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Critical Minerals and the Green Energy Transition: A Review of Geological and Economic Risks and Constraints.

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Abstract

Evon Luxie Wilfred The global shift towards clean technologies is fundamentally reshaping demand for mineral resources, leading to a decline in hydrocarbon-based and other fossil fuel energy sources. Making a new energy security for a lifetime. Technologies that were centred on fossil fuels or carbon emissions can be replaced by clean energy with mineral resources. The clean technologies include solar photovoltaics, wind turbines, and electric vehicle batteries. These technologies and industries are mineral-intensive and require these reserves. This review synthesises the transition through a multidisciplinary lens, integrating geological and economic perspectives. It also reviews the uneven distribution of ore reserves and declining ore grades driven by extraction. The review concludes that policy frameworks must move beyond decarbonization targets to explicitly incorporate geological resource assessment and supply chain resilience, so that the transition to renewable energy is not undermined by the very mineral constraints it depends upon.

Keywords: *critical minerals, green energy, geological constraints, economic risks*

1. INTRODUCTION:

For a very long time, fossil fuels have been used all over the world. Green energy lies within the paradigm of using renewable resources over non-renewable resources like fossil fuels, such as coal, natural gas, etc. Decarbonization is a way which is the elimination of eliminating greenhouse gas emissions to reduce the global temperature rise. Also, the green energy transition lies within electrification, such as switching vehicles to EV, Industrial equipment's to run on clean electricity. The Transition involves traditional fossil fuel replacement with renewable, low-carbon technologies (Gielen et al. 2019). Critical minerals are the primary resource relied upon in the green energy transition. Clean energy needs mineral resources. Minerals and metals are the fundamentals of modern technology, which provides a foundation for different sustainable communities and industries. These are crucial resources for building a greener and more equitable future. Mineral resources are essential for the sustainable production of materials for technology and energy storage systems (Jowitt et al. 2020, Pommeret et al. 2022, Geol. Soc. Am. 2023). The conversion off fossils fuels to low-carbon energy sources will depend upon minerals (Bazilian 2018). Recently, critical minerals have been a sharper focus in achieving sustainability and the effort to combat climate change. Several applications of metals and minerals are integral in every aspect of the modern world. The classification and definition of critical minerals vary in every country; different countries have their own definition and classification of critical minerals (Graedel et al., (2015a). Minerals are considered critical when they are essential in economic and technological development, and their potential, extraction and supply face risks. Since they play a major role in clean technologies and zero-carbon technologies, demand for these grows exponentially. Demand for these minerals grows significantly as the global community's targets to achieve net-zero emissions by 2050 (citation). Electric vehicles require six times more minerals than a car, while wind turbines need more than ten times more mineral resources. This increasing demand for these minerals and lack of any other alternatives makes the role of these mineral resources critical in the green energy transition. When the extraction is profitable, these concentrations are termed ore deposits (Arndt & Ganino 2012). Therefore, the criticality of an element is obtained or determined based on three main aspects: The geological constraints of the green energy transition, which primarily relies upon critical minerals is they are concentrated in a few geographical locations and mining areas. Ores are generally localised in certain geologic or tectonic zones. Also, declining ore grades and higher energy and processing costs per ton occur as high-grade deposits deplete, dropping energy return on Investment (EROI). The discovery and active mining of the reserves and the reserve

estimation to carry out takes years to finally come out. Also, the demands of the reserves play a crucial role. Coming to the economic risks on the supply chain security, reserve estimates and the profitable extraction have to be reviewed This review brings out the geological and economic perspective to examine and review the constraints that critical mineral supply places on the pace and resilience of the energy transition.

2. GEOLOGICAL CONSTRAINTS ON CRITICAL MINERAL SUPPLY 2.1THE ORE LOCALIZATION AND GEOGRAPHIC DISTRIBUTION

There is no officially accepted list of critical minerals, and the classification varies according to different aspects like supply risks, ore reserves, and also the needs and priorities of policymakers and industries, and they can often vary in time. Mineral ore localisation is the structural or tectonic setting where the ore is concentrated for economic viability and extraction. Where the exploration or extraction objective is to find the mineralisation of a certain mineral. India Has Majorly 30 minerals stated as critical minerals by the Ministry of Mines (Ministry of Mines Deposits of Heavy Metals Required for Crucial Industries, n.d.) Figure given. According to the Institute for Energy Economics and Financial Analysis (IEEFA), from the 30 minerals identified by the Indian government, the analysis focuses on minerals such as cobalt, copper, graphite, lithium and nickel due to their role in renewable energy technologies, batteries and electrification systems. Lithium, cobalt and nickel are 100 percent import depended on India. (Gielen, 2021a) In India which targets 500gigawatt (GW) of fuel capacity and 50 per cent of energy capacity from renewables by 2030. 2.1.1 Lithium (Li) Lithium is often called as “white gold”, is a lightweight mineral with increasing importance as it is used as a major part of the green energy transition. Lithium plays a major role in this transition by contributing to lithium-ion batteries for powering electric vehicles; this has raised global demand for lithium as they favour high energy. Lithium naturally occurs in two isotopic forms, 6Li and 7Li and is found in various minerals such as spodumene, petalite, lepidolite and amblygonite. The lithium extraction market becomes tight as not every ore reserve can be extracted from the Earth's crust. Lithium is present in the crust enough, but the extraction capacity makes it less available. (Ministry of Mines Deposits of Heavy Metals Required for Crucial Industries, n.d.) Globally, 90% of the ore reserves are from Australia and in India it is localised in Jammu and Kashmir and Karnataka. The Salal-Haiman area in the Reasi district holds a massive inferred resource of 5.9 million tonnes of lithium ore. The Marlagalla-Allapatna area in the Mandya District has smaller hard rock lithium deposits (xeni & ka, n.d.) The Geological Survey of India (GSI) has undertaken projects involved in exploration of critical and strategic minerals and has given thrust to increase the number of exploration projects across the country. GSI has increased its exploration projects for critical and strategic minerals from 118nos. in 2021-22 to 196 nos. Since the amendment of the MMDR Act, 2015, details of cumulative resource augment by GSI for critical and strategic minerals at various cut-off and different average grades for lithium are 12.3 million tonnes (Ministry of Mines Deposits of Heavy Metals Required for Crucial Industries, n.d.) 2.1.2Rare Earth Elements (REEs) The REEs include 15 lanthanide elements and two transition metals. REEs are found difficult to refine to pure metal because of their reactivity. (Castor & Hedrick,2006). There are mainly two types of REEs: light rare earth elements (LREE) and heavy rare earth elements (HREE). The rare earth elements in India are localised mainly in the massive deposits found in the Coastal beach sands, which lie along the “Ratna Garbha” coastline in Andhra Pradesh, as well as Monazite sand on the southern Kerala beaches, then in Odisha and Tamil Nadu (Ministry of Mines Deposits of Heavy Metals Required for Crucial Industries, n.d.) India, the rare earth permanent magnets (REPMs), which are high-performance magnets essential for electric vehicles, wind turbines, electronics, aerospace, etc are being considered for establishing a domestic ecosystem in self-reliance in critical materials. As per the Union Budget 2026-27, which announced that the rare earth corridors are dedicated to mining, processing, research, and manufacturing of rare earth permanent magnets. The rare earth permanent magnets act as a proxy for the green energy transition, as they are the strongest types of permanent magnets. (Ministry of Mines Deposits of Heavy Metals Required for Crucial Industries, n.d.) 2.1.3Cobalt & Nickel These ores are generally found in association with the copper and chromite ores. In India, these are localised as small deposits in the eastern and Northern belts in Odisha and Jharkhand. The Ultra-basic belts of Sukinda Valley in Odisha. In the green energy Transition and technologies, nickel and cobalt are critical as they are used in industries like austenitic stainless steels, high pressure alloys, and high-nickel cathodes (NMC, NCA) in lithium-ion batteries (IEA, 2025; Naldrett, 2004). These ores are seen predominantly

in magmatic sulfide, laterites mainly and sediment-hosted copper belts (Arndt et al., n.d.) 2.1.4 Graphite Graphite is a naturally occurring mineral which is a pure form of carbon. It is a key mineral in lithium-ion batteries, refractories and lubricants. Its major role in the green and clean energy transition makes it a critical mineral. Its high electrical and thermal conductivity, lubricity, and thermal stability make it a major role in lithium-ion batteries, which fuel electric power vehicles and renewable technologies. The graphite reserves in India are predominantly in Arunachal Pradesh and Tamil Nadu. India. (Hira, 2025) . 2.1.5 Vanadium and Molybdenum The Proterozoic Khetabari Formation, Bomdila Group of the Lesser Himalayan sequence, Arunachal Pradesh has been identified by the GSI as the main vanadium mineralisation in India. Vanadium, which is a strategic mineral, has gained importance primarily due to its role in clean energy and industrial systems. Vanadium redox-flow batteries (VRB), which provide large-scale storage capacity, have leveraged usage in clean energy technologies like wind, solar and other renewable industries. The lithium-vanadium-phosphate batteries produce high voltages and high energy-to-weight ratios, which makes them the ideal reserve for the clean energy industry. (Gogoi et al., n.d.) . Tamil Nadu has the Molybdenum blocks at the Mannadipatti and Marudipatti blocks. In Malanjkhand mines in Madhya Pradesh and Rakha mines in Jharkhand, molybdenum is recovered as by-products from copper mines. 2.2. Ore Grade Decline and Extraction Complexity This is a most critical and structural challenge that the mining industry globally faces regarding the reserves essential especially for clean energy technology. Since the demand for these minerals is rising that is geologically, the ore reserves are depleting, and there come high quality risks and a spike in energy costs (Xeni & ka, n.d.)

3. ECONOMIC RISKS IN MINERAL SUPPLY CHAINS

3.1 Supply chain concentration and strategic Dependency In the geopolitical environment and economic environment, the critical mineral reserves have risen rapidly as these minerals are crucial for primarily clean energy technologies, high-tech industries, aerospace and advanced manufacturing, etc. They play a central part in energy security and broader economic resilience. (IEA 2025). As per the IEA, which highlighted the Mineral supply chains face the most pressing challenges for economic security and stability. Processing and refining are the major part were the economic risks and stability play a role. The mineral reserve ore estimate has been a very influential factor determining mining, supply chain and economic viability of the reserve. The ore grade and reserve determine the concentration of valuable minerals, which directly affects how much ore should be extracted, refined and produced. Primarily, the ore grade defines and tells the reserve estimate and supply chain security. Every mining project and the quality, distribution and estimate of the minerals the grade determines and influences how mines maximise resource value while maintaining sustainable and economically viable operations. (mining frontier) The economics become most viable when the project evaluation and mining. Studying the feasibility, anticipated value of ores should exceed the costs associated with extraction, transportation, processing, etc. Declining ore grades are increasing challenges in the economic security of minerals. (mining frontier) 3.2 Price volatility and market Structure The market structure of this critical mineral reserve is comparatively smaller, which makes its price sensitive and shifts demand. The current energy security revolves around the accessibility of energy resources. Disruptions in critical resources affect energy security. Market structure primarily relies upon production and extraction. Critical minerals are not traded as such as oil, which limits opportunities to hedge against price volatility; it allows commodity traders to play a key role in matching producers and consumers. (IRENA 2023)

4. CONCLUSION

The Transition to green or clean energy is fundamentally dependent on the use of critical mineral resources to achieve net-zero carbon emissions. Replacing emissions from fossil fuels requires tapping into mineral reserves essential to renewable technologies such as batteries, solar panels, and wind turbines. However, these critical mineral reserves are often geographically concentrated, making each resource vulnerable to potential supply risks, extraction challenges, and geopolitical complications. The economics of mineral concentration and the complexities introduced by international relations mean that access to and the security of mineral supply chains are never guaranteed. Additionally, not every resource present in the Earth's crust can be

easily or economically extracted and utilised, further complicating the clean energy transition. Understanding the economic and geological risks and constraints provides a structured framework for clean technologies. Bridging earth science with energy and supply economic policy can enable the transition to renewable energy.

5. References & Bibliography

1. Arndt, N., Kesler, S., & Ganino, C. (n.d.). Springer Mineralogy Metals and Society. Retrieved http://www.springer.com/series/13488
2. Gielen, Dolf. (2021a). Critical materials for the energy transition. International Renewable Energy Agency.
3. Gielen, Dolf. (2021b). Critical materials for the energy transition. International Renewable Energy Agency.
4. Gogoi, B., Sahoo, S., Mahanta, B. N., Das, G., Singh, M. A., Chasie, K., Srivastava, M., & Oza, B. (n.d.). Occurrence of Vanadium mineralization in the Khetabari Formation of Bomdila Group, Arunachal Pradesh, North East India: Geological and geostatistical considerations. In Indian Journal of Geosciences (Vol. 78, Number 1).
5. Hira, A. (2025). The geopolitics of the green transition and critical Strategic minerals. International Journal, https://doi.org/10.1177/00207020251332595 80(2), 217–245.
6. Ministry of Mines Deposits of Heavy Metals Required for Crucial Industries. (n.d.).
7. xeni, & ka. (n.d.). The Role of Critical World Energy Outlook Special Report Minerals in Clean Energy Transitions. Retrieved www.iea.org/t&c/