15], respectively. It is important to note that the import figures referenced encompass a range of industries across India and are not limited to the renewable energy sectors (solar, wind, and BESS) analysed in this study. Material recovery from end-of-life clean technologies presents a partial mitigation strategy. Copper recovery is expected to increase by ~92 times its current level of ~1.7 KT in 2023 by 2070, whereas nickel recovery is projected to grow by ~99 times by 2070 as compared to ~0.55 KT in 2030. In contrast, cobalt and lithium indicate minimal growth, with cobalt expected to rise ~10 times (in KT) and lithium anticipated to rise ~12 times (in tonnes) by 2070, compared to negligible recovery in 2023. However, graphite recovery faces technical constraints due to separation difficulties and structural complexity, necessitating exclusion from recovery projections.

Way Forward Towards India's CE Mineral Transition

The study reveals critical challenges and opportunities in India's CE mineral transition by 2070. Despite limitations in data availability and modelling constraints, the research demonstrates that CM demand will increase dramatically, with materials like copper, graphite, and lithium projected to rise 18-156 times under the deterministic scenario. The findings highlight significant vulnerabilities in India's CE transition strategy, particularly the heavy import dependency on essential minerals like cobalt, lithium, and nickel. Key bottlenecks identified include limited graphite recoverability and the absence of domestic lithium production, which pose substantial risks to energy storage deployment. The analysis further reveals that current recycling capabilities are insufficient to address the projected supply gap.

Based on these insights, we recommend a three-pronged policy approach: promoting CE technologies with optimized mineral requirements, securing CM reserves through domestic development and sustainable import partnerships, and strengthening the mineral recovery ecosystem through appropriate policy support. Success in achieving net-zero emissions by 2070 will depend on establishing robust domestic supply chains and effectively implementing these policy measures. Future research should address the current limitations, particularly in data availability and technology trajectories, to provide more precise projections and policy guidance for India's CE transition.■

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