CRITICAL MINERALS IN THE CONTEXT OF THE ENERGY, GREEN AND DIGITAL TRANSITION: IMPLICATIONS FOR SUSTAINABLE DEVELOPMENT AND APPLIED RESEARCH

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Abstract: The green transition, driven by decarbonization, ecological constrains, and digital transformation, has led to a sharp increase in demand for critical minerals. These resources are essential for renewable energy infrastructure, electric mobility, and digital technologies. The green transition does not eliminate energy dependencies, but reconfigures them. Instead of oil, critical minerals become the new strategic asset. This change entails risks of supply crises, geopolitical conflicts and environmental pressures, if it is not managed through coherent policies, investments in diversification of sources. This paper explores the current state of research on the impact of the green transition on both energy and non-energy mineral resources, and the challenges of sustainable exploitation.

Keywords: critical minerals, green transition, energy transformation, digital economy, sustainable mining.

1. INTRODUCTION

The global shift toward a low-carbon economy is no longer a singular energy transition but a multidimensional transformation encompassing ecological and digital domains. This triadic transition redefines the role of mineral resources, positioning them as strategic assets for technological sovereignty, energy security, and sustainable development. These resources are essential for renewable energy infrastructure, electric mobility, and digital technologies.

Renewable energy technologies require significantly more minerals per unit of energy than fossil-based systems. Lithium, cobalt, nickel, and copper are indispensable for batteries, electric vehicles, and smart grids. The European Union's Critical Raw Materials Act (2023) aims to secure supply chains and reduce dependence on imports.

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Digital infrastructure—cloud computing, AI, 5G—has intensified demand for rare earth elements and high-purity metals. Semiconductors, sensors, and data centers rely on stable access to these materials, making them essential for both civilian and strategic applications. Ecological transition imposes harsher environmental standards. Mining operations must comply with biodiversity protection, water management, and carbon neutrality goals. Research focuses on low-impact extraction, circular economy models, and community engagement.

2. LITERATURE REVIEW

The twin transition - accelerated digitalization of industry and the energy transition toward low-carbon technologies — is reshaping the demand, supply, risks, and management practices of mineral resources. Recent scientific literature highlights four major trends: (i) end-to-end mining digitalization (IoT, AI, geomodelling, digital twins) improves efficiency and transparency with measurable impacts on resource utilization; (ii) the energy transition amplifies demand for critical minerals (copper, lithium, nickel, cobalt, graphite, rare earth elements) and shifts risk toward geographic supply concentration; (iii) circular economy strategies and urban mining become strategic in securing non-energy materials; (iv) life-cycle assessment (LCA) methodologies expanding to incorporate criticality and abiotic depletion in sustainability evaluations [1–5].

Scientific work published in 2023–2025 treats the "twin transitions" as the interdependence of digitalization and decarbonization, with significant material implications. Electrification of mobility and expansion of renewable power increase the material intensity of the energy system, while digitalization (data, sensors, automation) reshapes how we identify, estimate, extract, process, and trace materials across the value chain. Editorials and reviews emphasize the pivotal role of economic geology in discovering critical mineral deposits, noting the rarity of certain deposit types (e.g., porphyry copper) and the difficulty of geographic diversification for resilient supply chains. [21, 25]

2.1. Digitalization in mining: from "mining 4.0" to geometallurgy and digital twins

Systematic reviews in Mineral Economics identify Internet of Things (IoT) and Artificial Intelligence (AI) as the dominant technologies in mining applications, with documented benefits in productivity, cost reduction, occupational safety, and information quality. [1] Research syntheses and academic monographs describe implementations of AI/ML, digital twinning, and immersive technologies (VR/AR), as well as organizational barriers to scaling digitalization enterprise-wide. [5]

Empirical evidence indicates measurable improvements in resource-use efficiency linked to digital-economic development. A 2011–2022 provincial panel study (China) shows that advancement of the digital economy significantly improves mineral resource utilization efficiency, with mediating effects through industrial upgrading and technological progress, and heterogeneous regional impacts. [3] Geometallurgy now leverages predictive workflows that integrate geological and metallurgical data to anticipate process performance and support blended mine-to-plant optimization. Data fusion pilots (e.g., Garpenberg Zn–Pb–Ag mine, Sweden) explore real-time ore tracking and digital-twin models of plant operations. [24, 25] Case studies in gold processing (Tropicana, Australia) demonstrate machine learning for throughput prediction, reducing forecast error and improving short-term production scheduling. [26]

Systematic reviews confirm the expansion of ML across exploration, exploitation, and reclamation, with dominant models including Support Vector Machines (SVM), Convolutional Neural Networks (CNN), and Random Forest (RF); editorials suggest the adoption of Graph Convolutional Networks (GCN) to capture spatial anisotropy in prospectivity mapping within irregular study areas. [7, 11] Digitalization reduces uncertainty and operational variability, translating into slower "consumption" dynamics of reserves via higher recoveries and lower technological losses; however, outcomes remain data-quality dependent, and AI models must be coupled with domain geological knowledge to avoid black-box pitfalls. [14, 9]

2.2. The energy transition: materiality, projected demand, and supply risks

Models and reviews from 2024–2025 indicate multiplicative demand increases by 2040/2050 for several critical materials (across NZE/APS scenarios): lithium (~8×), graphite (~4–5×), copper (~2×). Heterogeneity is large across materials: from slightly negative projections for tungsten to ~1300% increases for lithium in conservative electricity-transition scenarios. [15] The IEA Global Critical Minerals Outlook 2024/2025 provides comprehensive demand–supply series (mining and refining), along with structured risk assessments (geopolitical, disruption response, ESG/climate). Findings point to potential supply gaps by ~2030 for certain materials without accelerated investment in mining, refining, and recycling. [2, 8, 21]

Geographic concentration is a defining vulnerability in the twin transitions: graphite (China ~77%), rare earth elements (China ~69%), cobalt (DRC ~74%), nickel (Indonesia ~50%) create chokepoints for EV and renewable energy value chains. Diversification of supply and processing, material substitution, and intensity reduction are identified as necessary countermeasures. [21, 22, 23] A 2024 Mineral Economics study estimates needs for 33 materials up to 2050, revealing large increases for aluminium, copper, nickel, and rare earths as pillars of electrification and digital infrastructure. Material differences are pronounced (e.g., aluminium > USD 42 billion sales at 2021 prices; lithium up to ~1300% quantitative growth). [25] Industry perspectives (2025) separate materials by sensitivity to the energy transition: aluminium/steel (tracking general GDP growth), copper/lithium/REE (accelerated by transition), thermal coal (structural decline). [28]

2.3. Circular economy and urban mining

Recent reviews document advanced reprocessing techniques for critical and secondary materials from tailings (e.g., leaching, hydrometallurgy) with dual benefits:

material security and environmental risk reduction. Case studies across copper, silver, tungsten, antimony, and gold highlight feasibility and the potential to close gaps in supply for clean technologies. [24] Editor's choice reviews (2025) synthesize recovery of rare earths and battery metals (lithium, cobalt, nickel) from mine tailings, advocating integrated circular frameworks combining resource recovery with environmental remediation. [15]

Systematic analyses of urban mining show that WEEE can serve as an anthropogenic stock for several CRMs (Au, Ag, Cu, Li, Co), but current global recycling rates remain low, underscoring the need for harmonized frameworks, infrastructure, and market development for secondary feedstock. [25, 26] Even under ambitious scenarios, improving e-waste recycling efficiency could materially reduce primary mining demand for copper and cobalt by up to ~40% by 2050, highlighting the importance of accelerating collection and processing infrastructure. [28]

2.4. Methods and Analytical Tools: LCA, Criticality and Materials Flow

LCA methodologies are evolving to incorporate criticality (abiotic depletion, supply concentration) via novel indicators such as the Raw Material Extraction/Reserve Index (RERI) and Gini-based metrics, applied in EV vs. diesel comparisons. Results show EVs reduce GHG emissions while potentially increasing impacts related to CRMs — emphasizing trade-offs and the necessity of circular strategies. [19] Editorials (2023) and perspectives (ACS JACS Au, 2023) call for integrating Planetary Boundaries (PB-LCA) into assessments of emerging decarbonization technologies, while sectoral assessments (DOE/INL, 2023) map criticality across 23 materials by energy importance and supply risk. [20, 22, 21, 23]

USGS Materials Flow resources provide historical and methodological baselines (recycling, in-use stocks, foreign reliance) useful for Materials Flow Analysis (MFA) and prioritizing interventions. [50] Econometric work (FIU, 2024) indicates that global supply-chain pressures explain a substantial share of long-run volatility in global inflation, whereas geopolitical risk shocks tend to exhibit shorter-lived effects. Surveys in 2025 place geopolitics and inflation at the top of corporate supply-chain concerns. [27] Comparative risk analyses (Oxford Economics/Proxima, 2025) describe reorientation (nearshoring, friendshoring) and reindustrialization as responses, while digitization (AI, automation, digital twins) becomes a pillar of resilience. Organizations increasingly shift priorities from lowest cost toward predictability and control. [25]

2.5. Discussion: Synergies and Tensions in the Twin Transitions

Synergies: Digitalization (AI/IoT) improves material efficiency (higher recoveries, lower losses), ESG traceability, and adaptive planning; geometallurgical workflows connect in-situ resources to plant performance, reducing uncertainty. [1, 24] Tensions: The pace of the energy transition accelerates demand for materials with concentrated supply; absent diversification, substitution, recycling, and process innovations (low-carbon/green metallurgy), supply gaps and price volatility may intensify [23]. Non-energy resources (copper, aluminium, steel, rare earths) are backbone materials for both transitions (electrification + digitalization); urban mining and tailings reprocessing hold real potential but require technical–economic frameworks, standards, and secondary-market infrastructure for scaling [25, 24, 15]. Methodological: LCA with criticality and MFA provides decision-grade evidence, but data quality/granularity remains a limitation; models must couple geological knowledge with AI to avoid overfitting and preserve interpretability [19, 5, 9].

3. CONCLUSIONS

1) End-to-end digital integration (exploration → processing → logistics) is a research-to-practice priority, with emphasis on multimodal data fusion and scalable digital twins. 2) Diversification and circularity should be quantified through LCA+criticality for energy and digital technologies; portfolio comparisons (battery chemistries, permanent magnets) under risk constraints are an emerging field. 3) Urban mining and tailings reprocessing are "low-hanging fruit" for non-energy resources, requiring techno-economic frameworks and standards for secondary feedstock quality. 4) Geopolitics necessitates resilience models (nearshoring, buffer stocks, digital transparency); research must link risk to system performance in material and energy terms.

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