Acta Montanistica Slovaca
ISSN 1335-1788
actamont.tuke.sk

# Aligning Research and Policy on Critical Raw Materials for a Resilient Green Transition

*Kristina RAZMINIENĖ[1] and Manuela TVARONAVIČIENĖ[2*]*

**Authors' affiliations and addresses:**
[1] Department of Economics and Engineering, Faculty of Business Management, Vilnius Gediminas Technical University, Vilnius, Lithuania
e-mail: kristina.razminiene@vilniustech.lt

[2] Department of Business Technologies and Entrepreneurship, Faculty of Business Management, Vilnius Gediminas Technical University, Vilnius, Lithuania
e-mail: manuela.tvaronaviciene@jssidoi.org

***Correspondence:**
Manuela Tvaronavičienė, Department of Business Technologies and Entrepreneurship, Faculty of Business Management, Vilnius Gediminas Technical University, Vilnius, Lithuania
tel.: +37068783944
e-mail: manuela.tvaronaviciene@jssidoi.org

**How to cite this article:**
Razminienė, K. and Tvaronavičienė, M. (2026). Aligning Research and Policy on Critical Raw Materials for a Resilient Green Transition. *Acta Monstanistica Slovaca*, Volume 31 (1), 73-89

**DOI:**
https://doi.org/10.46544/AMS.v31i1.06

**Abstract**
As global efforts to combat climate change accelerate, the green transition has emerged as a key policy and research focus. Central to this transition are critical raw materials (CRMs), which underpin low-carbon technologies such as electric vehicles, wind turbines, and battery systems. However, these materials often have low recycling rates and are sourced from geopolitically sensitive regions, presenting sustainability and security challenges. This study provides a novel contribution by combining a bibliometric analysis of academic literature with a policy synthesis of European strategic assessments to explore how these material constraints are represented and addressed. The study aims to identify dominant research themes related to the green transition, CRMs, and the circular economy, while also evaluating how these themes align with real-world risks and governance gaps. Using VOSviewer, 124 Scopus-indexed publications were analyzed for keyword co-occurrence, revealing four thematic clusters: strategic materials and sustainability; material flows and environmental management; energy infrastructure and technology; and governance and policy. These were complemented by an analysis of EU policy documents evaluating CRMs based on supply risk, economic importance, and recycling input rates. The findings reveal a significant mismatch between the high strategic value of materials such as neodymium, cobalt, and lithium and their minimal rates of end-of-life recycling. Additionally, the concentration of CRM supply chains in regions like China and the Democratic Republic of Congo poses systemic risks. This integrated approach reveals an emerging interdisciplinary consensus and provides a replicable framework for aligning research, policy, and circular economy strategies in the context of sustainable transitions.

**Keywords**
Circular economy, green transition, critical raw materials (CRMs), recycling, energy resilience, sustainability

## Introduction

The accelerating urgency of climate change mitigation has led to a growing emphasis on the green transition – a systemic shift toward low-carbon, resource-efficient economies. Critical raw materials (CRMs) are central to this transformation, serving as indispensable inputs for clean energy technologies such as electric vehicles, wind turbines, and battery storage systems (Liang, Kleijn, Tukker & van der Voet, 2022; Tvaronavičienė, 2024; Richert & Łebkowski, 2025).

Simultaneously, the circular economy has emerged as a framework for minimizing resource extraction and environmental degradation by promoting material reuse, recycling, and sustainable product design (Bazienė & Gargasas, 2023; Gerasimova, Prause & Hoffmann, 2023; Naimoğlu & Kavaz, 2023; Rezk et al., 2023; Cusenza, Novi, Daddi, Girardi & Iraldo, 2024; Rezk et al., 2024; Ruginė & Žilienė, 2024; Miszczak, Kriviņš & Kaze, 2024).

Recent literature underscores that this transformation will significantly increase demand for various critical materials (Pariso, Picariello & Marino, 2023), often in supply chains vulnerable to geopolitical instability.

For instance, lithium, cobalt, and rare earth elements are expected to experience exponential demand growth – up to 26 times in the case of lithium – driven by the adoption of electric vehicles and renewable infrastructure (Jannesar Niri et al., 2024). However, these supply chains remain fragile due to their geographic concentration, particularly in regions such as China and the Democratic Republic of Congo (Artudean, Kertész, Popa, Bacali & Szabó, 2024; Ku et al., 2024) 2024. These vulnerabilities are compounded by low end-of-life recycling rates for many CRMs, typically below 1%, which highlight systemic weaknesses in the current resource governance model (Butu, Rodino & Butu, 2023).

Moreover, recent research illustrates how circular economy practices can enhance energy resilience by reducing reliance on virgin material extraction, fostering self-sufficiency, and mitigating the effects of energy shocks (Tvaronavičienė, Razminienė & Adekola, 2024). Social media discourse around initiatives like the European Green Deal also reveals a growing societal expectation for sustainable and just transitions, with key public concerns focused on energy policy, industrial innovation, and environmental justice (Balcarova et al., 2024).

Although several studies have addressed supply risks, circular metrics, and material flows, relatively few have analyzed how academic discourse aligns with actual policy strategies. This study addresses that gap by combining a bibliometric analysis of academic research with a synthesis of European policy documents to explore the strategic coherence between the two domains. This dual-method approach builds on recent calls for integrated frameworks that evaluate circular economy performance and its policy implications in the energy transition (Cusenza et al., 2024; Mendoza, Gallego-Schmid, Velenturf, Jensen & Ibarra, 2022; Piccinetti et al., 2025; Rezk et al., 2025; Churikanova et al., 2025).

The aim of this study is to explore the structure and focus areas of academic research at the intersection of the green transition, CRMs, and the circular economy. Specifically, it seeks to map how scholarly attention is distributed across key themes, technologies, and policy dimensions, and to assess how critical raw material dependencies may affect the resilience and sustainability of energy transitions.

The paper is structured around two core analytical components. The first section presents a bibliometric analysis of Scopus-indexed academic publications, mapping keyword co-occurrences to identify prevailing research clusters on the green transition, the circular economy, and CRMs. The second section offers a policy-based synthesis using strategic documents from the European Commission, focusing on material risk profiles, economic significance, and recycling potential. This structure enables a combined evaluation of scholarly focus and policy-relevant material challenges that shape the trajectory of the green transition.

## Research Methodology

To analyze the thematic structure of academic research on the green transition, CRMs, and the circular economy, a bibliometric method was employed using the VOSviewer software. The objective was to identify key research clusters, recurring themes, and keyword relationships within the existing literature.

The dataset was compiled from the Scopus database, a leading bibliographic repository for peer-reviewed literature across disciplines. The search terms included combinations of "green transition," "circular economy," and "critical raw materials," yielding 124 relevant documents. Only documents indexed in Scopus were considered to ensure quality and consistency. No restrictions were applied on document type or publication year to capture a comprehensive view of the field.

The bibliometric analysis focused on keyword co-occurrence patterns to reveal thematic linkages and research trends. All keywords from the selected documents were extracted, and a minimum occurrence threshold of five was set to filter out less significant terms. This threshold resulted in 42 keywords being included in the analysis.

VOSviewer was then used to generate a network visualization of the co-occurrence data. In the resulting map, each keyword is represented as a node, with node size reflecting the frequency of appearance across the dataset. Links between nodes denote co-occurrence relationships, with link strength corresponding to the number of documents in which both keywords appear together.

The software's clustering algorithm grouped related keywords into four distinct thematic clusters, each visualized in a different color. This clustering is based on the strength of co-occurrence ties, allowing for the identification of underlying research themes.

The generated co-occurrence map served as a basis for qualitative interpretation. Each cluster was analyzed to determine its thematic focus, with particular attention to the keywords' relevance to the green transition discourse. Keywords like "recycling," "critical raw materials," and "supply chains" were examined not only for their frequency but also for their centrality in the network, as indicated by their total link strength. This interpretive step enabled the identification of dominant research areas and emerging trends at the intersection of sustainability, material dependency, and innovation policy.

This study also integrates a secondary methodological component: an analytical synthesis of policy frameworks and strategic assessments related to CRMs within the context of the EU's energy transition. The synthesis draws from official documents, including the European Commission's Study on Critical Raw Materials (Grohol, GROW, & European Commission, 2023) and the Supply Chain Analysis and Material Demand Forecast in Strategic Technologies and Sectors in the EU – A Foresight Study (Carrara et al., 2023).

The analysis applied the EU's dual-indicator methodology, which evaluates CRMs based on their Supply Risk (SR) and Economic Importance (EI). Materials were categorized as critical if they met or exceeded $SR \geq 1.0$ and $EI \geq 2.8$, thresholds that indicate significant vulnerability and strategic relevance. These indicators were used to identify materials most vital to renewable energy technologies (e.g., wind turbines, batteries, solar photovoltaics (PV)) and most susceptible to supply disruptions.

In addition to official metrics, the study incorporated End-of-Life Recycling Input Rates (EOL-RIR) to assess the circularity potential of each CRM. These recycling rates offer insight into which materials are currently underutilized in secondary sourcing strategies and may benefit from targeted policy intervention.

By mapping material applications, supply vulnerabilities, and recycling performance, this component complements the bibliometric analysis by embedding the academic discourse within a policy-relevant framework. It allows for a more holistic understanding of how raw material constraints may shape or inhibit the green transition, providing critical input for scenario planning, resource governance, and circular economy design.

## Bibliometric Analysis of the Green Transition, Circular Economy, and Critical Raw Materials

In recent years, the concept of the green transition has gained prominence as governments, industries, and researchers seek strategies to mitigate climate change, reduce environmental degradation, and promote sustainable economic development. Closely linked to this transition are the principles of the circular economy, which aim to minimize waste and optimize resource use, and the growing reliance on CRMs, essential for clean technologies such as batteries, wind turbines, and electric vehicles. As academic interest in these interconnected topics expands, it becomes important to understand the structure and focus areas of existing research. To this end, a bibliometric analysis was conducted using VOSviewer to map keyword co-occurrences and identify dominant themes in the literature. The following section presents and interprets the results of this analysis, offering insights into how scholarly attention is clustered around specific materials, technologies, policy frameworks, and environmental considerations within the broader discourse on the green transition.

**Results of the Co-occurrence Analysis.** To map the thematic landscape of research on the "green transition" in relation to the circular economy and CRMs, a bibliometric analysis using VOSviewer was conducted. The dataset comprised 124 documents retrieved from the Scopus database. The analysis used a co-occurrence method with all keywords, setting a minimum occurrence threshold of 5. This yielded 42 keywords that met the criteria, which were grouped into four distinct thematic clusters based on their co-occurrence strength.

The resulting VOSviewer map visually represents each keyword as a node. The size of each node indicates the frequency of keyword occurrence, while lines (links) between nodes show how frequently those keywords appear together in documents. Keywords that tend to co-occur form clusters, which are assigned distinct colors in the visualization. These clusters reveal underlying thematic groupings in the literature. As shown in Figure 1, keywords are grouped into four color-coded clusters, each representing a distinct thematic focus within the field.

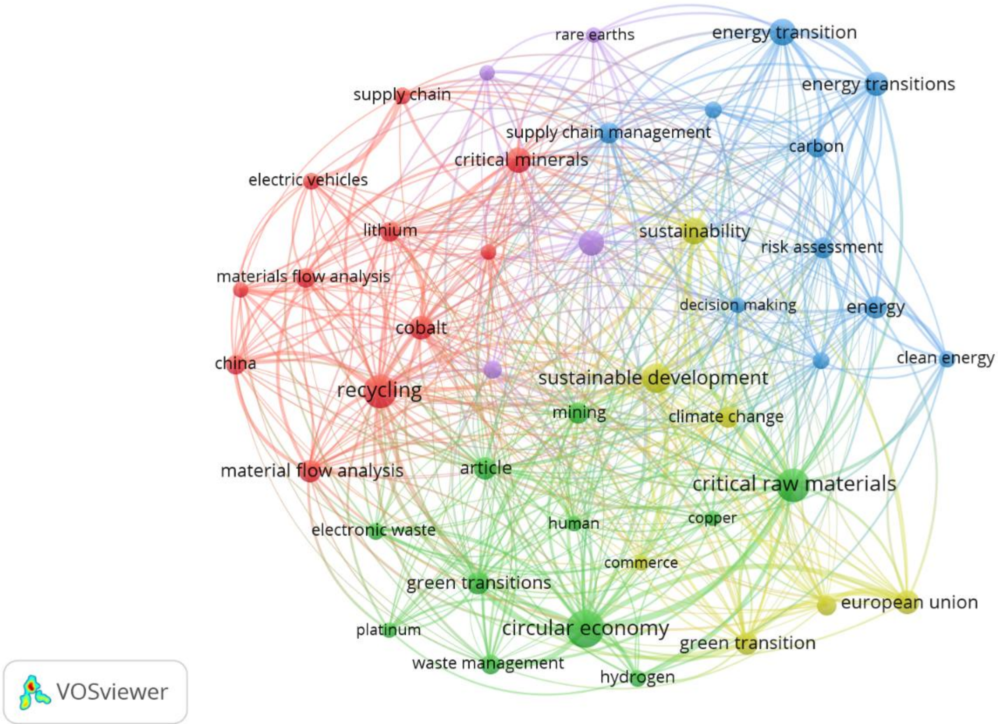


*Figure 1. Keyword co-occurrence network map generated using VOSviewer based on 124 Scopus-indexed documents related to "green transition", "circular economy", and "critical raw materials". Node size reflects keyword frequency; line thickness represents co-occurrence strength. Clusters are color-coded and indicate thematic groupings in the literature.*

Cluster 1 (15 items) is centered on strategic materials and sustainability. It includes terms like *carbon, circular economy, critical minerals, critical raw materials, energy transition, sustainability, sustainable development,* and *rare earths.* This cluster highlights the emphasis on essential raw materials and systemic shifts required for a sustainable green transition, particularly in relation to energy systems and resource dependencies.

Cluster 2 (14 items) appears to focus on material flows and environmental management, comprising keywords such as *electronic waste, cobalt, lithium, china, mining, recycling, waste management,* and *materials flow analysis*. This cluster reflects the practical and geographical dimensions of resource extraction and waste, with a significant focus on material recovery and environmental impact, particularly regarding the roles of China and Europe.

Cluster 3 (10 items) represents themes related to energy technologies and infrastructure, including *alternative energy, electric vehicles, hydrogen, copper, supply chain management,* and *risk assessment*. These keywords suggest a focus on technical solutions and the supporting infrastructure needed for a successful transition to low-carbon systems.

Cluster 4 (4 items) groups policy and high-level conceptual terms: *commerce, European Union, green transition,* and *green transitions*. Though smaller, this cluster likely represents governance and institutional frameworks at national and supranational levels, highlighting strategic planning and policy development.

Among the keywords, *recycling* had the highest total link strength (114), underscoring its centrality in the research network. Other highly connected keywords included *circular economy* (92), *cobalt* (82), *critical raw materials* (80), and *supply chains* (70), pointing to dominant themes and frequently studied topics.

Note: Although the keyword *"article"* appeared with a high link strength (70), it was excluded from the interpretive analysis. This term likely entered the dataset as a result of document-type metadata in bibliographic records and does not represent a thematic concept relevant to the research field.

This analysis reveals a multidimensional structure of the research field, with prominent focuses on materials science, energy systems, policy frameworks, and sustainability practices. The clustering reflects a growing interdisciplinary effort to tackle the complexities of the green transition through both technical and policy lenses.

**Essential Raw Materials and Systemic Shifts in the Green Transition.** The sustainability of the green transition depends heavily on securing access to CRMs while minimizing geopolitical, environmental, and social risks. Recent research underscores that technological shifts alone are insufficient; instead, a systemic transformation is required – one that reconciles material needs, socio-political justice, and circular economy integration. A growing body of literature reflects this complexity by exploring the interdependencies between CRMs, energy systems, and governance structures.

Studies such as Ge, Liu & Zhong (2024), Granvik, Hanski, Lähdesmäki, Jokilaakso & Huttunen-Saarivirta (2025), Schulze, Kullmann, Weinand & Stolten (2024) employ advanced modeling tools to forecast the supply and demand of CRMs under various energy transition scenarios. These models simulate how electrification pathways – particularly those involving electric vehicles, wind energy, and energy storage – intensify demand for materials such as lithium, cobalt, and dysprosium. All three studies converge on the finding that such demand could outpace supply, resulting in material bottlenecks that jeopardize transition timelines. For example, Granvik et al. (2025) show how lithium and dysprosium may face acute shortages unless mitigated by recycling or reduced demand. Ge et al. (2024) expand the view to a global scale, linking climate targets to mineral stress points across sectors. Schulze et al. (2024) critique the dominant modeling practices in transition planning, pointing out that many energy models ignore raw material constraints altogether, leading to unrealistic projections. These concerns are echoed by McKenna et al. (2025) and Moore, Marquis, Shanks & Wall (2024), who specifically highlight rare earth elements (REEs) such as neodymium and dysprosium, widely used in permanent magnets for wind turbines and other clean energy technologies. They note that these elements suffer from low recycling rates and are subject to geopolitical risk due to heavy supply concentration in a few countries, particularly China. Despite this, they argue, REEs are often excluded or underweighted in transition planning models, creating blind spots in both policy and investment strategy. Zwickl-Bernhard (2024) advances this conversation by showing how integrating recycling and remanufacturing dynamics into solar energy system models can significantly alter both material demand forecasts and risk assessments. Feichtinger & Posch (2025) further refine this line of inquiry by offering a distance-based criticality metric that provides a more nuanced way to prioritize materials that are both strategically important and vulnerable to supply disruptions.

Beyond technical modeling, a parallel research stream reveals the political and ethical dimensions of CRM dependency, particularly in how extraction practices disproportionately affect vulnerable communities and ecosystems. Barragan-Contreras (2025) and Kainiemi, Laukkanen & Levänen (2025) provide a critical lens on the techno-optimistic narratives that dominate energy transition discourse, arguing that they often obscure the socio-ecological injustices generated by green extractivism. They highlight how the pursuit of strategic minerals like lithium and cobalt frequently displaces indigenous communities, exacerbates labor exploitation, and triggers environmental degradation – especially in the Global South, where regulatory protections are weaker. Vivoda (2024) extends this critique by exploring the controversial frontier of deep-sea mining, which, while offering access to untapped sources of CRMs, poses significant risks to poorly understood marine ecosystems and lacks an effective global regulatory regime. Similarly, Zanoletti, Bresolin, & Bontempi (2024) emphasize that even terrestrial mining operations, when conducted in ecologically sensitive regions, can undermine biodiversity and violate community rights. Both studies converge on the idea that insufficient governance capacity – at both national and international levels – enables these harms, and that stronger frameworks for environmental justice, stakeholder participation, and ecological oversight are urgently needed in CRM supply chains.

While Kamran, Raugei & Hutchinson (2023) and Patil, Struis & Ludwig (2023) focus primarily on technological advancements – such as electrochemical and urban mining techniques – for recovering CRMs like cobalt and platinum, they also acknowledge that the long-term viability of these methods depends on embedding them within ethical and transparent supply chains. Their studies underscore that simply recovering materials is not enough if it perpetuates inequitable global sourcing patterns or fails to reduce environmental burdens. In parallel, Popa & Szabó (2024, 2025) emphasize broader systemic challenges, highlighting the severe environmental degradation associated with rare-earth mining, including toxic waste and radioactive byproducts. They argue that without justice-centered strategies – such as design for recyclability, increased support for remanufacturing, and stronger regulatory oversight – recycling risks becoming a superficial solution that leaves the underlying problems of overconsumption and geopolitical dependence unaddressed. Interestingly, Adamczyk, Komorek, Kokowska-Pawłowska & Nowak (2024) explore the untapped potential of coal combustion residues – specifically fly ash and bottom ash – as secondary sources of REEs, offering a novel bridge between circular economy goals and the environmental legacies of fossil-based energy systems. Their study reveals that certain types of ash, particularly those from electrostatic precipitators in Polish lignite power plants, are enriched in light REEs, such as neodymium and lanthanum. By applying advanced chemical and mineralogical analysis, they demonstrate how targeted extraction from this waste stream can simultaneously reduce environmental hazards, reclaim valuable materials, and contribute to EU strategic autonomy. This approach exemplifies how transitioning economies can integrate remediation of past energy practices with forward-looking resource resilience strategies, potentially unlocking domestic CRM supplies without the need for new mining operations.

Governance also plays a central role in shaping CRM outcomes, particularly within the EU's evolving strategic agenda. Gao (2025) and Polverini, Alfieri, Spiliotopoulos & Arcipowska (2024) analyze how the EU's green and digital transitions often suffer from internal inconsistencies – where ambitious policy narratives are not always backed by institutional capacity or harmonized implementation. Glencross (2024) and Moore et al. (2024) go further, framing the EU's recent policy moves, including the Critical Raw Materials Act (CRMA), as a departure from liberal trade paradigms toward more interventionist geo-economic strategies aimed at reducing dependence on China and other external suppliers. Compagnoni, Grazzi, Pieri & Tomasi (2025) and von

Rennenberg, Yu, Fraccascia & Yazan (2024) explore the operational dimensions of such policies, focusing on Extended Producer Responsibility (EPR) and waste trade restrictions. While these tools are meant to strengthen circularity, they also face challenges, including uneven enforcement and administrative inefficiencies across member states. Jakimów, Samokhalov & Baldassarre (2024) illustrate these tensions in their analysis of titanium supply chains, where the EU's lack of midstream processing infrastructure continues to rely on foreign actors, especially the U.S. and Russia.

Ottomano Palmisano, Rocchi, Negri & Piscitelli (2025) expand on this critique by highlighting the inconsistent application of the European Green Deal and showing how divergent national strategies undermine collective CRM goals. Alataş, Hiçyılmaz & Karakaya (2024) and Considine, Galkin, Hatipoglu & Aldayel (2023) similarly call for more integrated governance that bridges environmental, industrial, and trade policies, cautioning that fragmented regulatory landscapes create inefficiencies and missed synergies.

To address CRM constraints, circular economy solutions have gained prominence across the literature. Popa & Szabó (2024, 2025) emphasize eco-design, modularity, and product longevity as essential strategies to reduce primary material inputs. Hackenhaar et al. (2025) complement this with the CriticS framework, which incorporates environmental and socio-economic factors into life-cycle-based criticality assessments. Chadly, Moawad, Salah, Omar, & Mayyas (2024) contribute a case-specific analysis of the photovoltaic sector, proposing recycling innovations and material substitutions to reduce reliance on Chinese supply chains. Compagnoni & Santini (2025) provide further evidence on the effects of EU regulations like RoHS and WEEE, showing how these policies have driven material innovation while inadvertently increasing complexity in electronic waste streams.

The role of innovation ecosystems is further elaborated by Carmona-Martínez et al. (2024) and Xu, Nassani, Qazi Abro, Naseem, & Zaman (2024), who emphasize the need for cross-border collaboration in CRM research and development, particularly for energy-intensive industries. This is echoed in the work of Dmitrieva & Solovyova (2023) and Mastronardi et al. (2024), who investigate advanced techniques for CRM recovery from industrial residues and electronic waste, demonstrating how technological breakthroughs can align economic feasibility with environmental responsibility.

Across the diverse range of methodologies and disciplinary approaches surveyed in this analysis, a clear consensus emerges: CRMs are not just passive inputs into the green transition – they are pivotal constraints and leverage points that shape its trajectory. The reviewed studies reveal that systemic, rather than merely technical, solutions are essential to address the complex challenges posed by material dependencies. Integrating material flows into energy and climate modeling is necessary to account for real-world limitations and to avoid overly optimistic projections that ignore supply bottlenecks or recycling delays. Moreover, the green transition cannot be effectively advanced without confronting the justice dimensions of CRM sourcing, as the extraction and processing of these materials often reproduce historical patterns of exploitation and inequality. The importance of governance and policy coherence is also strongly emphasized, with calls for integrated strategies that align environmental, industrial, and trade objectives. Finally, innovation in circular economy practices – ranging from eco-design and advanced recycling to the recovery of CRMs from waste – emerges as a critical pathway to reduce dependency and enhance resilience. In this light, the green transition is best understood not as a purely technological shift, but as a materially grounded, politically charged, and globally interconnected transformation.

**Critical Raw Materials and Recycling Technologies as Pillars of a Circular Green Transition.** The transition to a green economy is increasingly constrained and shaped by the availability, recyclability, and governance of CRMs. Across the reviewed literature, a recurring theme is the indispensable role that raw materials – particularly lithium, cobalt, copper, REEs, and phosphorus – play in technologies central to decarbonization, and how circular economy strategies such as recycling and material recovery serve as key enablers for sustainable transitions.

Recent studies highlight that the demand for CRMs such as lithium, cobalt, and REEs is rising sharply, largely because these elements are essential components in key green technologies. Lithium and cobalt are vital for rechargeable batteries used in electric vehicles (EVs) and energy storage systems, while REEs such as neodymium and dysprosium are indispensable for manufacturing permanent magnets used in wind turbines and high-efficiency electric motors. Copper, another increasingly critical material, is crucial for power transmission in renewable energy systems such as solar panels and grid infrastructure (Podobińska-Staniec, Wiktor-Sułkowska, Kustra & Lorenc-Szot, 2025; Priore, Compagnoni & Favot, 2025; Zanoletti et al., 2024).

However, the growing reliance on these materials presents major challenges. First, they are geologically scarce – meaning that economically viable deposits are limited and unevenly distributed around the globe. Second, their supply chains are highly geopolitically concentrated. For example, China dominates the global market for REEs, and the Democratic Republic of Congo supplies the majority of the world's cobalt. This geographic concentration makes supply chains vulnerable to geopolitical tensions, trade restrictions, or conflicts. Third, the extraction of these materials often has high environmental and social costs, including habitat destruction, water contamination, high energy consumption, and human rights violations in mining regions.

Adding to the challenge is the increasing complexity of modern electronics. Devices like smartphones, tablets, and smart appliances are multifunctional, combining multiple technologies into compact, lightweight forms. This design trend has led to greater material diversity and miniaturization, making devices harder to disassemble and recycle. As a result, many CRMs become difficult to recover at the end of life, and their demand continues to grow with each new generation of technology. This intensifies dependency on primary extraction and underscores the need for secure, sustainable, and circular supply systems (Adamczyk et al., 2024; Lorenc, Podobińska-Staniec, Wiktor-Sułkowska & Kustra, 2024).

Recycling technologies are positioned as crucial tools for mitigating raw material scarcity and enabling a circular economy. By extracting valuable materials from used products, recycling reduces the pressure on primary mining and helps secure long-term supply chains. For example, battery recycling and electrochemical recovery techniques are increasingly being developed to reclaim critical materials such as cobalt and platinum from spent batteries and fuel cells. These methods offer a more sustainable and often less polluting alternative to traditional mining and refining processes, particularly when powered by renewable electricity (Luo, Yang & Jiang, 2025; Makarava et al., 2024; Mastronardi et al., 2024; Matz, Bensmann, Hanke-Rauschenbach & Minke, 2024).

Beyond conventional recycling, bioleaching and urban mining present innovative approaches to resource recovery. Bioleaching uses microorganisms – such as bacteria or fungi – to extract metals from e-waste, while urban mining focuses on recovering CRMs from discarded electronics, often referred to as the "above-ground mine." These approaches are especially valuable given the low formal recycling rates of e-waste globally and the concentration of CRMs in consumer electronics. Not only do they help close material loops, but they also offer a more environmentally friendly pathway to resource security by reducing reliance on extraction from ecologically sensitive or politically unstable regions (Eikeng, Makhsoos & Pollet, 2024; Ferreira-Filipe, Duarte, Hursthouse, Rocha-Santos & Silva, 2025).

Multiple papers identify systemic barriers – such as weak regulation, fragmented governance across sectors, and the increasing complexity of product design – as major impediments to effectively scaling circular practices. Weak or inconsistent policies at both national and EU levels can lead to a lack of incentives or enforcement mechanisms to drive recycling and reuse initiatives. Fragmented governance often leads to misalignment between industrial, environmental, and economic strategies, hindering intersectoral collaboration. Additionally, complex product designs that do not account for end-of-life recovery make disassembly and material separation technologically and economically challenging (Ciftci & Lemaire, 2023; Kalpakchiev, Jacobs, Fraundorfer, Martin-Ortega & Cordell, 2025).

Conversely, several success factors are repeatedly highlighted across the literature. These include establishing cohesive, binding policy frameworks – such as the EU Battery Regulation and the Critical Raw Materials Act – that set clear recycling targets and material traceability requirements. Coordinated action among stakeholders, including governments, manufacturers, recyclers, and consumers, is also emphasized as essential for achieving material recovery goals. Furthermore, integrating eco-design principles into product development can significantly ease disassembly and increase the recyclability of components, ultimately supporting the broader goals of a circular economy (Jakimów et al., 2024; Zeng et al., 2022).

The EU's heavy reliance on CRM imports from countries such as China and the Democratic Republic of Congo exposes it to significant geopolitical risks, supply disruptions, and price volatility. This dependence is particularly acute for materials like REEs and cobalt, which are essential to the green transition but are concentrated in politically sensitive or unstable regions. For example, past export restrictions by China or instability in the DRC have demonstrated how supply bottlenecks can undermine industrial planning and strategic autonomy (Cimprich et al., 2023; Jia et al., 2022).

In response, the EU is increasingly positioning circular economy strategies – such as secondary sourcing through recycling and the development of localized, closed-loop supply chains – as key instruments not only for environmental sustainability but also for geopolitical resilience. These approaches reduce reliance on external actors, shorten supply chains, and enhance control over material flows within Europe. Thus, circularity becomes a dual-purpose strategy that strengthens both climate goals and energy and industrial security (Granados-Fernández, Montiel, Díaz-Abad, Rodrigo & Lobato, 2021; Wang et al., 2024).

In sum, raw materials are foundational yet constraining elements of the green transition. Recycling technologies, especially when supported by coherent policy and design strategies, not only mitigate environmental and geopolitical risks but also actively enable a more circular and resilient economy.

**Infrastructure for Low-Carbon Innovation.** As global efforts intensify to combat climate change and achieve climate neutrality, the transformation of energy systems toward low-carbon models has emerged as a central challenge. This transformation is not solely reliant on deploying cleaner technologies but requires the development of integrated infrastructure systems and a secure supply of materials critical to the green economy. A growing body of research focuses on the technical underpinnings and logistical enablers of a sustainable energy transition, revealing an intricate landscape where resilient material supply chains, efficient recycling systems, and coordinated regulatory frameworks must support innovations in energy production and storage. These components are essential to ensure both the environmental viability and the geopolitical stability of the transition.

Many studies indicate that CRMs such as lithium, cobalt, neodymium, and copper are essential for energy systems, electric vehicles (EVs), and renewable infrastructure. However, the increasing demand for these materials is highlighting geopolitical dependencies and shortcomings in recycling efforts. For instance, Granvik et al. (2025) introduce forecasting tools designed to help align the supply of CRMs with the demand generated by the green transition. They emphasize the need for improved mining practices, alternative strategies, and efficient recycling pipelines. Similarly, McKenna et al. (2025) note the rising demand for REEs in wind turbines and point out that challenges such as end-of-life recycling and permitting delays are significant hurdles.

Recycling plays a crucial role in addressing the scarcity of CRMs by closing the loop in material use and reducing dependency on virgin extraction. Hackenhaar et al. (2025) propose a sophisticated method, CriticS, that integrates supply risk and economic importance into lifecycle assessment (LCA) frameworks. This approach allows for more tailored decision-making by enabling stakeholders to assess raw material criticality based on multiple customizable criteria. By integrating raw material considerations early in product design, CriticS improves the sustainability profile of industrial systems. In parallel, Sala & Richert (2025) underscore the transformative potential of 3D printing technologies, which minimize material waste, enable distributed and on-demand production, and reduce the need for complex supply chains – thereby boosting resilience in material sourcing and use. Moreover, Compagnoni & Santini (2025) provide a case study in how policy can drive technological transitions. They illustrate how European Union regulations, specifically RoHS and REACH, have successfully promoted the substitution of hazardous and resource-intensive materials with more sustainable alternatives and facilitated the transition toward dematerialized electronics. These legislative instruments set a precedent for integrating CRM considerations into product standards and industrial design, thereby reinforcing circular-economy goals across sectors.

Hydrogen plays a pivotal role in decarbonizing hard-to-abate sectors such as heavy industry, long-haul transport, and high-temperature industrial processes, where direct electrification is less feasible. Schulze et al. (2024) emphasize the importance of integrating material flow and raw material demand into energy modeling frameworks to ensure that hydrogen systems are evaluated not only for energy efficiency but also for their reliance on critical inputs such as platinum-group metals. This holistic modeling approach enables a more realistic and sustainable assessment of hydrogen's role in energy transitions by accounting for upstream material constraints and supply chain vulnerabilities. Meanwhile, Mastronardi et al. (2024) introduce a breakthrough in hydrogen fuel cell technology by developing an alkaline electrochemical deposition method for recycling platinum. This technique significantly reduces the environmental footprint and cost of catalyst recovery by enabling platinum reuse within fuel cells, thereby promoting a circular approach to resource management. Their method also enables the use of less expensive, more sustainable substrates, making hydrogen technology production more accessible and scalable. Together, these studies illustrate how material efficiency and recycling innovation are critical to unlocking hydrogen’s full potential as a clean energy carrier.

Electric vehicles are central to the transition, but their infrastructure depends on extensive, globally interconnected supply chains that span from raw material extraction to end-of-life recycling. This complexity introduces significant sustainability and ethical challenges. Kainiemi et al. (2025) and Popa & Szabó (2025) raise concerns about environmental justice and social equity, particularly in the context of cobalt and lithium mining in the Global South, where communities often bear the brunt of environmental degradation, water scarcity, and labor exploitation. These conditions raise critical questions about the moral foundation of clean energy technologies that rely on ethically problematic resource extraction. Addressing these injustices requires not only technical solutions but also governance reforms that ensure inclusive participation and benefit-sharing.

Compagnoni et al. (2025) focus on Extended Producer Responsibility (EPR) frameworks, highlighting their role in enhancing battery waste tracking, collection, and recycling processes. EPR policies shift accountability for end-of-life management from consumers to producers, potentially creating incentives for design improvements and investment in circular infrastructure. However, the paper also acknowledges that despite these advances, large-scale CRM recovery is unlikely to be fully realized before 2030 due to current technological limitations, fragmented recycling networks, and low collection rates. This delay underscores the urgent need for coordinated policy action and investment to accelerate the maturation of battery recycling systems.

Several papers underscore that technological solutions must be matched with robust, forward-looking supply chain strategies to ensure the resilience and autonomy of green transition pathways. von Rennenberg et al. (2024) advocate for the expansion of urban mining practices, which involve recovering valuable materials from end-of-life products in densely populated areas, thereby reducing dependence on primary extraction and mitigating environmental impacts. They also explore how digital tools and criticality assessments can guide policy design to improve resource recovery efficiency. Similarly, Vivoda (2024) examines the potential of deep-sea mining as an alternative sourcing method for CRMs. While acknowledging its technological and environmental uncertainties, the study argues that, if properly governed, deep-sea mining could diversify supply and reduce the geopolitical vulnerabilities currently associated with terrestrial mining in politically unstable regions.

Gao (2025) provides a meta-perspective by critiquing the European Union's fragmented approach to implementing its digital and green agendas. The analysis reveals that although the EU rhetorically commits to strategic autonomy and sustainability, operational alignment across member states and policy domains is often lacking. This misalignment undermines the EU's capacity to integrate circular-economy principles and supply-chain resilience into its broader industrial strategy. The paper calls for stronger coordination mechanisms, harmonized regulatory frameworks, and enhanced data-sharing infrastructures to bridge policy silos and support the systemic transformations needed for a low-carbon economy.

Together, these studies emphasize that while breakthroughs in clean technologies, such as hydrogen systems, electric vehicles, and energy-efficient manufacturing, are crucial, they cannot drive the green transition on their own. A comprehensive and integrated infrastructure is needed – one that encompasses resilient, diversified supply chains for CRMs, robust circular economy mechanisms to enable material recovery and reuse, and harmonized policy frameworks that align industrial strategy with environmental and social justice goals. These structural supports must be embedded at multiple levels – local, national, and transnational – and actively coordinate innovation, investment, and governance to overcome current bottlenecks and ensure the equitable, sustainable scaling of low-carbon systems.

**Governance and Institutional Frameworks for the Green Transition and CRMs.** This sub-section captures a policy-centric and conceptual strand of research that examines how national and supranational institutions – especially in the EU – shape the strategic direction of the green transition through regulations, planning, and cross-border coordination. The selected references reflect this focus, each offering unique insights into governance structures, coherence, and the policy instruments used to manage the complexities of CRM supply and circularity.

Several studies emphasize the European Union's evolving role not only as a regulatory body but also as a strategic planner and policy entrepreneur, actively shaping the trajectory of the green and digital transitions. This leadership is especially evident in how the EU aligns CRM's governance with its broader environmental and industrial goals. Feichtinger & Posch (2025) examine the EU's CRM assessments and the 2023 CRM Act, which institutionalize benchmarking tools and classification systems that enable systematic forecasting, lifecycle management, and strategic raw-material prioritization across sectors. These tools underpin a long-term vision of sustainability and resilience in raw material supply. Complementing this perspective, Gao (2025) introduces a framework to assess coherence in EU governance, revealing a gap between rhetorical commitment and operational execution. While high-level policy documents integrate green and digital ambitions, implementation across member states remains uneven, often hindered by sectoral silos and varying political will. Adding a geopolitical dimension, Glencross (2024) contextualizes CRM policy within a broader shift toward geo-economic industrial strategy. Here, the EU's move toward resilience and strategic autonomy marks a departure from traditional market liberalism, using tools such as the CRM Act to encourage domestic sourcing, reduce reliance on external suppliers, and reassert industrial sovereignty in a volatile global landscape.

In terms of supranational monitoring and policy evaluation, Ottomano Palmisano et al. (2025) employ the PROMETHEE II decision-aiding tool to assess the implementation of the European Green Deal across member states. Their findings illustrate disparities in policy ambition and effectiveness, underscoring the importance of supranational coordination mechanisms and performance monitoring to ensure alignment. Compagnoni et al. (2025) show how EU Extended Producer Responsibility (EPR) regulations influence international trade patterns in battery waste, indirectly reinforcing EU policy reach beyond its borders through market mechanisms and data harmonization tools.

National and regional policy differentiation also emerges as a critical theme. Fletcher & Dunk (2023) provide a broader perspective by examining the role of state-led industrial policy and techno-political strategy in shaping energy transition outcomes. Their study underscores how national governments in Europe increasingly act as mediators between global market forces and local socio-economic needs, particularly by mobilizing industrial policy tools to support green infrastructure and domestic supply chain development. This reflects a resurgence of state involvement in energy planning and in the governance of raw materials, particularly in response to the dual imperatives of decarbonization and resilience. Their findings illustrate the growing complexity of national strategies that must simultaneously address environmental, economic, and geopolitical objectives, often in coordination – but occasionally in tension – with supranational EU frameworks. Vezzoni (2023) explores policy fragmentation and implementation challenges at the member-state level, particularly how regional disparities in industrial capacity and administrative structures affect the uptake of circular economy strategies. Similarly, Hyvönen, Koivunen & Syri (2024) examine Finland as a case study for managing tensions between green energy expansion and local justice, reflecting how national policies may both align with and diverge from EU-level sustainability and social equity goals.

Finally, several authors highlight the strategic autonomy and industrial sovereignty objectives that have become increasingly central to EU policy frameworks. Glencross (2024) and Feichtinger & Posch (2025) both stress that instruments like the CRM Act and battery regulations are not merely environmental policies but also tools for geopolitical positioning, aimed at reinforcing Europe's control over critical inputs for green and digital technologies. These policies seek to reduce Europe's reliance on third countries, particularly China, by setting ambitious targets for domestic extraction (10%), processing (40%), and recycling (25%) of CRMs by 2030. Such measures are also supported by accelerated permitting and funding mechanisms. Paleari (2024) expands this perspective by illustrating how Extended Producer Responsibility (EPR) serves as a lever to enhance CRM recovery by shifting operational and financial responsibility from public authorities to private producers. This approach not only improves accountability and traceability within product lifecycles but also promotes circular economy goals at both the national and EU levels. Together, these studies reflect a growing consensus that industrial policy, when aligned with environmental objectives, is indispensable for securing a resilient, sovereign, and circular European economy.

Together, these studies show a dynamic interplay between supranational planning, predominantly steered by the EU, and the diverse national strategies employed by member states to advance the green transition. The EU takes a central role, establishing overarching policy frameworks, regulatory instruments, and ambitious targets – such as the CRM Act's benchmarks for 10% domestic extraction, 40% processing, and 25% recycling of CRMs by 2030. These targets underscore the EU's strategic ambition to embed resilience and autonomy into its green and digital transformation. However, the success of these supranational visions hinges on their translation into coherent national actions. Across the examined literature, it is evident that the degree of coherence varies considerably, shaped by sectoral capabilities, administrative structures, political will, and socio-economic contexts at the national and regional levels. This creates a dynamic governance environment where alignment is not automatic but must be continually negotiated through monitoring mechanisms, policy learning, and multilevel coordination.

## Synthesis on Material Risk Profiles, Economic Significance, and Recycling Potential

The transition toward renewable energy systems is not only an environmental imperative but also a strategic challenge grounded in material security. Technologies such as wind turbines, solar PV, batteries, and electrolyzers require a range of CRMs that are indispensable for performance and efficiency. However, these materials often come with significant risks due to concentrated supply chains, limited recyclability, and high economic dependence. This section draws on the European Commission's Study on Critical Raw Materials (Grohol et al., 2023) and the Supply Chain Analysis and Material Demand Forecast in Strategic Technologies and Sectors in the EU – A Foresight Study (Carrara et al., 2023), which together provide the methodological framework, risk indicators, and strategic guidance that inform the following analysis.

**Critical Raw Materials and Their Role in Renewable Technologies.** The European Commission identifies CRMs through a comprehensive evaluation that incorporates both Supply Risk (SR) and Economic Importance (EI). This dual-assessment framework aims to determine which materials are essential for the EU's economy and are simultaneously exposed to significant supply chain vulnerabilities. According to the 2023 methodology, a material qualifies as "critical" if it demonstrates a high likelihood of supply disruption – quantified as an SR score equal to or greater than 1.0 – and is also deemed significantly relevant to the EU economy, indicated by an EI score of 2.8 or higher. This method ensures that materials identified as critical are not only scarce or difficult to obtain but also play a vital role in strategic sectors such as renewable energy, mobility, and digital infrastructure (Grohol et al., 2023).

**SR ≥ 1.0**, a threshold that signifies a substantial vulnerability to disruptions in the supply of raw materials. This level of supply risk implies that the material in question is sourced from highly concentrated markets, geopolitically unstable regions, or countries with weak governance, and that the EU relies heavily on imports for its acquisition. When a material's SR reaches or exceeds this benchmark, it indicates that any external shock – such as political conflict, trade restrictions, or logistical breakdowns – could significantly threaten the EU's ability to maintain stable and continuous access to that material, thereby jeopardizing energy security and industrial continuity.

**EI ≥ 2.8**, a benchmark that signifies the material's substantial contribution to the EU's economic activity and its importance across strategic industrial sectors. This high level of economic importance is determined by examining the role a material plays in value-added manufacturing processes, particularly in industries deemed critical to the EU's green and digital transitions, such as renewable energy, aerospace, mobility, and information technology. The more integral a material is to high-value sectors and the more difficult it is to replace without performance or cost penalties, the higher its economic importance. A material that reaches or exceeds this threshold is considered essential not only for maintaining industrial competitiveness but also for achieving long-term policy goals related to sustainability, resilience, and technological innovation.

Table 1 summarizes key CRMs essential to various renewable energy technologies, including wind turbines, batteries, and solar PV. It highlights each material's application within the sector, evaluates its supply risk and economic importance as defined by the EU's 2023 criticality methodology, and presents its end-of-life recycling input rates (EOL-RIR). These indicators collectively demonstrate which materials are most vulnerable to supply disruptions and least likely to be recovered through circular practices, thereby informing policy priorities for securing long-term material resilience.

*Table 1. Critical Raw Materials (CRMs) in the Renewable Energy Sector, their Applications, Supply Risk, Economic Importance, and Recycling Rates (based on Grohol, GROW & European Commission, 2023)*

| Material | Use in Renewables | SR (2023) | EI (2023) | Recycling Rate (EOL-RIR) |
|---|---|---|---|---|
| Neodymium (REE) | Wind turbine magnets, EV motors | Very High | Very High | <1% |
| Dysprosium (REE) | Heat-resistant magnets in turbines and motors | Very High | High | <1% |
| Lithium | Batteries for EVs, storage | High | High | <1% |
| Cobalt | Li-ion batteries | High | High | ~16% |
| Natural Graphite | Battery anode material | High | High | <1% |
| Silicon Metal | Solar PV cells, semiconductors | Medium | Very High | ~10% |
| Gallium | High-efficiency PV, semiconductors | Very High | Moderate–High | <1% |
| Platinum | Electrolyzers, fuel cells | High | High | ~50% |
| Manganese | Batteries (NMC cathodes) | Moderate | Moderate | ~40% |
| Nickel | EV batteries | Strategic | High | ~30% |
| Copper | Wiring, grid, windings in turbines | Strategic | Very High | ~45% |

These materials are unevenly distributed globally, with a pronounced concentration in a small number of supplier countries, particularly China. China alone accounts for approximately 85–100% of the global supply of REEs, making it the leading exporter of several other critical materials as well. This dominance establishes significant structural dependencies for the European Union, which heavily relies on these imports to support its renewable energy infrastructure. The concentration of supply not only creates logistical bottlenecks but also introduces geopolitical vulnerabilities. Any disruption stemming from trade policies, diplomatic tensions, or domestic policies in these key supplier countries could have immediate and far-reaching effects on the EU's ability to access essential raw materials. This dependency underscores the strategic urgency of diversifying supply sources and investing in domestic capabilities for extraction, processing, and recycling.

**The EU Criticality Methodology: Understanding SR and EI.** The EU criticality assessment methodology is based on two equally important indicators: SR and EI. Both metrics are used to evaluate a material's overall criticality to the EU's economy and strategic autonomy.

SR reflects the EU's vulnerability to disruptions in the supply of raw materials. Several factors contribute to this risk. First, the global concentration of material supply is assessed using the Herfindahl-Hirschman Index (HHI), which measures the distribution of production across countries. A high HHI suggests a strong dependence on a small number of suppliers, increasing the risk of geopolitical or economic disruptions. Second, the governance quality of supplier countries, evaluated using the Worldwide Governance Indicators (WGI), is critical. Low political stability, weak regulatory frameworks, or corruption in supplier countries elevate the probability of supply interruptions. Third, the EU's import reliance adds to SR, particularly when sourcing materials from outside the EU. However, this risk can be mitigated by increasing recycling rates, which reduces dependency on primary imports. Finally, substitution difficulty plays a role; materials that cannot be easily or economically replaced increase overall SR due to their irreplaceable roles in technology.

EI, on the other hand, gauges how vital a material is to EU industries and the EU economy as a whole. This metric begins by mapping materials to strategic industrial sectors, as classified under NACE codes, including renewable energy, electric mobility, aerospace, defense, and digital technologies. The EI score assesses the added value of these sectors to the EU economy and their dependence on specific materials. Crucially, it also factors in substitution difficulty – the fewer effective alternatives a material has, the more economically indispensable it becomes. A high EI score reflects not only the centrality of a material to industrial value chains but also the potential economic disruption if its supply is compromised.

The threshold values used in this methodology are $SR \geq 1.0$ and $EI \geq 2.8$. These values serve as benchmarks to classify materials as critical. When both thresholds are met, the material is considered crucial for the EU's industrial resilience, technological advancement, and strategic autonomy. This dual focus ensures that policy decisions address both the availability of materials and their role in supporting the EU's long-term strategic goals.

**Circular Economy: A Key Lever for Energy Resilience.** While primary extraction currently dominates material flows in the renewable energy sector, the circular economy offers a strategic opportunity to enhance long-term energy resilience and reduce external supply dependencies. One of the most effective pathways within the circular economy is the development of advanced recycling systems. These systems are especially important for materials such as platinum, copper, and manganese, which already benefit from relatively well-established recovery processes. Efficient recycling not only conserves resources but also mitigates the impact of global market fluctuations and geopolitical risks by enabling the EU to reclaim materials from end-of-life products.

In addition to recycling, reuse, and remanufacturing represent promising avenues to extend the life of CRM-containing products. However, these practices remain largely underdeveloped, particularly in complex systems such as batteries and electronic devices, where material separation and component refurbishment pose technical challenges. As a result, the potential for scaling reuse and remanufacturing remains limited without targeted investment and regulatory support.

Another crucial but currently underutilized aspect is design-for-recyclability. Products like wind turbines and solar panels often lack features that allow for easy disassembly or efficient material recovery, making end-of-life processing inefficient and costly. Encouraging manufacturers to adopt design principles that prioritize recyclability from the outset could significantly improve material recovery rates and reduce waste.

Lastly, material substitution can offer some relief from CRM dependence, especially for select materials with viable alternatives. However, substituting CRMs often involves performance trade-offs or increased production costs. For instance, alternatives to REEs in permanent magnets or lithium in batteries may reduce dependency but sacrifice efficiency, lifespan, or energy density.

Despite growing policy attention and the EU's strategic commitments, actual Recycling Input Rates (RIRs) remain troublingly low for many strategic materials. For example, end-of-life recovery rates for neodymium, dysprosium, lithium, and gallium are still under 1%, reflecting significant gaps in collection, processing technology, and market incentives. Improving these rates is essential not only for reducing reliance on primary sources but also for enabling a sustainable, closed-loop economy capable of supporting a secure and resilient energy transition.

**Green Transition and Energy Shock Preparedness.** The green transition, while essential for achieving climate neutrality and energy sustainability, also exposes the European Union to new and complex vulnerabilities, particularly given its reliance on CRMs. Recent global crises, such as the COVID-19 pandemic and geopolitical instability, have demonstrated how quickly and severely international supply chains can be disrupted. These disruptions emphasized the urgent need for proactive measures to ensure that the renewable energy transition remains resilient in the face of future shocks.

At the heart of this issue lies the EU’s exposure to vulnerabilities in upstream supply chain segments, especially in the mining and initial processing of CRMs. The fact that many of these materials are sourced from a limited number of countries – chiefly China – presents a structural risk. A disruption in supply from these countries, whether due to export restrictions, political instability, or economic competition, could significantly derail clean technology deployment.

Another critical concern is the time dimension. Developing new mining operations or scaling up recycling infrastructure involves long lead times. Consequently, the EU's capacity to respond swiftly to a crisis is constrained by the slow pace of expansion in raw material supply. This time lag means that even temporary shocks can lead to long-term setbacks in capacity growth and technology deployment.

Moreover, overreliance on a narrow group of trade partners heightens systemic risk. A concentrated supply base undermines strategic autonomy and leaves the EU susceptible to external pressures that could compromise both the pace and direction of its green transition.

To address these multifaceted risks, the EU must adopt a broad and forward-looking strategy. This includes diversifying sourcing through reliable international trade partnerships, investing in domestic extraction and processing capabilities, and accelerating the development of recycling and reuse infrastructure. Furthermore, enhancing research and development in materials efficiency and substitution technologies will be key to reducing dependency on high-risk materials altogether.

These strategic goals are now being translated into policy through instruments like the Critical Raw Materials Act. By embedding these priorities into legislative and industrial planning frameworks, the EU aims to strengthen its energy resilience while continuing to lead the global shift toward a sustainable, low-carbon economy.

The renewable energy transition is fundamentally reliant on a narrow group of CRMs that are both highly economically significant and subject to substantial supply risk. These materials are indispensable for manufacturing key technologies such as wind turbines, solar panels, and electric vehicle batteries. However, their procurement is often concentrated in geopolitically sensitive regions, rendering the EU particularly susceptible to supply chain disruptions. While circular economy practices – such as recycling, reuse, and substitution – offer important mitigation strategies, they are currently not developed to a scale that can fully offset the EU’s reliance on primary raw materials. End-of-life recovery rates for many of these materials remain alarmingly low, and technological barriers continue to impede large-scale substitution without performance losses. Therefore, ensuring the resilience of the green transition requires establishing a robust, diversified raw-material ecosystem. This must include enhanced domestic supply capabilities, strategic international partnerships, and accelerated investment in circular innovation. Only through this multifaceted approach can the EU fortify its energy system against future shocks and advance toward a sustainable, low-carbon economy.

## Conclusion

The findings of this study highlight several core insights into the research and policy discourse surrounding the green transition and its material foundations. The bibliometric analysis identified four dominant clusters in the literature. The first centers on strategic materials and sustainability, encompassing terms such as "carbon," "energy transition," and "sustainable development," with a strong focus on the role of CRMs. The second cluster addresses material flows and environmental management, reflecting interest in recycling, waste management, and geographic considerations such as the role of China and Europe. The third cluster is oriented around energy technologies and infrastructure, including terms related to electric vehicles, hydrogen, and supply chain logistics. Lastly, the fourth cluster focuses on governance and policy, particularly the role of institutions like the European Union in shaping transition pathways.

Among all keywords, "recycling" emerged as the most interconnected term, underscoring its central importance to the field. Other highly connected terms included "circular economy," "cobalt," and "critical raw materials," reinforcing their prominence in both academic and policy discussions.

The policy synthesis extended these findings by emphasizing the critical vulnerabilities associated with specific materials. Several CRMs – such as neodymium, dysprosium, lithium, and cobalt – are indispensable for low-carbon technologies like wind turbines, electric vehicles, and batteries, yet exhibit extremely low recycling rates, often below 1%. This disparity between strategic importance and circular recovery indicates a structural weakness in current sustainability strategies.

Moreover, the geographic concentration of CRM supply chains, particularly in politically sensitive regions such as China and the Democratic Republic of Congo, presents significant risks to supply stability. These dependencies underscore the need for enhanced circular economy mechanisms, such as recycling infrastructure, product design for disassembly, and domestic recovery capabilities within the EU.

Overall, the study reveals an interdisciplinary consensus: achieving a resilient and sustainable green transition requires integrated approaches to CRM management that combine scientific innovation, coherent policy-making, and circular economy strategies.

This integrative framework – blending bibliometric analysis with policy synthesis – represents a novel contribution to the field. By revealing a critical gap between the strategic importance of materials like neodymium, lithium, and cobalt and their extremely low recycling rates, the study exposes an oversight in current academic and policy planning. Moreover, by highlighting the concentration of CRM supply chains in politically sensitive regions, it underscores the need for localized circular economy strategies and better-coordinated EU policies. The identification of four distinct yet interlinked research clusters further strengthens the study's contribution, illustrating how an interdisciplinary consensus is emerging across sustainability, environmental management, technological infrastructure, and governance.

## References

Adamczyk, Z., Komorek, J., Kokowska-Pawłowska, M., & Nowak, J. (2024). Distribution of Rare Earth Elements in Ash from Lignite Combustion in Polish Power Plants. *Materials*, 17(18). https://doi.org/10.3390/ma17184477

Alataş, S., Hiçyılmaz, B., & Karakaya, E. (2024). Material demand and material efficiency for sustainable development in the European Union countries: A stochastic frontier analysis. *Sustainable Development*, 32(1), 166–183. https://doi.org/10.1002/sd.2648

Artudean, D., Kertész, N., Popa, D.-C., Bacali, L., & Szabó, L. (2024). Navigating Supply Chain Shortages in the Transition to Sustainable Transportation: The Role of Critical Materials Beyond Batteries †. Engineering Proceedings, 79(1). https://doi.org/10.3390/engproc2024079013

Balcarova, T., Pilarova, L., Prokop, M., Jadrna, M., Kvasnickova Stanislavska, L., & Pilar, L. (2024). Analysis of green deal communication on twitter: environmental and political perspective. *Frontiers in Environmental Science*, 12. https://doi.org/10.3389/fenvs.2024.1370568

Barragan-Contreras, S. J., Paterson, M., Jackson, J., Trommer, S., Behuria, P., & Hickey, S. (2025). Capturing the disruptive nature of green energy transitions: A political economy approach. *Energy Research and Social Science*, 123. https://doi.org/10.1016/j.erss.2025.104039

Bazienė, K., & Gargasas, J. (2023). Sustainable innovative technology solutions for the energy sector. *Entrepreneurship and Sustainability Issues*, 11(2), 215-226. https://doi.org/10.9770/jesi.2023.11.2(15)

Butu, A., Rodino, S., & Butu, M. (2023). Global Research Progress and Trends on Critical Metals: A Bibliometric Analysis. *Sustainability* (Switzerland), 15(6). https://doi.org/10.3390/su15064834

Carmona-Martínez, A. A., Rontogianni, A., Zeneli, M., Grammelis, P., Birgi, O., Janssen, R., … Jarauta-Córdoba, C. (2024). Charting the Course: Navigating Decarbonisation Pathways in Greece, Germany, The

Netherlands, and Spain's Industrial Sectors. *Sustainability* (Switzerland), 16(14). https://doi.org/10.3390/su16146176

Carrara, S., Bobba, S., Blagoeva, D., Dias, A., Cavalli, P., Georgitzikis, A., … Somers, T. (2023). Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study. https://doi.org/10.2760/334074

Chadly, A., Moawad, K., Salah, K., Omar, M., & Mayyas, A. (2024). State of global solar energy market: Overview, China's role, Challenges, and Opportunities. *Sustainable Horizons*, 11. https://doi.org/10.1016/j.horiz.2024.100108

Churikanova, O., Pilova, D., Giordano, B., Piccinetti, L., & Amoruso, M. (2025). Circular economy and smart specialisation business strategies: the Dnipropetrovsk region case. *Insights into Regional Development,* 7(1), 109-130. https://doi.org/10.70132/y8378689786

Ciftci, M. M., & Lemaire, X. (2023). Deciphering the impacts of 'green' energy transition on socio-environmental lithium conflicts: Evidence from Argentina and Chile. *Extractive Industries and Society*, 16. https://doi.org/10.1016/j.exis.2023.101373

Cimprich, A., Young, S. B., Schrijvers, D., Ku, A. Y., Hagelüken, C., Christmann, P., … Hool, A. (2023). The role of industrial actors in the circular economy for critical raw materials: a framework with case studies across a range of industries. *Mineral Economics*, 36(2), 301–319. https://doi.org/10.1007/s13563-022-00304-8

Compagnoni, M., Grazzi, M., Pieri, F., & Tomasi, C. (2025). Extended Producer Responsibility and Trade Flows in Waste: The Case of Batteries. *Environmental and Resource Economics*, 88(1), 43–76. https://doi.org/10.1007/s10640-024-00907-5

Compagnoni, M., & Santini, E. (2025). The evolution of the EU electronics market and its impact on direct material consumption: Lessons from the past. *Ecological Economics*, 235. https://doi.org/10.1016/j.ecolecon.2025.108630

Considine, J., Galkin, P., Hatipoglu, E., & Aldayel, A. (2023). The effects of a shock to critical minerals prices on the world oil price and inflation. *Energy Economics*, 127. https://doi.org/10.1016/j.eneco.2023.106934

Cusenza, M. A., Novi, A., Daddi, T., Girardi, P., & Iraldo, F. (2024). A multidimensional and multi-criteria framework for measuring the circularity of energy generation systems at national level. *Journal of Cleaner Production*, 448. https://doi.org/10.1016/j.jclepro.2024.141578

Dmitrieva, D., & Solovyova, V. (2023). Russian Arctic Mineral Resources Sustainable Development in the Context of Energy Transition, ESG Agenda and Geopolitical Tensions. *Energies*, 16(13). https://doi.org/10.3390/en16135145

Eikeng, E., Makhsoos, A., & Pollet, B. G. (2024). Critical and strategic raw materials for electrolysers, fuel cells, metal hydrides and hydrogen separation technologies. *International Journal of Hydrogen Energy,* 71, 433–464. https://doi.org/10.1016/j.ijhydene.2024.05.096

Feichtinger, G., & Posch, W. (2025). Evaluation of European Critical Raw Material Assessments under Energy Transition Considerations: Applications and Prospects. *Circular Economy and Sustainability*. https://doi.org/10.1007/s43615-024-00493-0

Ferreira-Filipe, D. A., Duarte, A. C., Hursthouse, A. S., Rocha-Santos, T., & Silva, A. L. P. (2025). Biobased Strategies for E-Waste Metal Recovery: A Critical Overview of Recent Advances. *Environments* - MDPI, 12(1). https://doi.org/10.3390/environments12010026

Fletcher, C. A., & Dunk, R. (2023). Recovery And Utilisation Of Municipal Solid Waste Incineration Bottom Ash: Implications For European Waste Management Strategy. *Detritus*, 23, 43–57. https://doi.org/10.31025/2611-4135/2023.17274

Gao, X. (2025). The EU's twin transitions towards sustainability and digital leadership: a coherent or fragmented policy field? *Regional Studies*, 59(1). https://doi.org/10.1080/00343404.2024.2360053

Ge, Z., Liu, J., & Zhong, C. (2024). Uncovering the mineral constraints on energy transition under climate change targets: A bibliometric review. *Energy Strategy Reviews*, 55. https://doi.org/10.1016/j.esr.2024.101520

Gerasimova, V., Prause, G., & Hoffmann, T. (2023). NFT-enriched smart contracts for smart circular economy models. *Entrepreneurship and Sustainability Issues*, 11(2), 93-110. https://doi.org/10.9770/jesi.2023.11.2(7)

Glencross, A. (2024). The geopolitics of supply chains: EU efforts to ensure security of supply. *Global Policy*, 15(4), 729–739. https://doi.org/10.1111/1758-5899.13388

Granados-Fernández, R., Montiel, M. A., Díaz-Abad, S., Rodrigo, M. A., & Lobato, J. (2021). Platinum recovery techniques for a circular economy. *Catalysts*, 11(8). https://doi.org/10.3390/catal11080937

Granvik, P., Hanski, J., Lähdesmäki, S., Jokilaakso, A., & Huttunen-Saarivirta, E. (2025). Critical raw materials for green transition: Key parameters and feasibility index for sufficiency. *Resources, Conservation and Recycling*, 218. https://doi.org/10.1016/j.resconrec.2025.108197

Grohol, M., GROW, C. V. D., & European Commission. (2023). Study on the Critical Raw Materials for the EU.

Hackenhaar, I. C., Moraga, G., Thomassen, G., Taelman, S. E., Bachmann, T. M., & Dewulf, J. (2025). CriticS: a resource criticality characterization method for life cycle assessment considering stakeholders' perspectives. *International Journal of Life Cycle Assessment*, 30(4), 749–769. https://doi.org/10.1007/s11367-025-02439-6

Hyvönen, J., Koivunen, T., & Syri, S. (2024). Review of Climate Strategies in Northern Europe: Exposure to Potential Risks and Limitations. *Energies*, 17(7). https://doi.org/10.3390/en17071538

Jakimów, M., Samokhalov, V., & Baldassarre, B. (2024). Achieving European Union strategic autonomy: circularity in critical raw materials value chains. *International Affairs*, 100(4), 1735–1748. https://doi.org/10.1093/ia/iiae127

Jannesar Niri, A., Poelzer, G. A., Zhang, S. E., Rosenkranz, J., Pettersson, M., & Ghorbani, Y. (2024). Sustainability challenges throughout the electric vehicle battery value chain. *Renewable and Sustainable Energy Reviews*, 191. https://doi.org/10.1016/j.rser.2023.114176

Jia, H., Zhou, Y., Wang, A., Wang, G., Li, T., Wang, C., … Li, P. (2022). Evolution of the Anthropogenic Gallium Cycle in China From 2005 to 2020. *Frontiers in Energy Research*, 10. https://doi.org/10.3389/fenrg.2022.944617

Kainiemi, L., Laukkanen, M., & Levänen, J. (2025). Multi-sectoral interactions in energy transition: Unveiling tensions between sustainability and justice. *Applied Energy*, 384. https://doi.org/10.1016/j.apenergy.2025.125437

Kalpakchiev, T., Jacobs, B., Fraundorfer, M., Martin-Ortega, J., & Cordell, D. (2025). Creating an Alternative Governance for Phosphorus Circularity Through Framings That Strengthen Intersectoral Policy Coherence in the EU: Constraints and Implementation Possibilities. *Sustainability* (Switzerland), 17(4). https://doi.org/10.3390/su17041478

Kamran, M., Raugei, M., & Hutchinson, A. (2023). Critical elements for a successful energy transition: A systematic review. *Renewable and Sustainable Energy Transition*, 4. https://doi.org/10.1016/j.rset.2023.100068

Ku, A. Y., Alonso, E., Eggert, R., Graedel, T., Habib, K., Hool, A., … Veeh, C. (2024). Grand challenges in anticipating and responding to critical materials supply risks. *Joule*, 8(5), 1208–1223. https://doi.org/10.1016/j.joule.2024.03.001

Liang, Y., Kleijn, R., Tukker, A., & van der Voet, E. (2022). Material requirements for low-carbon energy technologies: A quantitative review. *Renewable and Sustainable Energy Reviews*, 161. https://doi.org/10.1016/j.rser.2022.112334

Lorenc, S., Podobińska-Staniec, M., Wiktor-Sułkowska, A., & Kustra, A. (2024). Value Chains In The Raw Materials Industry – The Example Of The Cobalt Value Chain | Łańcuchy Wartości W Przemyśle Surowcowym – Przykład Cobalt Value Chain. *Gospodarka Surowcami Mineralnymi / Mineral Resources Management*, 40(1), 5–24. https://doi.org/10.24425/gsm.2024.149302

Luo, J., Yang, Y., & Jiang, Y. (2025). Assessing the antecedents, processes, and consequences of sustainable electric vehicle battery recycling: A systematic literature review. *International Journal of Production Economics*, 282. https://doi.org/10.1016/j.ijpe.2025.109551

Makarava, I., Vänskä, J., Kramek, A., Ryl, J., Wilson, B. P., Yliniemi, K., & Lundström, M. (2024). Electrochemical cobalt oxidation in chloride media. *Minerals Engineering*, 211. https://doi.org/10.1016/j.mineng.2024.108679

Mastronardi, V., Gamberini, A., Zappia, M. I., Zuo, Y., Abruzzese, M., Bagheri, A., … Bellani, S. (2024). Alkaline electrochemical deposition of Pt for alkaline electrolyzers. *International Journal of Hydrogen Energy*, 80, 261–269. https://doi.org/10.1016/j.ijhydene.2024.07.086

Matz, L., Bensmann, B., Hanke-Rauschenbach, R., & Minke, C. (2024). Resource-Efficient Gigawatt Water Electrolysis in Germany—A Circular Economy Potential Analysis. *Circular Economy and Sustainability*, 4(2), 1153–1182. https://doi.org/10.1007/s43615-024-00345-x

McKenna, R., Lilliestam, J., Heinrichs, H. U., Weinand, J., Schmidt, J., Staffell, I., … Ramirez Camargo, L. (2025). System impacts of wind energy developments: Key research challenges and opportunities. *Joule*, 9(1). https://doi.org/10.1016/j.joule.2024.11.016

Mendoza, J. M. F., Gallego-Schmid, A., Velenturf, A. P. M., Jensen, P. D., & Ibarra, D. (2022). Circular economy business models and technology management strategies in the wind industry: Sustainability potential, industrial challenges and opportunities. *Renewable and Sustainable Energy Reviews*, 163. https://doi.org/10.1016/j.rser.2022.112523

Miszczak, K., Kriviņš, A., & Kaze, V. (2024). Challenges and drivers of green and sustainable spatial development: a case study of Lower Silesia and Latvia. *Entrepreneurship and Sustainability Issues*, 12(2), 85-98. https://doi.org/10.9770/b7283449476

Moore, K. R., Marquis, E., Shanks, K., & Wall, F. (2024). Mining of primary raw materials as the critical foundation of 'sustainable' metals: a wicked problem for technology innovation clusters. *Philosophical*

*Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,* 382(2284). https://doi.org/10.1098/rsta.2023.0241

Naimoğlu, M., & Kavaz, I. (2023). Energy use tendencies in a resource-abundant country: the case of Canada. *Insights into Regional Development*, 5(4), 65-79. https://doi.org/10.9770/ird.2023.5.4(5)

Ottomano Palmisano, G., Rocchi, L., Negri, L., & Piscitelli, L. (2025). Evaluating the Progress of the EU Countries Towards Implementation of the European Green Deal: A Multiple Criteria Approach. *Land*, 14(1). https://doi.org/10.3390/land14010141

Paleari, S. (2024). The Role of Strategic Autonomy in the EU Green Transition. *Sustainability* (Switzerland), 16(6). https://doi.org/10.3390/su16062597

Pariso, P., Picariello, M., & Marino, A. (2023). Circular economy and rare materials: a challenge for the European countries. *Entrepreneurship and Sustainability Issues,* 11(2): 79-92. https://doi.org/10.9770/jesi.2023.11.2(6)

Patil, A. B., Struis, R. P. W. J., & Ludwig, C. (2023). Opportunities in Critical Rare Earth Metal Recycling Value Chains for Economic Growth with Sustainable Technological Innovations. *Circular Economy and Sustainability*, 3(2), 1127–1140. https://doi.org/10.1007/s43615-022-00204-7

Podobińska-Staniec, M., Wiktor-Sułkowska, A., Kustra, A., & Lorenc-Szot, S. (2025). Copper as a Critical Resource in the Energy Transition. *Energies*, 18(4). https://doi.org/10.3390/en18040969

Polverini, D., Alfieri, F., Spiliotopoulos, C., & Arcipowska, A. (2024). Towards a recyclability index for photovoltaic modules: Methodology, challenges and policy implications. *Progress in Photovoltaics: Research and Applications*. https://doi.org/10.1002/pip.3781

Popa, D.-C., & Szabó, L. (2024). Securing Rare Earth Permanent Magnet Needs for Sustainable *Energy Initiatives. Materials*, 17(22). https://doi.org/10.3390/ma17225442

Popa, D.-C., & Szabó, L. (2025). Overcoming Catch-22 for rare earth metals in green transition: Solutions in electrical machine manufacturing. *Renewable and Sustainable Energy Reviews*, 207. https://doi.org/10.1016/j.rser.2024.114917

Piccinetti, L., Elseify, M. K., Santoro, D., Piccinetti, A., Khasawneh, A., & Rezk, M. R. (2025). Inclusive adoption of circular economy in Egypt: communication and stakeholder engagement among low- and middle-income communities. *Insights into Regional Development*, 7(4), 154-175. https://doi.org/10.70132/a8272892652

Priore, R., Compagnoni, M., & Favot, M. (2025). Innovation in rare earths recycling: A quantitative and qualitative analysis of patent data. *Resources Policy*, 102. https://doi.org/10.1016/j.resourpol.2025.105519

Rezk, M. R., Kapiel, T. Y., Piccinetti, L., Salem, N., Khasawneh, A., Santoro, D., Montagnino, F. M., El-Bary, A. A., & Sakr, M. M. (2023). Circular economy in Egypt: an overview of the current landscape and potential for growth. *Insights into Regional Development*, 5(3), 45-57. https://doi.org/10.9770/ird.2023.5.3(3)

Rezk, M. R., Hassan, M. M., Omoruyi, T. U., El-Bary, A. A., & Piccinetti, L. (2025). Policy options in accelerating circular economy adoption in the Gulf countries. *Insights into Regional Development,* 7(2), 43-66. https://doi.org/10.70132/h2693793554

Rezk, M. R., Piccinetti, L., Salem, N., Omoruyi, T. U., & Santoro, D. (2024). Nigeria's transition to a circular economy: challenges, opportunities and future perspectives. *Insights into Regional Development*, 6(2), 11-23. https://doi.org/10.9770/IRD.2024.6.2(1)

Ruginė, H., & Žilienė, R. (2024). Towards a new framework of circular economy. *Entrepreneurship and Sustainability Issues,* 11(3), 278-289. https://doi.org/10.9770/jesi.2024.11.3(19)

Richert, M., & Łebkowski, P. (2025). Development of automotive industry trends and demand for critical raw materials worldwide. *Entrepreneurship and Sustainability Issues*, 12(4), 325-360. http://doi.org/10.9770/p3487798764

Sala, D., & Richert, M. (2025). Perspectives of Additive Manufacturing in 5.0 Industry. *Materials*, 18(2). https://doi.org/10.3390/ma18020429

Schulze, K., Kullmann, F., Weinand, J. M., & Stolten, D. (2024). Overcoming the challenges of assessing the global raw material demand of future energy systems. *Joule*, 8(7), 1936–1957. https://doi.org/10.1016/j.joule.2024.05.016

Tvaronavičienė, M. (2024). The Transition towards Renewable Energy: The Challenge of Sustainable Resource Management for a Circular Economy. *Energies*, 17, 4242. https://doi.org/10.3390/en17174242

Tvaronavičienė, M., Razminienė, K., & Adekola, A. F. (2024). Transition towards a circular economy to build societal resilience to energy shocks. *Journal of Infrastructure, Policy and Development*, 8(15), 10414. https://doi.org/10.24294/JIPD10414

Vezzoni, R. (2023). Green growth for whom, how and why? The REPowerEU Plan and the inconsistencies of European Union energy policy. *Energy Research and Social Science*, 101. https://doi.org/10.1016/j.erss.2023.103134

Vivoda, V. (2024). Uncharted depths: Navigating the energy security potential of deep-sea mining. *Journal of Environmental Management*, 369. https://doi.org/10.1016/j.jenvman.2024.122343 von Rennenberg, T., Yu, Y., Fraccascia, L., & Yazan, D. M. (2024). Circularity Reinforcement of Critical Raw Materials in Europe: A Case of Niobium. *Circular Economy and Sustainability*, 4(4), 2449–2472. https://doi.org/10.1007/s43615-024-00369-3

Wang, P., Wang, C., Li, J., Hubacek, K., Sun, L., Yang, F., … Feng, K. (2024). Incorporating platinum circular economy into China's hydrogen pathways toward carbon neutrality. *PNAS Nexus*, 3(5). https://doi.org/10.1093/pnasnexus/pgae172

Xu, Y., Nassani, A. A., Qazi Abro, M. M., Naseem, I., & Zaman, K. (2024). FinTech revolution in mineral management: Exploring the nexus between technology adoption and sustainable Resource utilization in an industry 4.0 context. *Heliyon*, 10(3). https://doi.org/10.1016/j.heliyon.2024.e24641

Zanoletti, A., Bresolin, B. M., & Bontempi, E. (2024). Building a Circular Economy for Lithium: Addressing Global Challenges. *Global Challenges*, 8(12). https://doi.org/10.1002/gch2.202400250

Zeng, A., Chen, W., Rasmussen, K. D., Zhu, X., Lundhaug, M., Müller, D. B., … Liu, G. (2022). Battery technology and recycling alone will not save the electric mobility transition from future cobalt shortages. *Nature Communications*, 13(1). https://doi.org/10.1038/s41467-022-29022-z

Zwickl-Bernhard, S. (2024). Integrating material recycling and remanufacturing in energy system optimization modeling: A review and showcase. *Advances in Applied Energy*, 16. https://doi.org/10.1016/j.adapen.2024.100198