

Review

From Tungsten to Lithium: Eight Decades of Critical Raw Materials Frameworks and the Sustainability Agenda in the European Union and the United States

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Abstract

Critical raw materials (CRMs) sit at the intersection of industrial strategy, climate policy, sustainable development, and geopolitics. This paper reviews how the concept has evolved since the 1939 US Strategic and Critical Materials Stock Piling Act, tracing the gradual addition of economic, energy, technological, environmental, and sustainability criteria to the original military framing. It then compares the methodologies developed by the European Union and the United States over the last fifteen years. The EU has published five consecutive lists between 2010 and 2023; the US has produced parallel frameworks through the U.S. Geological Survey and the Department of Energy, each weighing supply risk, economic importance, environmental impact, and clean energy relevance differently. The 2023 EU list is examined in detail, including the addition of copper and nickel on strategic rather than quantitative grounds. Convergences and divergences across the three frameworks are discussed, alongside their alignment with the United Nations Sustainable Development Goals—particularly SDG 7, SDG 9, SDG 12, and SDG 13—and the progressive integration of circular economy targets, recycling indicators, and environmental impact considerations into criticality assessment. The analysis shows that sustainability has become a structural axis of CRM policy rather than a peripheral concern. The review provides the methodological background for a companion paper that applies the EU methodology to resource-rich Latin American countries (Chile, Brazil, and Peru).

Keywords: critical raw materials; supply risk; EU criticality methodology; US Geological Survey (USGS); Department of Energy (DOE); sustainable development goals; strategic materials; circular economy; geopolitics; resource management



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1. Introduction

The management of raw materials has historically been a driver of geopolitical strategy, technological innovation, and economic planning. While material selection has always been an inherent part of engineering and industrial design, the formal concept of a “critical material”—one whose supply disruption would cause significant economic or security harm—did not emerge until the aftermath of World War I, when the strategic vulnerability of depending on foreign resources became undeniable [1,2].

Today, the criticality of raw materials is no longer a concern confined to defense planners. The rapid expansion of low-carbon technologies—electric vehicles, wind turbines, photovoltaic panels, and fuel cells—has dramatically increased the demand for a range

of materials with highly concentrated global supply chains. Lithium, cobalt, rare earth elements, gallium, and platinum group metals are among those whose supply risk has escalated alongside their industrial relevance. This dynamic has placed CRM policy at the intersection of industrial strategy, environmental sustainability, and geopolitical resilience [3,4].

As can be seen in Figure 1, both the European Union and the United States have responded with structured, periodically updated lists of critical raw materials, each accompanied by specific methodological frameworks. The EU has published five successive lists (in 2010, 2014, 2017, 2020, and 2023), progressively refining its methodology and expanding its scope. In the US, the US Geological Survey (USGS) and the Department of Energy (DOE) have developed parallel yet distinct approaches, reflecting different institutional priorities—the USGS focusing on broad geological supply risk, and the DOE emphasizing clean energy relevance [5–7].

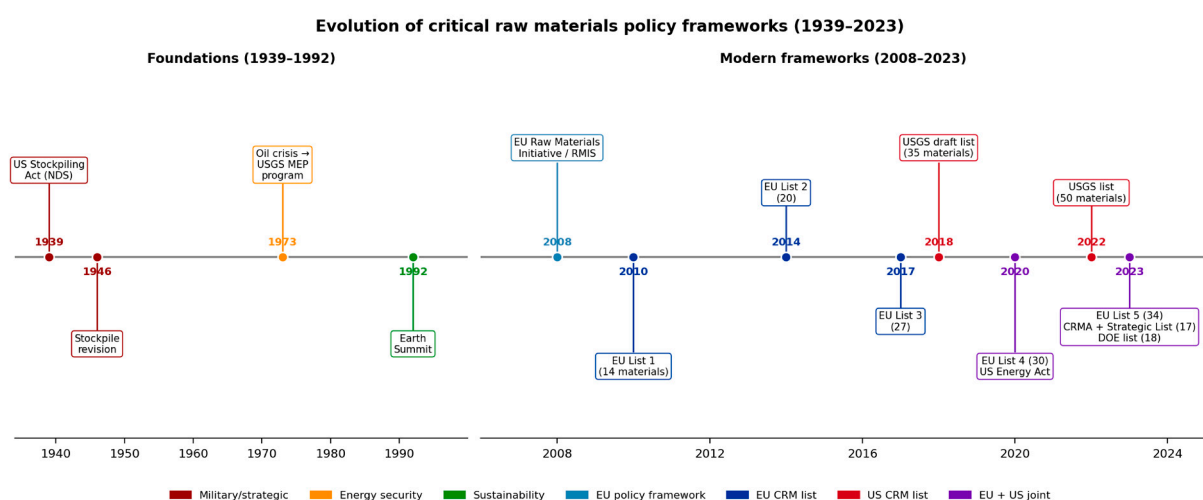


Figure 1. Evolution of critical raw materials policy frameworks from the 1939 US Strategic and Critical Materials Stock Piling Act to the 2023 EU CRM list and the Critical Raw Materials Act. Colour codes indicate the dominant rationale of each milestone. Source: Authors’ elaboration based on the corpus documents (Table S1).

Despite the growing body of literature on CRMs, there remains a lack of synthesized, up-to-date studies that simultaneously trace the historical evolution of the concept, compare EU and US methodologies across their most recent iterations, and explicitly frame the analysis within the Sustainable Development Goals (SDGs). This paper addresses that gap [8,9] and offers a longitudinal and comparative review covering the period from the earliest formal use of the term “critical material” (1939) to the most recent EU and US lists published in 2022–2023.

The specific objectives of this paper are: (1) to trace the historical emergence and conceptual evolution of the critical materials framework; (2) to analyze and compare the EU and US methodologies for CRM identification, including their most recent updates; (3) to identify the drivers behind changes in CRM lists over time; and (4) to connect CRM policy to the broader sustainability agenda through the lens of the UN SDGs. A companion paper (Part II) applies the EU methodology empirically to the cases of Chile, Brazil, and Peru.

2. Materials and Methods

2.1. Research Design

This study is a comparative policy analysis [10,11] of the CRM assessment frameworks published by the European Union, the U.S. Geological Survey (USGS), and the U.S.

Department of Energy (DOE). The analytical approach employs directed content analysis [12], in which predefined categories guide the examination of documents. The categories were derived from the National Research Council’s Criticality Matrix [13] and comprised (1) axes of criticality classification; (2) quantitative thresholds and indicators; (3) treatment of recycling and substitution; (4) temporal horizon; and (5) alignment with the UN Sustainable Development Goals.

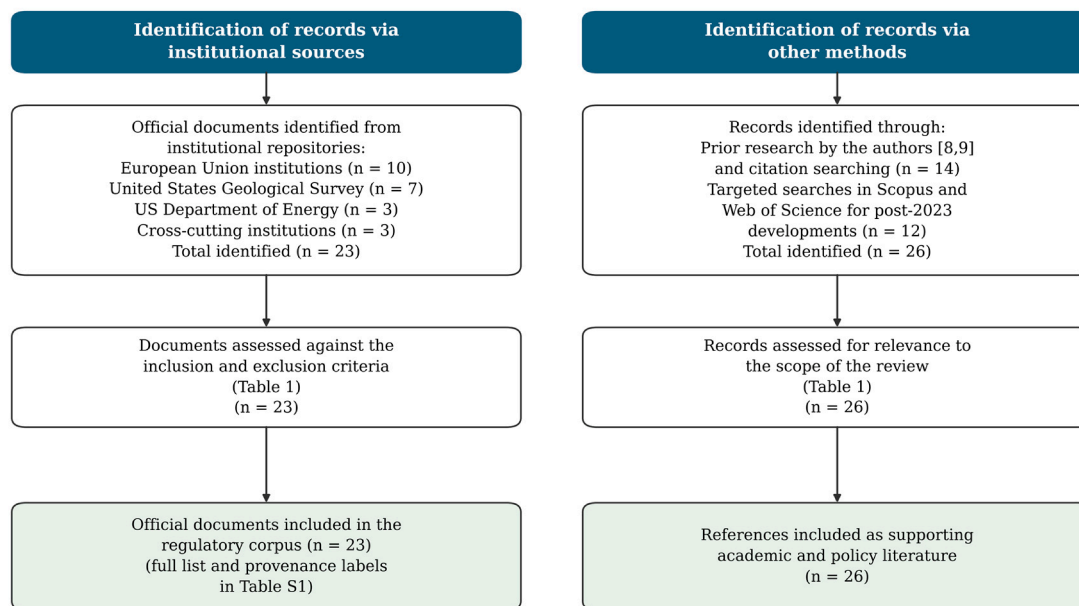
2.2. Source Selection and Corpus

The primary corpus was assembled in previous research conducted by the authors under the direction of E.M.R.-N. [8,9], during which official regulatory and methodological documents that define, revise, or justify a CRM list—published by the EU, USGS, or DOE and covering the period 1939–2023—were identified, extracted, categorised, and reconciled. This corpus comprises 23 documents: 10 from the EU (five CRM list publications with methodology reports, the CRMA proposal and annexes, RMIS documentation, and the 2023 Final Report [5,14–16]); 7 from the USGS (the 1939 and 1946 Acts, 2018 draft list, 2021 methodology review, 2022 final list, and Mineral Commodity Summaries 2024 [6,17–20]); 3 from the DOE (2010 strategy, 2019 update, 2023 assessment [7,13]); and 3 cross-cutting documents (NRC 2008 report [13], UN 2030 Agenda [21], Energy Act of 2020 [22]). The complete list is provided as Supplementary Table S1, where the provenance of each item (Báscones Velasco [8] or Muñoz Gutiérrez [9]) is labelled.

The supporting peer-reviewed literature was identified through backward citation searching from that corpus and from the prior studies [8,9], complemented with targeted searches in Scopus and Web of Science using the terms “critical raw materials” AND (“methodology” OR “supply risk” OR “economic importance” OR “sustainable development goals”), restricted to 2008–2026 and screened for relevance to the rationale, evolution, or comparative positioning of the three frameworks. The inclusion and exclusion criteria applied to both the documentary corpus and the supporting literature are summarised in Table 1, and the corpus construction process is presented in Figure 2, following the flow-diagram structure of the PRISMA 2020 statement [23], with records identified outside database searches reported through the “identification via other methods” stream.

Table 1. Inclusion and exclusion criteria applied in the construction of the corpus.

Inclusion Criteria	Exclusion Criteria
Official documents (acts, regulations, communications, strategies, technical assessments and critical materials lists) addressing raw material criticality, issued by EU institutions, the USGS or the US DOE, 1939–2023.	Press releases, news items and non-institutional grey literature without traceable institutional authorship.
Peer-reviewed publications addressing criticality assessment methodology, critical raw materials policy frameworks, or their historical development.	Documents dealing with raw materials but not with criticality frameworks or assessment methodology.
Documents that establish, revise or operationalise a criticality framework or a critical materials list.	Superseded working drafts where a consolidated or final version exists (the final version was retained).
Language: English; official documents also in Spanish where applicable.	Duplicate records across sources.



Flow diagram adapted from the PRISMA 2020 statement (Page et al., 2021).
Official documents directly cited in the manuscript appear both in the regulatory corpus (Table S1) and in the reference list; the provenance of every item is labelled in Table S1.

Figure 2. Flow diagram of the corpus construction, adapted from the PRISMA 2020 statement [23], distinguishing identification via institutional sources from identification via other methods (the authors’ prior research [8,9], citation searching, and targeted database searches). The full regulatory corpus and the provenance of each item are documented in Table S1. Source: Authors’ elaboration.

2.3. Analytical Procedure

For each CRM framework iteration, data were extracted on: (a) the list of materials classified as critical; (b) thresholds applied; (c) indicators per assessment axis; (d) materials added or removed; (e) stated justifications; and (f) references to sustainability or circular economy. Extraction was performed independently by I.B.V. and I.M.G. within the prior studies that assembled the corpus [8,9] and reconciled by E.M.R.-N. The comparative analysis proceeded in three steps: individual characterization of each framework, construction of cross-framework comparison tables (Table 2 and Figure 3), and mapping of CRM–SDG relationships (Figure 4).

Table 2. Comparative overview of EU and US CRM methodological frameworks.

Dimension	EU (2023)	USGS (2022)	DOE (2023)
Primary axes	EI + SR	Supply risk only	IE + SR
Economic axis weight	Yes (NACE sector value added)	No	Clean energy demand (70%)
Threshold for classification	$EI \geq 2.8$ AND $SR \geq 0.1$	$SR \geq 0.4$	$IE \geq 3$ AND $SR \geq 3$
Recycling factor	Yes (EoLRIR)	Limited	Substitutability
Number of materials (latest list)	34	50	18
Time horizon	5-year rolling data	Current snapshot	Short (2020–2025) + Medium (2025–2035)
Review frequency	Every 4 years (mandatory)	As needed	As needed

Source: Authors’ elaboration based on [5–7].

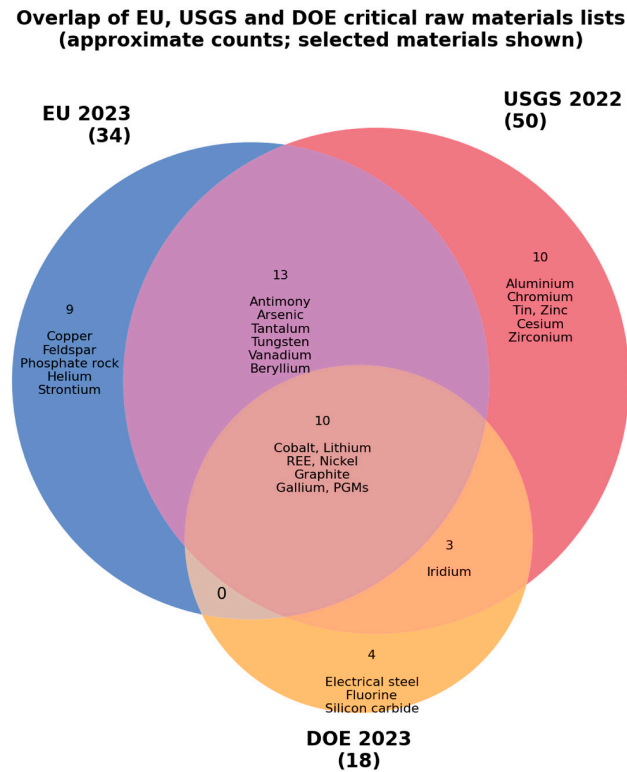


Figure 3. Overlap of materials classified as critical by the 2023 EU, 2022 USGS, and 2023 DOE frameworks. Numbers indicate approximate material counts in each Venn region; selected materials are shown to illustrate where each framework converges with or diverges from the others. Source: Authors’ elaboration based on [5–7].

Critical raw materials as enablers and threats to the Sustainable Development Goals

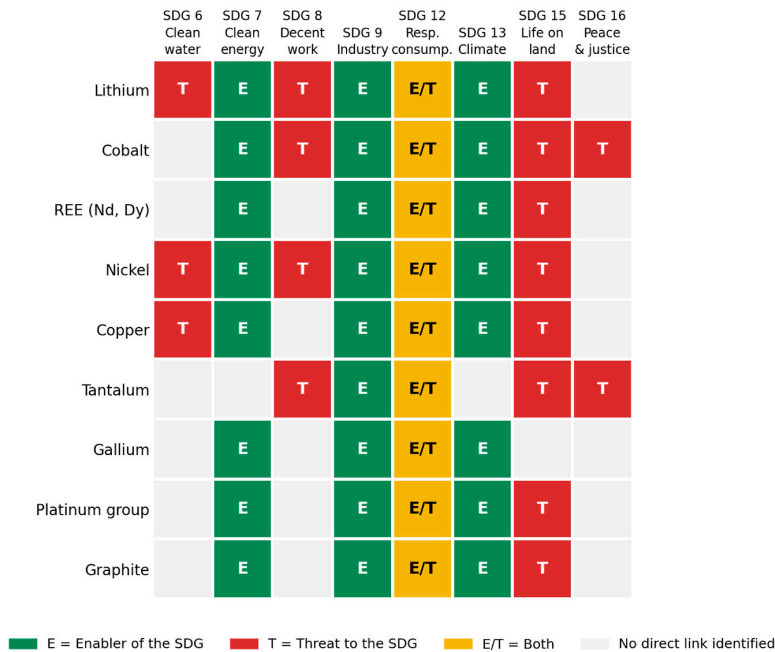


Figure 4. Critical raw materials as enablers (E) and threats (T) to selected Sustainable Development Goals. “E/T” marks materials whose link to a given SDG operates in both directions, typically through enabling clean energy applications while also generating end-of-life waste flows (SDG 12). The figure is illustrative; the exact pattern for any given material depends on its specific supply chain. Source: Authors’ elaboration based on [21] and the corpus documents (Table S1).

3. Historical Context and Conceptual Evolution

3.1. *Origins of the Concept: From World War I to the Cold War*

The term “critical material” emerged formally in 1939 in the United States with the Strategic and Critical Materials Stock Piling Act, which established the National Defense Stockpile (NDS). However, the strategic rationale predates this legislation. Germany’s defeat in World War I was partly attributed to resource shortages, prompting Allied nations—particularly the UK and the US—to begin systematic stockpiling of materials considered essential for industrial and military production [17,18].

A particularly illustrative case is tungsten, whose strategic importance became evident during both World Wars. Used in armor-piercing munitions, tank plating, and high-speed cutting tools, tungsten was the object of intense geopolitical competition. Spain and Portugal emerged as pivotal suppliers, and Allied pre-emptive buying programmes—combined with the threat of cutting off oil exports to Spain—were used to limit German access to Iberian tungsten [24]. The episode illustrates the interplay of geopolitics, materials engineering, and industrial strategy that continues to define CRM policy today.

Following World War II, the 1946 revision of the Stockpiling Act expanded the governance framework, adding multiple federal departments and establishing more rigorous congressional oversight. The stockpile grew significantly through the 1950s, driven by Cold War planning scenarios that anticipated prolonged conventional conflict requiring sustained industrial output. However, the recognition that nuclear warfare would be shorter and more decisive led to a strategic de-prioritization of stockpiling from the late 1950s onward [17].

3.2. *Broadening of Criticality Criteria: Economic, Energy, and Environmental Dimensions*

From the 1960s onward, criticality criteria expanded well beyond military applications. In the 1960s, materials were released from US stockpiles to address industrial shortages of copper, zinc, antimony, and lead—marking the first time economic criteria explicitly governed CRM policy decisions [17]. The 1973 oil crisis further catalyzed the incorporation of energy security considerations, prompting the USGS to launch its Minerals for Energy Production (MEP) program and establishing energy relevance as a core criticality dimension [19].

Environmental considerations entered the framework progressively through landmark events: the 1972 Stockholm Conference, the 1992 Earth Summit, the 2000 Millennium Development Goals, the 2015 Paris Agreement, and the 2030 Agenda for Sustainable Development. These milestones established sustainability as a legitimate and increasingly central criterion in CRM assessment—not only through the environmental impact of extraction and processing, but also through the role of CRMs in enabling low-carbon technologies [21].

By the early twenty-first century, a critical material was no longer defined solely by its military importance. A comprehensive definition must capture several dimensions: (1) geological scarcity or difficulty of extraction; (2) concentrated geographic distribution of reserves; (3) high economic importance in current or emerging applications; (4) limited substitutability; and (5) relevance to sustainability transitions, including both environmental impact of supply chains and essentiality for clean energy technologies [1,3,8].

4. EU Critical Raw Materials Methodology and Its Evolution

4.1. *The Raw Materials Information System and the Five EU Lists*

The European Commission developed the Raw Materials Information System (RMIS) in 2008 as the institutional backbone for CRM assessment. Since then, five CRM lists have been published in 2010 (14 materials), 2014 (20 materials), 2017 (27 materials),

2020 (30 materials), and 2023 (34 materials), reflecting a consistent expansion in scope and methodological sophistication [5,14]. The EU defines a critical raw material as one that both exceeds defined thresholds of economic importance ($EI \geq 2.8$) and supply risk ($SR \geq 0.1$), and for which no adequate substitutes are available [15].

A significant innovation in the 2023 list was the parallel introduction of a separate “Strategic Raw Materials List”, comprising 17 materials of exceptional importance for the green and digital transition, defense, and space sectors. This list is governed by the Critical Raw Materials Act, which mandates that all strategic raw materials must also appear on the broader critical list, and sets benchmarks for domestic extraction, processing, and recycling capacity [15].

4.2. Core Methodological Parameters

The EU methodology for determining CRM status is built around two primary axes: Economic Importance (EI) and Supply Risk (SR). EI is calculated as a weighted sum of the value added by industrial sectors that use the material (using two-digit NACE codes), adjusted for the substitutability of the material within each application (SIEI). SR is a composite indicator that reflects the supply concentration of the material globally, weighted by the governance quality of supplier countries (using the World Governance Index, WGI), the EU’s import dependence (IR), and the end-of-life recycling input rate (EoLRIR), which captures the contribution of recycled material to reducing primary supply dependence [15,16].

The Herfindahl–Hirschman Index (HHI), as applied by the EU, serves as a key concentration indicator, penalizing supply structures dominated by a small number of countries. A notable methodological feature is the EU’s preference for EU-sourced data over global or third-country data, a design choice intended to improve consistency and reduce fluctuations caused by data source changes. This preference has practical implications: in the 2023 revision, the removal of indium from the list was partly explained by the shift from global to EU-weighted supply data, which reduced its calculated SR [15].

4.3. Changes Between the 2020 and 2023 EU Lists

The transition from the 2020 to the 2023 EU list involved both content changes and limited methodological adjustments. In terms of content, six materials were added: arsenic, copper, feldspar, manganese, nickel (battery grade), and metallic titanium. Three materials were removed: indium, natural rubber, and titanium (in its broader form, excluding metallic titanium). Several materials underwent nomenclature changes, including fluorspar (now fluorite) and tantalum (from the Spanish-influenced “tantálio” to the anglicized form) [15].

Two additions deserve particular attention: copper and nickel (battery grade) were included despite not meeting the quantitative thresholds ($EI \geq 2.8$; $SR \geq 0.1$). For copper, the Commission argued that its unique electrical performance and the depth of its integration into electrification technologies make it irreplaceable, and that its highly diversified supply chain does not fully account for contractual risks and project ownership structures [15]. For nickel, similar arguments were made, noting that dominant production in Indonesia, the Philippines, and Russia creates geopolitical exposure not fully captured by the standard SR metric.

These strategic inclusions raise questions about the reproducibility of the assessment. If materials can be classified as critical on grounds that override quantitative thresholds without a formalized protocol, the boundary between evidence-based assessment and political judgement becomes unclear. The criteria applied to copper—depth of integration and contractual risk—could in principle extend to other widely used metals,

and future revisions risk inconsistency unless the conditions for strategic overrides are explicitly codified.

The 2023 methodology also introduced, for the first time, a formal protocol for the Strategic Materials List, based on three parameters: the number of strategic technologies that use the material, the quantity required per unit of technology, and projected global demand growth for the relevant technologies (DF/C—demand forecast-to-current production ratio). This is complemented by an assessment of the difficulty of scaling up production, measured by the reserves-to-production ratio and current production scale [15].

4.4. Drivers of Criticality Changes Between 2020 and 2023

The drivers behind specific changes in the 2023 EU list are varied and illustrative of how CRM assessment integrates multiple data streams. Manganese entered the list due to a collapse of domestic EU production following the halting of mining in Bulgaria and Hungary, which increased import dependence from South Africa (33% to 41%) and Gabon (26% to 33%). Feldspar's SR increased due to Turkey's growing share of EU supply (now 51%), effectively doubling import concentration. Arsenic was added following a rise in its EI from 2.6 to 3.0, driven by its growing role in NACE sectors C23 (non-metallic mineral products) and C24 (basic metals) [15].

Conversely, natural rubber was removed despite 100% EU import dependence, owing to an increase in its recycling rate (from 1% to 5%) and a decrease in its substitution difficulty score (from 0.99 to 0.90). Indium was removed due to a methodological shift in how supply data was weighted, combined with improved classification of its end uses. These cases demonstrate that CRM status is not a static property of a material but a dynamic assessment that responds to market changes, data improvements, and methodological refinements [15,16].

The distinction matters for policy credibility. Indium's supply chain did not undergo a structural transformation between 2020 and 2023; its removal was driven primarily by a change in how EoLRIR was weighted. Without formal sensitivity analysis identifying whether each near-threshold material's classification is robust to plausible alternative assumptions, stakeholders cannot distinguish materials that are genuinely critical from those whose status is contingent on specific parameter choices.

5. US Critical Materials Frameworks: USGS and DOE

5.1. The USGS Approach and the 2022 List

The US Geological Survey (USGS), operating under the Department of the Interior, has developed a quantitative approach to CRM assessment rooted in supply risk analysis. Its methodology, formalized in the 2021 review following the mandate of the Energy Act of 2020, employs three tiers depending on data availability: (1) quantitative supply risk evaluation using net import reliance, production concentration outside the US, and country weights reflecting governance and supply disposition; (2) semi-quantitative evaluation for single-point-of-failure scenarios; and (3) qualitative assessment where quantitative data is insufficient [6,20].

A material is classified as critical if its quantitative supply risk score exceeds 0.4. The 2022 USGS list contains 50 materials—a substantial expansion from the 35 included in the 2018 draft list. Notable additions include nickel and zinc. Materials removed include helium (since the US is a net exporter), potassium, rhenium, strontium (all three just below the 0.4 threshold with key suppliers being politically stable countries such as Canada, Spain, and Chile), and uranium (excluded due to its classification under nuclear fuels, outside the USGS mandate under the Energy Act) [6,20].

5.2. The DOE Approach and the 2023 List

The Department of Energy's CRM methodology has remained structurally stable since its introduction in 2010, adapting the National Research Council's Criticality Matrix to emphasize clean energy relevance [7,13]. It evaluates materials across two axes: (1) Importance to Energy (IE), weighted between clean energy demand (70%) and substitutability (30%); and (2) Supply Risk (SR), weighted across basic availability (40%), competing technology demand (10%), political and social factors (20%), co-dependence with other markets (10%), and producer diversity (20%). Materials scoring ≥ 3 on both axes are classified as critical [7].

The 2023 DOE list contains 18 materials, evaluated for both a short-term window (2020–2025) and a medium-term window (2025–2035). Compared to the 2019 list, key additions at the medium-term horizon include nickel, graphite, platinum, silicon carbide, iridium, praseodymium, terbium, copper, silicon steel, silicon, aluminum, and fluorine, all driven by their central role in electric vehicle drivetrains, wind turbines, hydrogen technologies, and power electronics. Palladium and rhodium were removed, reflecting the projected shift away from catalytic converters as hydrogen technologies mature [7].

5.3. Comparative Analysis: EU vs. US Methodological Frameworks

While the EU, USGS, and DOE frameworks share a common conceptual ancestry in the NRC's Criticality Matrix, they differ substantially in scope, weighting, and institutional priorities. Table 2 summarizes the key methodological differences, and Figure 3 illustrates the resulting overlap and divergence at the level of individual materials.

A fundamental structural difference lies in the orientation of each framework. The USGS approach is sector-agnostic and geologically grounded, identifying vulnerability to supply disruption regardless of end use. The DOE approach, by contrast, filters materials through the lens of clean energy, making it highly relevant for climate transition planning but potentially overlooking materials critical for other economic sectors. The EU approach is the most comprehensive, integrating economic importance across all sectors of the economy while also incorporating supply chain governance and recycling rates. However, it is also the most complex to implement and the most sensitive to data sources and weighting choices [5–7].

A cross-list comparison reveals substantial overlap in materials classified as critical by all three frameworks (cobalt, lithium, rare earth elements, graphite, and platinum group metals), reflecting genuine geophysical and economic consensus. However, important divergences exist: the USGS list includes uranium, rhenium, and cesium, absent from both EU and DOE lists; the DOE uniquely includes silicon carbide and silicon steel, reflecting the clean energy focus; and the EU is unique in formally listing copper, which falls below its own quantitative thresholds [6,7,15].

Evaluatively, the USGS framework is the most robust to data uncertainty but lacks prioritization—all 50 materials receive equal status. The DOE is the most useful for energy planning but structurally biased: its 70% clean-energy weighting may exclude materials critical for defense or healthcare. The EU approach is the most comprehensive but also the most fragile, as the indium case and the copper/nickel overrides both demonstrate. Conflicting classifications are most likely for materials with moderate supply risk and sector-specific importance, where small differences in weighting or scope determine the outcome. Two sources of divergence should be distinguished: strategic priority (e.g., USGS including uranium under a broader security mandate; EU omitting it because nuclear fuels follow a separate regulatory track) and methodological design (e.g., silicon carbide appearing only on the DOE list because only that framework uses technology-specific demand intensity). Recognizing which divergences are preference-driven and which are methodology-driven is essential for any future harmonization effort.

6. Critical Raw Materials and the Sustainable Development Goals

Critical raw materials lie at the heart of the sustainability agenda for a simple reason: the same materials that make the green and digital transitions possible—lithium and cobalt in batteries, rare earth elements in wind turbines and electric motors, gallium and germanium in semiconductors, platinum group metals in fuel cells—also carry significant environmental, social, and geopolitical costs across their supply chains. CRM policy therefore sits inside the framework of the United Nations Sustainable Development Goals (SDGs) rather than alongside it [21,25,26].

Six SDGs are particularly relevant: SDG 7 (Affordable and Clean Energy), SDG 8 (Decent Work and Economic Growth), SDG 9 (Industry, Innovation and Infrastructure), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 15 (Life on Land). The role of CRMs is double-edged. They enable SDG 7 and SDG 13 by underpinning low-carbon technologies, and they support SDG 9 as critical inputs to advanced manufacturing. At the same time, they can undermine SDG 15 through mining-related habitat destruction, and SDG 12 through linear material flows that produce large volumes of electronic and industrial waste. Figure 4 summarises this dual character for a representative set of materials and SDGs.

Specific cases illustrate how the tension plays out at material level. Tantalum (coltan), essential for electronic capacitors, is sourced largely from conflict zones in the Democratic Republic of Congo, with documented impacts on SDG 8 and SDG 16 (Peace, Justice and Strong Institutions). Rare earth elements, mined primarily in China under highly polluting conditions, raise SDG 15 concerns. Lithium extraction from South American salt flats—in Chile, Argentina, and Bolivia—consumes very large volumes of water in hyper-arid ecosystems, putting pressure on SDG 6 (Clean Water and Sanitation) [8,9].

The trade-off is not merely conceptual but arithmetic: meeting EU electric vehicle targets requires a several-fold increase in lithium, cobalt, and nickel supply, the extraction of which directly undermines SDGs 6, 15, and 8. If the EU meets its 10% domestic extraction benchmark, it must authorize mining under strict environmental regulation at higher cost; if it relies on imports, it externalizes environmental and social costs to weaker-governance producer countries. No CRM framework currently quantifies this trade-off or provides tools to navigate it.

The social dimensions extend beyond conflict minerals. Artisanal and small-scale mining accounts for a significant share of global cobalt and tantalum production, often under conditions raising concerns about child labour and community displacement. CRM frameworks currently assess supply risk without incorporating labour or community impact indicators, and while the EU's Conflict Minerals Regulation (2017/821) [15] and the proposed Corporate Sustainability Due Diligence Directive address some of these issues, they operate as separate instruments rather than integrated components of the CRM methodology itself.

At the policy level, the EU Critical Raw Materials Act (2023) [15] is the first regulation designed to address this tension head-on. It sets benchmarks for strategic materials of 10% domestic extraction, 40% domestic processing, and 15% recycling of annual EU consumption by 2030 [15]. These benchmarks operationalize the circular economy principles embedded in SDG 12. Recent reviews in *Sustainability* assessing the EU policy package—the CRMA, the Batteries Regulation, the Ecodesign for Sustainable Products Regulation with Digital Product Passports, and the recast Waste Shipments Regulation—argue that this combined toolkit creates clearer investment signals for secondary supply but that its effectiveness will depend on whether ex post evaluation, traceability systems, and trade rules are aligned with the just-transition agenda [26,27]. Similar evidence on the use of secondary sources, from urban mining of e-waste to recovery from mining tailings, points

in the same direction: the only way to make CRM policy serve, rather than work against, the SDGs is to close material loops at every value chain stage [28].

7. Discussion

Three patterns emerge from the comparative review.

The first is that criticality is not a permanent property of a material. Supply expansion, recycling innovation, technological substitution, and geopolitical normalisation can move a material off the critical list, as the cases of natural rubber and indium (EU 2023) and of helium and rhenium (USGS 2022) make clear [5,29]. This is what justifies the mandatory four-year revision cycle of the EU list and a similarly periodic approach in the US.

The second pattern is a clear move toward qualitative and forward-looking assessment. Copper and nickel were added to the 2023 EU list despite not meeting the quantitative EI and SR thresholds, on the basis of strategic considerations: depth of integration in electrification (copper) and concentrated production in Indonesia, the Philippines, and Russia (nickel). The DOE goes further by separating short-term (2020–2025) and medium-term (2025–2035) horizons, and the EU has added a parallel Strategic Materials List based on technology penetration, intensity of use, and projected demand growth [7,15]. The direction of travel is the same: future frameworks will combine quantitative supply risk metrics with demand-side forecasting and geopolitical scenario analysis.

The third pattern is the tension between comprehensiveness and operational simplicity. The EU framework is the most sophisticated and the most data-sensitive: the removal of indium in 2023, driven in part by a change in how EoLRIR was weighted, shows how a methodological adjustment can move a material across a regulatory threshold [5,16]. The USGS approach is simpler and more robust to data variability but ignores the economic dimension. Hybrid designs—quantitative metrics complemented by structured expert panels—are what both the EU and the DOE already use for borderline cases, and they probably represent the most pragmatic balance for future revisions [6,7,16].

These patterns reveal an unresolved tension: CRM frameworks aspire to objectivity, yet the most consequential decisions—which materials to include, how to weight risks, whether to override quantitative results—are inherently normative. Four methodological challenges remain open: (1) formalizing conditions for strategic overrides; (2) incorporating demand-side forecasting without introducing instability across revision cycles; (3) integrating social and environmental supply-chain indicators into frameworks that currently treat criticality as a function of supply concentration and economic importance alone; and (4) designing assessments useful to both resource-consuming and resource-producing economies.

One gap stands out: none of the major resource-holding nations—including Chile, Brazil, and Peru, all of which sit on reserves that are critical to EU and US supply chains—publishes an official CRM list of its own. Their national criticality profiles are different from those of resource-dependent economies, and any global CRM policy that ignores this asymmetry will struggle to be either equitable or effective. The companion paper (Part II) addresses this gap by applying the EU methodology to those three Latin American economies.

For these economies, criticality operates in reverse: the risk is demand volatility and extraction costs, not supply disruption. Chile holds approximately 36% of known lithium reserves but lacks a formal criticality assessment to evaluate whether accelerating extraction to meet EU and US demand is compatible with its own water security objectives. A supply-side CRM framework would need to invert the EU's logic—assessing not whether supply is at risk, but whether demand growth and extraction rates are sustainable from the producer's perspective. The companion paper (Part II) confirms that criticality profiles differ substantially between consuming and producing economies.

8. Implications, Limitations, and Future Research

8.1. Implications

From a theoretical standpoint, this review makes three contributions. First, it documents how criticality has evolved from a military-strategic concept to a multidimensional policy instrument integrating economic, environmental, and sustainability criteria [1,3]. Second, it shows that the apparent convergence across frameworks (all three flag cobalt, lithium, and rare earth elements) masks fundamental divergence in analytical architecture—the EU’s two-axis model, the USGS’s single-axis supply risk approach, and the DOE’s clean-energy-weighted matrix reflect different institutional epistemologies of what ‘criticality’ means. Third, the inclusion of copper and nickel on the 2023 EU list on strategic grounds—despite failing quantitative thresholds—reveals the growing normative dimension of ostensibly data-driven classification systems.

At a practical level, the EU framework’s sensitivity to data source changes (illustrated by indium’s removal in 2023) suggests that methodological transparency and stability matter as much as analytical sophistication. For industry, the cross-jurisdictional divergence means that companies operating in both markets should monitor all three lists, as strategic classifications may carry regulatory consequences under the Critical Raw Materials Act. For resource-rich countries, the absence of equivalent national frameworks represents both a governance gap and a strategic opportunity addressed in the companion paper.

8.2. Limitations

This study relies exclusively on published documents and the academic literature without incorporating interviews from the institutions responsible for CRM assessment; stated rationales may not capture the full range of considerations involved. The geographic scope is limited to the EU and the US, omitting significant efforts by Japan (JOGMEC), Australia, and China, which limits generalizability. The CRM–SDG connection is analytical rather than empirical: we map conceptual and regulatory linkages but do not measure actual policy impact on SDG indicators. Finally, the directed content analysis approach involves interpretive judgement in categorizing framework features; although extraction was performed independently by two authors and reconciled by a third, alternative predefined categories could emphasize different aspects.

8.3. Future Research

The companion paper (Part II) has applied the EU methodology to Chile, Brazil, and Peru, demonstrating that criticality profiles differ substantially between resource-consuming and resource-holding economies and that the methodological gap on the supply side can be addressed with existing tools. Building on that foundation, three directions merit further investigation: (1) extending the application to additional resource-rich regions—particularly Sub-Saharan Africa and Southeast Asia—where mining plays a dominant economic role but formal criticality assessments remain absent, and where different industrial structures and governance contexts may reveal additional methodological limitations; (2) measuring the policy effectiveness of the EU’s circular economy benchmarks (15% recycling, 40% domestic processing by 2030) and of the CRMA’s sourcing and due diligence obligations, which requires longitudinal panel data on material flows and firm-level responses not yet available; and (3) studying the integration of demand-side forecasting and geopolitical scenario analysis—building on what the DOE’s dual time-horizon approach and the EU’s Strategic Materials List have started—into a unified criticality framework that combines quantitative supply risk metrics with foresight methods such as technology road mapping and Delphi panels.

9. Conclusions

This paper has traced eight decades of critical raw materials frameworks, from the 1939 US Strategic and Critical Materials Stock Piling Act to the 2023 EU Critical Raw Materials Act and the parallel USGS and DOE assessments. The concept that began as a narrow military-strategic notion now incorporates economic importance, supply risk, environmental impact, recycling potential, and clean energy relevance, and is one of the few policy areas where industrial strategy, climate policy, and the SDG agenda converge on the same set of materials.

The EU, USGS, and DOE frameworks share their conceptual roots in the National Research Council's Criticality Matrix but diverge in scope, weighting, and institutional priorities. The EU's two-axis methodology (Economic Importance $\times$ Supply Risk) is the most comprehensive but also the most sensitive to data sources; the USGS approach is geologically grounded and sector-agnostic; and the DOE framework is explicitly built around the clean energy transition. Between the 2020 and 2023 EU lists, the changes were driven by market evolution (manganese and feldspar), methodological adjustments (indium), technological relevance (metallic titanium and arsenic), and explicit strategic political judgements (copper, nickel).

CRM management is, in practice, an instrument of the SDG agenda. CRMs both enable and threaten sustainability objectives, depending on how their supply chains are governed. Without circular economy measures—increased recycling, domestic processing, substitution research—there is no pathway in which CRM policy advances SDG 7, 12, and 13 together rather than trading one against another. Recent EU policy is moving in that direction; whether it delivers will depend on the next decade of implementation.

Two further directions follow. First, future frameworks should integrate demand-side forecasting and geopolitical scenario analysis, building on what the 2023 EU Strategic Materials List and the DOE's medium-term assessment have started. Second, the methodological gap on the supply side—the absence of CRM lists from resource-rich countries—needs to be closed. That is the subject of the companion paper, which applies the EU methodology to Chile, Brazil, and Peru.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/su18157972/s1>. Table S1. Primary corpus of official documents analyzed ($n = 23$), by issuing institution, year, document type, role in the analysis, corresponding main-text reference, and provenance. Section numbers refer to the main text of the revised manuscript.

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References

- Hofmann, M.; Hofmann, H.; Hagelücken, C.; Hool, A. Critical raw materials: A perspective from the materials science community. *Sustain. Mater. Technol.* **2018**, *17*, e00074. [CrossRef]
- Schrijvers, D.; Hool, A.; Blengini, G.A.; Chen, W.-Q.; Dewulf, J.; Eggert, R.; Faulstich, M.; Genderen, E.; Goddin, J.; Habib, K.; et al. A review of methods and data to determine raw material criticality. *Resour. Conserv. Recycl.* **2020**, *155*, 104617. [CrossRef]
- Graedel, T.E.; Harper, E.M.; Nassar, N.T.; Reck, B.K. On the materials basis of modern society. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, 6295–6300. [PubMed]
- Massari, S.; Ruberti, M. Rare earth elements as critical raw materials: Focus on international markets and future strategies. *Resour. Policy* **2013**, *38*, 36–43. [CrossRef]
- European Commission. *Study on the Critical Raw Materials for the EU 2023—Final Report*; European Commission: Brussels, Belgium, 2023.
- Nassar, N.T.; Fortier, S.M. *Methodology and Technical Input for the 2021 Review and Revision of the U.S. Critical Minerals List*; U.S. Geological Survey Open-File Report 2021-1045; USGS: Reston, VA, USA, 2021.
- U.S. Department of Energy. *Critical Materials Assessment*; DOE: Washington, DC, USA, 2023.
- Báscones Velasco, I. Gestión de Recursos y Materiales en Relación con los Objetivos de Desarrollo Sostenible. Bachelor's Thesis, Universidad Carlos III de Madrid, Leganés, Spain, 2021.
- Muñoz Gutiérrez, Í. *Materias Primas Críticas y su Influencia Geopolítica. Análisis de Metodologías y Sectores Estratégicos con Relación a los ODS*. Master's Thesis, Universidad Carlos III de Madrid, Madrid, Spain, 2024.
- Tosun, J.; Leininger, J.; Limberg, J. Comparative Policy Analysis. In *Handbook of Research Methods and Applications in Comparative Policy Analysis*; Edward Elgar: Cheltenham, UK, 2022.
- Peters, B.G. *Comparative Public Policy*; Cambridge University Press: Cambridge, UK, 2018.
- Hsieh, H.-F.; Shannon, S.E. Three Approaches to Qualitative Content Analysis. *Qual. Health Res.* **2005**, *15*, 1277–1288. [CrossRef] [PubMed]
- National Research Council. *Minerals, Critical Minerals, and the U.S. Economy*; National Academies Press: Washington, DC, USA, 2008.
- European Commission. Internal Market, Industry, Entrepreneurship and SMEs: Critical Raw Materials. Available online: https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en (accessed on 20 May 2024).
- European Commission. *Annexes to the Proposal for a Regulation of the European Parliament and of the Council Establishing a Framework for Ensuring a Secure and Sustainable Supply of Critical Raw Materials*; COM (2023) 160 final; European Commission: Brussels, Belgium, 2023.
- Blengini, G.A.; Nuss, P.; Dewulf, J.; Nita, V.; Peiró, L.T.; Vidal-Legaz, B.; Latunussa, C.; Mancini, L.; Blagoeva, D.; Pennington, D.; et al. EU methodology for critical raw materials assessment: Policy needs and proposed solutions for incremental improvements. *Resour. Policy* **2017**, *53*, 12–19. [CrossRef]
- Leith, C.K. The International Aspect of the Mineral Industry. *Ann. Am. Acad. Pol. Soc. Sci.* **1930**, *150*, 98–104. [CrossRef]
- U.S. Congress. *Strategic and Critical Materials Stock Piling Act of 1939*; Public Law 76-117, 53 Stat. 811; U.S. Government Printing Office: Washington, DC, USA, 1939.
- U.S. Geological Survey. *Mineral Commodity Summaries 2024*; USGS: Reston, VA, USA, 2024.
- Fortier, S.M.; Nassar, N.T.; Lederer, G.W.; Brainard, J.; Gambogi, J.; McCullough, E.A. *Draft Critical Mineral List—Summary of Methodology and Background Information*; U.S. Geological Survey Open-File Report 2018-1021; USGS: Reston, VA, USA, 2018.
- United Nations. *Transforming Our World: The 2030 Agenda for Sustainable Development*; A/RES/70/1; United Nations: New York, NY, USA, 2015.
- Energy Act of 2020, Public Law 116-260, Division Z, 134 Stat. 2422, 2020. Available online: <https://democrats-science.house.gov/bills/the-energy-act-of-2020> (accessed on 20 July 2026).
- Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* **2021**, *372*, n71. [CrossRef] [PubMed]
- Calvo, G.; Valero, A.; Valero, A. How can strategic metals drive the economy? Tungsten and tin production in Spain during periods of war. *Extr. Ind. Soc.* **2019**, *6*, 8–14. [CrossRef]
- Sovacool, B.K.; Ali, S.H.; Bazilian, M.; Radley, B.; Dohrn-van Rossum, G.; Okatz, J.; Dominish, E.; Florin, N. Sustainable minerals and metals for a low-carbon future. *Science* **2020**, *367*, 30–33. [CrossRef] [PubMed]
- Rembisz, W. Circular Economy Pathways for Critical Raw Materials: European Union Policy Instruments, Secondary Supply, and Sustainable Development Outcomes. *Sustainability* **2026**, *18*, 562. [CrossRef]

27. Kowal, B. Efficient Use of Critical Raw Materials for Optimal Resource Management in EU Countries. *Sustainability* **2022**, *14*, 6554. [[CrossRef](#)]
28. Kaźmierczak, U. Role of Circular Economy in Increasing Raw Material Supply by Modern Mining Industry in Lower Silesia, Poland. *Sustainability* **2026**, *18*, 816. [[CrossRef](#)]
29. U.S. Department of the Interior. Final List of Critical Minerals. 2022. Available online: <https://www.federalregister.gov/document/s/2022/02/24/2022-04027/2022-final-list-of-critical-minerals> (accessed on 20 July 2026).

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