

# **Critical Raw Materials in the European Union: Strategic Autonomy, Circular Innovation and Sectoral Vulnerability**

**Paloma Moya and Alberto Sáez**

Universidad a Distancia de Madrid (Madrid, Spain)

\*Correspondence to: Paloma Moya E-Mail: [paloma.moya@udima.es](mailto:paloma.moya@udima.es)

Artificial intelligence tools were used to gather and consult information during preparation. The content, analysis, and conclusions presented in this document are attributed to the authors.

## **Abstract**

### **Purpose**

This preliminary working paper examines the European Union's sectoral vulnerability to critical raw materials (CRMs) and analyses how the Critical Raw Materials Act (CRMA), together with related EU policy instruments, reconfigures CRM governance as a lever for open strategic autonomy, innovation and industrial resilience. It also considers where EU innovation and circularity efforts are prioritised along the CRM value chain and which CRM segments exhibit potential for scaling secondary materials markets through circular business-model innovation.

### **Design/methodology/approach**

The paper develops a policy-oriented analytical framework linking open strategic autonomy, innovation capabilities and CRM value-chain transformation. The analysis combines a structured examination of EU policy instruments with recent scholarship on mission-oriented industrial policy, innovation under resource constraints, circular economy and supply-chain resilience. Vulnerability is conceptualised as joint exposure to concentrated import dependence and limited circularity and substitution capacity.

### **Preliminary findings**

The analysis indicates that Europe's CRM vulnerability is materially differentiated and structurally shaped by supplier concentration and weak circular buffering in several value chains. EU innovation and circularity efforts are uneven across CRM segments, and strategically relevant CRMs remain comparatively weakly covered by current portfolio instruments. The growth of secondary raw materials markets is therefore expected to depend on market-forming conditions that make circular models bankable and industrially deployable.

### **Practical implications**

For managers, CRMs should be treated as a strategic innovation variable and incorporated into technology roadmaps, partnering strategies, procurement decisions and business-model design. For policymakers, the preliminary results emphasise portfolio completeness, coherent multi-level governance, standards, traceability and demand-creation instruments.

**Keywords:** Critical raw materials; Critical Raw Materials Act; Net-Zero Industry Act; Mission-oriented industrial policy; Circular economy; Secondary materials markets; Business model innovation; Supply-chain resilience; Advanced materials; Strategic autonomy.

**Paper type:** Preliminary research paper / working paper.

## **1. Introduction and preliminary objective**

Critical raw materials occupy a central position in the European Union's decarbonisation, digitalisation and industrial-resilience agendas. Scientific research on CRMs has often focused on quantifying primary material supply and demand flows, while circularity dynamics have frequently been confined to end-of-life recycling rates. This working paper adopts the broader premise that material criticality is neither intrinsic nor static, but emerges from the interaction between supply risk, value-chain configuration, sectoral dependence and the capacity for adaptation through substitution, reuse, recycling and product redesign (Erdmann and Graedel, 2011; Schrijvers et al., 2020).

The EU's climate-neutrality and digital-leadership ambitions increase the strategic relevance of CRMs because low-carbon and digital technologies are materially intensive. Upstream activities include exploration, mining, refining and purification; midstream activities include chemical conversion, separation and metallurgical refinement; downstream stages include manufacturing, technological integration, recycling and recovery. Each stage creates different forms of vulnerability, from long permitting cycles and capital intensity to processing bottlenecks, technological dependence and limited substitutes in final applications.

The CRMA and the Net-Zero Industry Act mark a shift toward mission-oriented industrial policy. Circular economy policy is not treated here as an environmental add-on, but as a strategic risk-management infrastructure that can reduce virgin material demand, improve secondary supply and support industrial resilience. The preliminary objective is therefore to clarify how EU-defined material criticality can translate into differentiated sectoral vulnerability, and how circularity, innovation and policy delivery instruments may mitigate that exposure.

## **2. Conceptual framework: from criticality to vulnerability**

### **2.1 Material criticality as a policy-defined construct**

In the EU framework, criticality is operationalised through Economic Importance (EI) and Supply Risk (SR). EI captures the strategic significance of a material for downstream industrial ecosystems, while SR captures exposure to supply disruption through concentration, governance risk, trade fragilities, import reliance, limited substitutability and related constraints. This EI-SR logic is embedded in the CRMA and supports the designation of critical and strategic raw materials.

Criticality is therefore not a description of upstream scarcity alone. It signals that the continuity of strategic value chains may be constrained unless mitigation mechanisms are activated at scale. Such mechanisms include diversification, substitution, circular inputs and strategic coordination across extraction, processing and recycling stages. In this working paper, material criticality is treated as the independent construct, operationalised through EI and SR, and sectoral material vulnerability is treated as the dependent construct.

## **2.2 Sectoral material vulnerability**

Sectoral vulnerability is an emergent outcome. A material may be critical, but its economic and strategic consequences are realised only when firms and sectors depend on that material for strategic products, industrial capabilities and innovation pathways. Vulnerability increases when sectors cannot sufficiently mitigate disruption through alternative sourcing, substitution or circular inputs. The CRMA recognises this transmission logic by requiring attention to the extraction, processing and recycling locations of strategic raw materials, including components containing critical materials. This distinction is important for policy and management. A list of critical materials does not by itself identify which industrial ecosystems are most exposed. The relevant question is how material-level criticality propagates through value chains and becomes binding for sector-level continuity, cost structures, technology deployment and competitiveness.

## **2.3 Transmission channels and mitigation capacity**

The criticality-to-vulnerability relationship is realised through value-chain transmission mechanisms. Geopolitical exposure increases susceptibility to export restrictions, strategic withholding and price shocks. Industrial concentration and chokepoints amplify disruption, especially where refining, processing or intermediate stages are geographically concentrated. Technological indispensability combined with limited substitutability can make disruption non-linear in applications such as batteries, permanent magnets, defence systems and advanced electronics. Mitigation depends on both circular reintegration and policy-innovation capacity. The end-of-life recycling input rate (EoL-RIR) measures the proportion of EU demand met by secondary materials recovered from end-of-life streams. An EoL-RIR of 0% signals no measurable circular contribution and therefore a structural reintegration gap. Low but non-zero values indicate incipient pathways that require scaling, yield improvement, quality upgrading and industrial qualification.

## **3. EU policy and innovation response architecture**

The EU response is organised around complementary frameworks. The CRMA provides binding ambitions and delivery mechanisms for extraction, processing and recycling. The Net-Zero Industry Act supports net-zero manufacturing capacity. The Competitiveness Compass and the Clean Industrial Deal position material security within broader agendas of competitiveness, decarbonisation and geopolitical resilience. Circular economy policy, including the 2020 Circular Economy Action Plan and prospective secondary-market instruments, provides the strategic basis for reducing exposure to primary supply disruption.

Strategic Projects are the operational delivery instrument for mobilising investment along critical value-chain stages. Their analytical significance is that project designation determines which vulnerabilities are addressed through investment, learning and scaling, and which remain exposed due to lack of comparable implementation mechanisms. Delivery coherence exists where policy diagnosis,

strategic-project mobilisation and binding regulation align with the material and sector combinations where vulnerability is concentrated.

Innovation capacity is equally important. Innovation ecosystems, clusters and Knowledge and Innovation Communities support the translation of scientific capability into industrial validation and market uptake. EIT RawMaterials, Horizon Europe, advanced-materials strategies and public-private partnerships contribute to education, entrepreneurship, collaborative research, substitution pathways, material efficiency and redesigned product architectures. In this sense, CRM governance is not only a supply-security agenda but also an innovation-management and market-formation problem.

#### **4. Research design and methodology**

The working paper follows a policy-oriented research design combining two evidence streams: a structured academic search and an analytical policy review based on EU official sources. The academic stream grounds constructs and mechanisms in scholarship on criticality, industrial policy, circular economy, business-model innovation and supply-chain resilience. The policy stream relies on binding instruments, Commission decisions and policy communications to ensure institutional precision. The empirical logic is portfolio-based. Material-level exposure is represented through EI and SR. Circular supply contribution is captured through EoL-RIR. Policy delivery mobilisation is assessed through EU-recognised Strategic Projects under Regulation (EU) 2024/1252. Materials are mapped to downstream EU sector groupings reflecting their dominant strategic use within industrial value chains, such as batteries and electrified transport, semiconductors and advanced electronics, or metallurgical and alloying applications.

Sectoral vulnerability is computed through aggregation of EI and SR at sector level. For each sector, the analysis considers the size of the material bundle, mean EI, mean SR and a composite vulnerability index. Dominant contributors are the materials with the highest combined EI-SR values. The approach is presented as a baseline mapping method: it is analytically consistent and useful for cross-sector comparison, while not yet incorporating sector-specific intensity coefficients or detailed bills of materials.

#### **5. Preliminary analysis of results**

##### **5.1 Sectoral vulnerability rankings**

The preliminary sectoral ranking indicates that CRM vulnerability is structurally concentrated rather than evenly distributed across EU industrial ecosystems. Metals and metallurgy, electronics/ICT/semiconductors, and defence/aerospace form the high-vulnerability group. Energy and transport and construction/infrastructure appear as moderate-vulnerability sectors, while chemicals/process industries and health/medical applications show lower relative vulnerability under the baseline index.

**Table 1. EU sectoral ranking of CRM vulnerability.**

Rank	EU sector	Tier	No. of CRMs	Mean EI	Mean SR	VI	Normalised VI	Dominant contributors (Top-5 CRMs)
1	Metals & metallurgy	High	6	6.33	2.28	90.48	15.08	Magnesium (30.34); Niobium (28.60); Tungsten (10.44); Antimony (9.72); Manganese (8.28)
2	Electronics, ICT & semiconductors	High	6	4.52	2.87	77.26	12.88	LREE (21.83); HREE (21.42); Gallium (14.43); Silicon metal (6.86); Germanium (6.48)
3	Defence & aerospace	High	6	5.82	2.15	74.17	12.36	Niobium (28.60); Tungsten (10.44); Titanium metal (10.08); Beryllium (9.72); Scandium (8.88)
4	Energy & transport	Moderate	7	4.90	1.90	68.11	9.73	PGM (19.17); Cobalt (19.04); Vanadium (8.97); Lithium (7.41); Graphite (6.12)
5	Construction & infrastructure	Moderate	5	4.68	1.80	43.10	8.62	Strontium (16.90); Boron (14.04); Aluminium/bauxite (6.96); Feldspar (4.80); Copper (0.40)
6	Chemicals & process industries	Lower	4	4.45	1.82	31.60	7.90	Phosphorus (15.51); Phosphate rock (6.40); Arsenic (5.51); Fluorspar (4.18)
7	Health & medical applications	Lower	2	4.30	1.55	14.31	7.16	Bismuth (10.83); Helium (3.48)

*Source(s): Authors' own elaboration.*

The ranking should be interpreted as an ecosystem signal. High-tier sectors are not driven by a single headline material, but by bundles of enabling inputs that combine economic relevance and supply-side fragility. Niobium, tungsten, rare earth elements, gallium, magnesium, titanium metal and other materials act as cross-sector contributors. This supports the proposition that vulnerability is a configuration effect across materials and stages, rather than a static property of individual minerals.

## 5.2 Strategic Projects coverage and portfolio selectivity

The Strategic Projects portfolio covers many strategic raw materials, especially those connected to batteries, electrification, rare earth permanent magnets and selected metallurgical inputs. However, not every critical raw material appears with comparable visibility. This matters because strategic-project designation channels investment attention, coordination capacity and industrial learning toward selected materials and stages. Where coverage is weak, vulnerabilities may remain even when the material is recognised as critical.

**Table 2. Crosswalk of materials covered by Strategic Projects, strategic raw materials and critical raw materials.**

Harmonised material label	Strategic Projects	Strategic raw materials	Critical raw materials
Bauxite / alumina / aluminium	Yes	Yes	Yes
Boron	Yes (battery grade)	Yes (metallurgy grade)	Yes
Cobalt	Yes	Yes	Yes
Copper	Yes	Yes	Yes
Gallium	Yes	Yes	Yes
Germanium	Yes	Yes	Yes
Lithium	Yes (battery grade)	Yes (battery grade)	Yes
Magnesium	Yes	Yes (metal)	Yes
Manganese	Yes (battery grade)	Yes (battery grade)	Yes
Graphite	Yes (battery grade)	Yes (battery grade)	Yes
Nickel	Yes (battery grade)	Yes (battery grade)	Yes (battery grade)
Platinum group metals	Yes	Yes	Yes
Tungsten	Yes	Yes	Yes
Rare earths for permanent magnets	Yes	Yes (Nd, Pr, Tb, Dy, Gd, Sm, Ce)	Covered at group level (LREE/HREE)
Bismuth	No	Yes	Yes
Silicon metal	No	Yes	Yes
Titanium metal	No	Yes	Yes
Arsenic	No	No	Yes
Antimony	No	No	Yes
Baryte	No	No	Yes
Beryllium	No	No	Yes
Coking coal	No	No	Yes
Feldspar	No	No	Yes
Fluorspar	No	No	Yes
Hafnium	No	No	Yes
Helium	No	No	Yes
Niobium	No	No	Yes
Phosphate rock	No	No	Yes
Phosphorus	No	No	Yes

Scandium	No	No	Yes
Strontium	No	No	Yes
Tantalum	No	No	Yes
Vanadium	No	No	Yes
Light rare earth elements (LREE)	No	No	Yes
Heavy rare earth elements (HREE)	No	No	Yes

---

*Source(s): Authors' own elaboration.*

The coverage pattern indicates partial alignment between criticality and delivery mobilisation. Some materials with zero or weak circular reintegration, or with defence and semiconductor relevance, remain comparatively less visible in the Strategic Projects sample. This does not imply that no initiatives exist, but it highlights potential blind spots in a portfolio-based delivery model.

### **5.3 Import reliance and circular reintegration**

For the highest-vulnerability sectors, the most relevant exposure pattern is the combination of high import reliance with low EoL-RIR. Where secondary inputs remain limited, disruptions translate more directly into sector-level continuity and innovation constraints. The materials underpinning metals and metallurgy, electronics and ICT, and defence and aerospace therefore require differentiated mitigation routes, including collection, dismantling, refining, traceability, certification and qualification.

**Table 3. Import reliance and end-of-life recycling input rates for CRMs underpinning the three high-vulnerability sectors.**

High-vulnerability sector	CRM	Import reliance	EoL-RIR
Metals and metallurgy	Magnesium	100%	13%
	Antimony	100%	28%
	Coking coal	66%	0%
	Manganese	96%	9%
	Niobium	100%	0%
	Tungsten	n/a	42%
Electronics and ICT	Gallium	98%	0%
	Germanium	42%	2%
	Silicon metal	64%	0%
	Tantalum	99%	0%
	LREE	100%	3%
	HREE	100%	4%
Defence and aerospace	Titanium metal	100%	19%
	Beryllium	n/a	0%
	Scandium	100%	0%
	Hafnium	0%	0%
	Niobium	100%	0%
	Tungsten	n/a	42%

*Source(s): Authors' own elaboration.*

Circularity is not a uniform solution. Where EoL-RIR is non-trivial, resilience gains may come from scaling throughput, improving yields and raising purity. Where EoL-RIR is zero or marginal, the task is closer to market formation: end-of-life streams must be made technically recoverable, industrially qualifiable and economically viable. For some CRMs, innovation through substitution, reduced material intensity or redesign may be necessary because recycling alone cannot generate short-term resilience.

## 6. Discussion

### 6.1 Sectoral concentration and use-based criticality

The analysis supports the view that EU CRM vulnerability is concentrated in a limited set of industrial ecosystems. Metals and metallurgy is exposed through inputs such as magnesium, niobium, tungsten, antimony and manganese. Electronics, ICT and semiconductors are exposed through rare earth elements, gallium, silicon metal and germanium. Defence and aerospace are exposed through niobium, tungsten, titanium metal, beryllium and scandium. These bundles matter because they connect raw-material access to innovation diffusion, manufacturing continuity and strategic autonomy.

A use-based interpretation of criticality is therefore necessary. Criticality becomes strategically meaningful only when linked to downstream dependence structures. The same material can produce different vulnerabilities depending on the sector, application, substitutability and value-chain stage.

This interpretation is consistent with the CRMA's value-chain orientation and with innovation-management perspectives that focus on bottlenecks, diffusion constraints and capability formation.

## **6.2 Delivery coherence and policy capacity**

Policy capacity depends on whether EU instruments can align strategic diagnosis with implementation mechanisms. The CRMA, NZIA, Clean Industrial Deal, Competitiveness Compass, circular economy instruments and advanced-materials strategy create an architecture for coordinated action. Yet the preliminary results suggest that policy activity is not the same as delivery coherence. Coherence requires that instruments target the stage where vulnerability binds, whether that stage is upstream extraction, midstream processing, recycling, substitution or market uptake.

Strategic Projects are useful delivery levers, but their selectivity creates the need for portfolio governance. Materials not well represented in the current project pipeline may require complementary instruments, especially where they are embedded in high energy-consuming industries, defence applications, semiconductor supply chains or other strategic sectors. Standards, traceability systems, public procurement, offtake agreements and demand-creation instruments can complement project designation by making secondary materials markets investable.

## **6.3 Managerial implications**

For firms, CRMs should be integrated into strategic management rather than handled only as a procurement problem. Managers should map material-specific vulnerability across products, suppliers and components; identify exposure to concentrated supply and midstream chokepoints; and connect CRM risk to technology roadmaps and business-model design. Circular procurement, long-term contracting, vertical coordination, offtake agreements and cross-firm collaboration can help stabilise access and distribute investment risk.

Business-model innovation is central where secondary materials markets are immature. Firms may need to participate in consortia across mining, processing, recycling, equipment manufacturing and downstream use. They may also need to develop traceability, certification and quality-assurance capabilities to qualify secondary inputs for high-specification applications. Human capital is also a constraint: dismantling, sorting, chemical separation, material recovery and negotiation skills become strategic capabilities in circular supply pathways.

## **7. Preliminary conclusions and next steps**

The preliminary analysis shows how EU criticality evidence can be translated into sectoral vulnerability profiles. High vulnerability concentrates in metals and metallurgy, electronics/ICT/semiconductors, and defence/aerospace. These sectors depend on bundles of CRMs with strong economic relevance and fragile supply. The results also indicate that low or zero circular reintegration limits the immediate buffering role of secondary supply, making vulnerability a function of both upstream criticality and downstream mitigation capability.

The CRMA articulates open strategic autonomy in the CRM domain by linking risk reduction, capacity building and normative alignment at EU level. However, the effectiveness of this governance model depends on portfolio completeness and delivery coherence. Strategic Projects strongly cover some battery and electrification materials, but several strategically relevant CRMs remain less visible. Future work should refine sectoral weighting through input-output data, bills of materials and material-flow accounts; expand circularity measurement beyond EoL-RIR; and track whether Strategic Projects reduce exposure over time.

As a preliminary working paper, the analysis is intended to serve as a basis for a fuller final version. The next development stage should deepen sector-specific evidence, especially in defence, aerospace, semiconductors and high energy-consuming industries; assess secondary-market formation mechanisms; and compare EU governance with the approaches of China and the United States under conditions of scarcity, rivalry and technological acceleration.

## **8. Research questions, hypotheses and analytical boundary conditions**

The preliminary model is organised around three research questions. First, it asks how EU criticality evidence, represented by EI and SR, translates into differentiated sectoral vulnerability profiles across EU industrial ecosystems. The associated hypothesis is that vulnerability concentrates in a limited set of industrial ecosystems where high EI and SR co-occur across multiple CRM inputs, producing higher composite exposure than in sectors with smaller or less critical material bundles.

Second, it asks through which value-chain transmission channels upstream material criticality becomes sector-level exposure, and to what extent EU policy capacity and delivery coherence provide a credible mitigation architecture. The associated hypothesis is that stronger policy capacity and delivery coherence reduce fragmentation and attenuate the transmission of criticality into sectoral vulnerability by targeting midstream chokepoints, substitutability constraints and circular reintegration gaps.

Third, it asks how far circular reintegration and innovation-oriented delivery instruments can mitigate CRM-related sectoral vulnerability, particularly in sectors characterised by high import reliance and weak end-of-life secondary contribution. The associated hypothesis is that lower EoL-RIR is associated with higher effective exposure in high-vulnerability sectors; mitigation therefore depends on circularity complemented by innovation instruments, Strategic Projects and advanced-materials pathways where recycling is structurally constrained.

The approach has defined boundaries. Sectoral aggregation is implemented as a baseline mapping approach and includes all CRMs mapped to an EU sector with equal weight. This means the index captures a criticality-driven exposure profile but does not yet weight each material by its quantitative input share within a given industrial system. EoL-RIR is also a proxy: it captures realised circular reintegration, but does not by itself measure collection potential, process yield, quality constraints, conversion feasibility or certification requirements.

Future refinement should therefore incorporate input-output tables, material-flow accounts and technology-specific bills of materials. It should also track project delivery longitudinally, because CRMA implementation is recent and evidence on realised investments, delivery milestones and measurable innovation outcomes remains limited. Sector-specific work is particularly important for defence, aerospace, semiconductor and high energy-consuming industries, where substitution and qualification constraints may be more severe than aggregate indicators suggest.

## References

- Antràs, P., & Chor, D. (2021). Global value chains (NBER Working Paper No. 28549). National Bureau of Economic Research. <http://www.nber.org/papers/w28549>
- Arjona, R., Connell, W., & Herghelegiu, C. (2023). An enhanced methodology to monitor the EU's strategic dependencies and vulnerabilities (Single Market Economics Papers, No. 14). Publications Office of the European Union.
- Baldassarre, B., Schepers, M., Bocken, N., Cuppen, E., Korevaar, G., & Calabretta, G. (2019). Industrial symbiosis: Towards a design process for eco-industrial clusters by integrating circular economy and industrial ecology perspectives. *Journal of Cleaner Production*, 216, 446–460. <https://doi.org/10.1016/j.jclepro.2018.12.091>
- Baldassarre, B., & Carrara, S. (2025). Critical raw materials, circular economy, sustainable development: EU policy reflections for future research and innovation. *Resources, Conservation and Recycling*, 215, 108060. <https://doi.org/10.1016/j.resconrec.2024.108060>
- Burghardt, C., Schäfer, M., & Weidlich, A. (2025). Closing the loop: Integrating material needs of energy technologies into energy system models. *IEEE*.
- Cimprich, A., Young, S. B., Schrijvers, D., Ku, A. Y., Hagelüken, C., Christmann, P., Eggert, R., Habib, K., Hirohata, A., Hurd, A. J., Lee, M.-Ha., Peck, D., Petavratzi, E., Tercero Espinoza, L. A., Wäger, 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, 301–319. <https://doi.org/10.1007/s13563-022-00304-8>
- Daw, G. (2025). Revising the “Economic importance” dimension: The European framework for critical raw materials, completed and illustrated using lithium. *Resources Policy*, 101, 105453. <https://doi.org/10.1016/j.resourpol.2024.105453>
- EIT RawMaterials. (2024). European competitiveness requires strategic investment commitment in raw materials [Policy paper]. EIT RawMaterials.
- EIT RawMaterials. (2025). European competitiveness requires strategic investment commitment to raw materials sector [Press release]. <https://eitrawmaterials.eu/press-releases/european-competitiveness-requires-strategic-investment-commitment-raw-materials>
- Erdmann, L., & Graedel, T. E. (2011). Criticality of non-fuel minerals: A review of major approaches and analyses. *Environmental Science & Technology*, 45(18), 7620–7630. <https://doi.org/10.1021/es200563g>
- European Commission. (2019, December 11). The European Green Deal (COM(2019) 640 final). Publications Office of the European Union. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52019DC0640>
- European Commission. (2020, March 11). A new circular economy action plan for a cleaner and more competitive Europe (COM(2020) 98 final). Publications Office of the European Union. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0098>
- European Commission. (2021a). “Fit for 55”: Delivering the EU's 2030 climate target on the way to climate neutrality (COM/2021/550 final). <https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52021DC0550>
- European Commission. (2021b). 2030 Digital Compass: The European way for the digital decade (COM/2021/118 final). <https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52021DC0118>
- European Commission. (2022). REPowerEU Plan (COM/2022/230 final). [https://eur-lex.europa.eu/resource.html?uri=cellar:fc930f14-d7ae-11ec-a95f-01aa75ed71a1.0001.02/DOC\\_1&format=PDF](https://eur-lex.europa.eu/resource.html?uri=cellar:fc930f14-d7ae-11ec-a95f-01aa75ed71a1.0001.02/DOC_1&format=PDF)
- European Commission. (2023). Study on the critical raw materials for the EU. Publications Office of the European Union. [https://single-market-economy.ec.europa.eu/publications/study-critical-raw-materials-eu\\_en](https://single-market-economy.ec.europa.eu/publications/study-critical-raw-materials-eu_en)
- European Commission. (2024). Advanced materials for industrial leadership (Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, COM(2024) 98 final). Publications Office of the European Union. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2024:98:FIN>
- European Commission. (2025a). Proposal for a regulation of the European Parliament and of the Council amending Regulation (EU) 2024/1252 (COM(2025) 946 final). European Commission. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52025PC0946>
- European Commission. (2025b). RESourceEU Action Plan: Accelerating our critical raw materials strategy to adapt to a new reality (COM(2025) 945 final). European Commission. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52025DC0945&qid=1756987182843>
- European Commission. (2025c). A Competitiveness Compass for the EU (COM(2025) 30 final). European Commission. [https://commission.europa.eu/document/download/10017eb1-4722-4333-add2-e0ed18105a34\\_en?filename=Communication\\_1.pdf](https://commission.europa.eu/document/download/10017eb1-4722-4333-add2-e0ed18105a34_en?filename=Communication_1.pdf)
- European Commission. (2025d). The Clean Industrial Deal: A joint roadmap for competitiveness and decarbonisation (COM(2025) 85 final). Publications Office of the European Union. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52025DC0085>
- European Commission. (2025e). Commission Decision (EU) 2025/840 of 25 March 2025 recognising certain critical raw materials projects as strategic projects under Regulation (EU) 2024/1252 (notified under document C(2025) 1904). Official Journal of the European Union. <https://data.europa.eu/eli/dec/2025/840/oj>

- European Commission. (2025f). Commission Decision (EU) 2025/1174 of 4 June 2025 recognising certain critical raw materials projects located in third countries and in overseas countries and territories as strategic projects under Regulation (EU) 2024/1252 (notified under document C(2025) 3491). Official Journal of the European Union. <https://data.europa.eu/eli/dec/2025/1174/oj>
- European Parliament and Council of the European Union. (2020). Regulation (EU) 2020/852 of 18 June 2020 on the establishment of a framework to facilitate sustainable investment, and amending Regulation (EU) 2019/2088. Official Journal of the European Union, L 198, 13–43. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32020R0852>
- European Parliament and Council of the European Union. (2023a). Regulation (EU) 2023/956 of 10 May 2023 establishing a carbon border adjustment mechanism. Official Journal of the European Union, L 130. <https://eur-lex.europa.eu/eli/reg/2023/956/oj/eng>
- European Parliament and Council of the European Union. (2023b). Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955 (recast). Official Journal of the European Union, L 231, 1–111. <http://data.europa.eu/eli/dir/2023/1791/oj>
- European Parliament and Council of the European Union. (2023c). Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652. Official Journal of the European Union, L, 2023/2413.
- European Parliament and Council of the European Union. (2024a). Regulation (EU) 2024/1252 of 11 April 2024 establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1724 and (EU) 2019/1020. Official Journal of the European Union, L 2024/1252. <https://data.europa.eu/eli/reg/2024/1252/oj>
- European Parliament and Council of the European Union. (2024b). Regulation (EU) 2024/1735 of 13 June 2024 on establishing a framework of measures for strengthening Europe’s net-zero technology manufacturing ecosystem and amending Regulation (EU) 2018/1724 (Text with EEA relevance). Official Journal of the European Union, L 2024/1735 (28 June 2024). <http://data.europa.eu/eli/reg/2024/1735/oj/eng>
- Falagas, M. E., Pitsouni, E. I., Malietzis, G. A., & Pappas, G. (2008). Comparison of PubMed, Scopus, Web of Science, and Google Scholar: Strengths and weaknesses. *The FASEB Journal*, 22(2), 338–342. <https://doi.org/10.1096/fj.07-9492LSF>
- Feichtinger, G., & Posch, W. (2025). Evaluation of European critical raw material assessments under energy transition considerations: Applications and prospects. *Circular Economy and Sustainability*, 5, 2057–2131. <https://doi.org/10.1007/s43615-024-00493-0>
- Friedrichs, S., Seitz, C., Bleeker, E., Vandebriel, R., Ouhajji, S., Duistermaat, E., Wiemann, M., Vennemann, A., Katsumiti, A., Buerki-Thurnherr, T., Gupta, G., Wick, P., Ortiz-Galvez, L. M., Wu, J., Weltring, K.-M., Haase, D., Heunisch, E., Pohl, A., Reilly, K., Guo, Z., Lynch, I., Exner, T., Hagenhoff, B., & Breitenstein, D. (2025). MACRAMÉ – Advanced characterisation methodologies to assess and predict the health and environmental risks of advanced materials. *Computational and Structural Biotechnology Journal*, 29, 95–109. <https://doi.org/10.1016/j.csbj.2025.03.032>
- Gauß, R., Burkhardt, C., Carencotte, F., Gasparon, M., Gutfleisch, O., Higgins, I., Karajić, M., Klossek, A., Mäkinen, M., Schäfer, B., Schindler, R., & Veluri, B. (2021). Rare earth magnets and motors: A European call for action (Report by the Rare Earth Magnets and Motors Cluster of the European Raw Materials Alliance). European Raw Materials Alliance. [https://www.eit.europa.eu/sites/default/files/2021\\_09-24\\_ree\\_cluster\\_report2.pdf](https://www.eit.europa.eu/sites/default/files/2021_09-24_ree_cluster_report2.pdf)
- Gorokhova, T., Shpatakova, O., Toponar, O., Zolotarova, O., & Pavliuk, S. (2023). Circular economy as an alternative to the traditional linear economy: Case study of the EU. *Revista de Gestão Social e Ambiental*, 17(5), e03385. <https://doi.org/10.24857/rgsa.v17n5-002>
- Graedel, T. E., Allwood, J., Birat, J. P., Buchert, M., Hagelüken, C., Reck, B. K., Sibley, S. F., & Sonnemann, G. (2011). What do we know about metal recycling rates? *Journal of Industrial Ecology*, 15(3), 355–366. <https://doi.org/10.1111/j.1530-9290.2011.00342.x>
- Grohol, M., & Veeh, C. (2023). Study on the critical raw materials for the EU 2023: Final report. Publications Office of the European Union. <https://doi.org/10.2873/725585>
- Gueye, S., Karanfil, F., & Omgba, L. D. (2025). Navigating the energy transition in the EU: Renewables, critical raw materials and emerging vulnerabilities. *Ecological Economics*, 237, 108696. <https://doi.org/10.1016/j.ecolecon.2025.108696>
- Henckens, M.L.C.M., van Ierland, E.C., Driessen, P.P.J. & Worrell, E. (2016) Mineral resources: Geological scarcity, market price trends, and future generations. *Resources Policy*, 49, pp. 102–111. doi: 10.1016/j.resourpol.2016.04.012.
- Hira, A. (2025). The geopolitics of the green transition and critical strategic minerals. *International Journal*, 80(2), 217–245. <https://doi.org/10.1177/00207020251332595>
- Hool, A., Helbig, C., & Wierink, G. (2023). Challenges and opportunities of the European Critical Raw Materials Act. *Mineral Economics*, 37, 661–668. <https://doi.org/10.1007/s13563-023-00394-y>
- Humphries, M. (2019). Rare earth elements: The global supply chain. Congressional Research Service. <https://crsreports.congress.gov/product/pdf/R/R41347>
- International Energy Agency. IEA (2023). The role of critical minerals in clean energy transitions. IEA. <https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions>
- International Energy Agency. IEA (2025). Global critical minerals outlook 2025. IEA. <https://www.iea.org/reports/global-critical-minerals-outlook-2025>

- Irún, B., Monferrer, D., and Moliner, M.A., 2020. “Network Market Orientation as a Relational Governance Mechanism to Public-Private Partnerships.” *Journal of Business Research* 121: 268–82.
- Irún, B., Moya, P., Monferrer, D., Moliner, M.A., & Bayonne, E., 2022. “The Key Role of European Clusters as Innovation Ecosystems, and Their Implication in the Successful International Promotion of the Member Companies in the Strategic Chinese Sectors: Net-Zero and Smart Cities, Smart Ports and Smart Factories.” In *Public Private Partnership Trends*. New York: Nova Science Publishers
- Jia, S., Meng, W., & Li, S. (2025). Risks of mineral resources in the supply of renewable energy batteries. *Scientific Reports*, 15, 10142. <https://doi.org/10.1038/s41598-025-94848-8>
- Kelly, S., & Chicksand, D. (2024). A critical exploration of bargaining in purchasing and supply management: A systematic literature review. *Group Decision and Negotiation*, 33(3), 617–646. <https://doi.org/10.1007/s10726-024-09879-9>
- Kowalski, P., & Katz, B. (2025). Special focus: Critical raw materials supply chains. In *Organisation for Economic Co-operation and Development, Economic security in a changing world* (pp. 40–49). OECD Publishing. <https://doi.org/10.1787/4eac89c7-en>
- Lee, R., Ahuja, J., & Čavoški, A. (2024). The geopolitics of access to critical minerals necessary to support energy transition. *Global Energy Law and Sustainability*, 5(2), 163–181. <https://doi.org/10.3366/gels.2024.0122>
- Martins, F. F., & Castro, H. (2020). Raw material depletion and scenario assessment in European Union – A circular economy approach. *Energy Reports*, 6, 417–422. <https://doi.org/10.1016/j.egy.2019.08.082>
- Mathieux, F., Ardente, F., Bobba, S., Nuss, P., Blengini, G. A., Alves Dias, P., ... Pavel, C. (2017). Critical raw materials and the circular economy – Background report (EUR 28832 EN). Joint Research Centre, European Commission.
- Nassar, N. T., Graedel, T. E., & Harper, E. M. (2015). By-product metals are technologically essential but have problematic supply. *Science Advances*, 1(3), e1400180. <https://doi.org/10.1126/sciadv.1400180>
- Podgornik, B. (2025). The role of materials in the green transition: opportunities, challenges, barriers and consequences. *Materials and Technology*, 59(3), 327–345. <https://doi.org/10.17222/mit.2025.1420>
- Ponomarenko, T., Nevskaya, M. & Jonek-Kowalska, I. (2021) Mineral Resource Depletion Assessment: Alternatives, Problems, results. *Sustainability*, 13 (2), p. 862. doi: 10.3390/su13020862.
- Ragonnaud, G. (2024, November). Implementing the EU’s Critical Raw Materials Act (EPRS Briefing PE 766.253). European Parliamentary Research Service. [https://www.europarl.europa.eu/RegData/etudes/BRIE/2024/766253/EPRS\\_BRI%282024%29766253\\_EN.pdf](https://www.europarl.europa.eu/RegData/etudes/BRIE/2024/766253/EPRS_BRI%282024%29766253_EN.pdf)
- Rizos, V., Righetti, E., & Kassab, A. (2024). Understanding the barriers to recycling critical raw materials for the energy transition: The case of rare earth permanent magnets. *Energy Reports*, 12, 1673–1682.
- Schrijvers, D., Hool, A., Blengini, G. A., Chen, W.-Q., Dewulf, J., Eggert, R., van Ellen, L., Gauss, R., Goddin, J., Habib, K., Hagelüken, C., Hirohata, A., Hofmann-Antenbrink, M., Kosmol, J., Le Gleuher, M., Grohol, M., Ku, A., Lee, M.-H., Liu, G., ... Wäger, P. A. (2020). A review of methods and data to determine raw material criticality. *Resources, Conservation & Recycling*, 155, 104617. <https://doi.org/10.1016/j.resconrec.2019.104617>
- Sprecher, B., Xiao, Y., Walton, A., Speight, J., Harris, R., Kleijn, R., Visser, G., & Kramer, G. J. (2014). Life cycle inventory of the production of rare earths and the subsequent production of NdFeB rare earth permanent magnets. *Environmental Science & Technology*, 48(7), 3951–3958. <https://doi.org/10.1021/es404596q>
- Tilton, J. E., & Guzmán, J. I. (2016). *Mineral economics and policy*. RFF Press.
- Tranfield, D., Denyer, D., & Smart, P. (2003). Towards a methodology for developing evidence-informed management knowledge by means of systematic review. *British Journal of Management*, 14(3), 207–222. <https://doi.org/10.1111/1467-8551.00375>
- Tröster, B., Papatheophilou, S., & Küblböck, K. (2025). Strategic autonomy meets global dependency: Instruments and implications of the EU’s raw materials policy with third countries (ÖFSE Briefing Paper No. 36). Austrian Foundation for Development Research (ÖFSE). <https://doi.org/10.60637/2025-bp36>
- United Nations. UN (2015). Paris Agreement. United Nations Framework Convention on Climate Change. <https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement>
- U.S. Geological Survey. USGS (2025). Mineral commodity summaries 2025. U.S. Department of the Interior. <https://pubs.usgs.gov/periodicals/mcs2025/mcs2025.pdf>
- Van de Velde, E., Braitto, N., Van Roy, V., Stanciauskas, V., Girdzijauskaitė, V., & Cakić, M. (2024). Industrial R&D&I investments and market analysis in advanced materials: Summary report. European Commission, Directorate-General for Research and Innovation. Publications Office of the European Union. <https://doi.org/10.2777/371763>
- Vakulchuk, R., & Overland, I. (2021). Central Asia is a missing link in analyses of critical materials for the global clean energy transition. *One Earth*, 4(12), 1678–1692. <https://doi.org/10.1016/j.oneear.2021.11.012>
- Wang, B., Wang, L., Zhong, S., Xiang, N., & Qu, Q. (2023). Assessing the supply risk of geopolitics on critical minerals for energy storage technology in China. *Frontiers in Energy Research*, 10, 1032000. <https://doi.org/10.3389/fenrg.2022.1032000>
- Wang, P., Cheng, H., & Tsafack Elvis, N. (2024). Analysis of patent innovation evolution and layout characteristics of global new textile materials technologies. *Fibres & Textiles in Eastern Europe*, 32(5), 27–38. <https://doi.org/10.2478/ftce-2024-0034>
- Wietschel, L., Helbig, C., Hillenbrand, M., & Thorenz, A. (2025). Integrated conceptual framework for resilience and criticality assessments for raw material supply chains. *Resources, Conservation and Recycling*, 218, 108249. <https://doi.org/10.1016/j.resconrec.2025.108249>

Zupic, I., & Čater, T. (2015). Bibliometric methods in management and organization. *Organizational Research Methods*, 18(3), 429–472.  
<https://doi.org/10.1177/1094428114562629>