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Review

Assessing Critical Raw Materials and Their Supply Risk in Energy Technologies—A Literature Review

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Abstract: Climate change is leading modern society to seek innovative solutions for sustainable development and a zero-carbon economy. Nevertheless, new technologies strongly rely on precious raw materials and might suffer from supply chain risks. The European Union has identified a set of raw materials deemed to be critical or strategic because they appear essential for energy transition technologies. Consequently, long-term energy system planning must factor in the availability of these critical raw materials when selecting specific technologies, as their supply could be affected by global policies or conflicts. This paper provides a literature review on the assessment of critical raw materials in energy technologies comparing the main approaches on critical raw materials content assessment in technologies, long-term planning studies considering critical raw materials, and the development of indicators for critical raw materials content in energy technologies. The main findings of this review suggest that existing reliable databases with the bill of materials, such as life cycle inventories, should be exploited and that proper indicators to rank the criticality of materials and the importance of a specific technology should be developed. These findings are discussed and organized proposing a method for the optimal planning of an energy technologies mix in regional or national energy systems considering the availability and future supply of critical raw materials.

Keywords: critical raw materials; energy; planning; review; supply chain

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1. Introduction

The global transition towards renewable energy is essential for mitigating climate change, reducing greenhouse gas emissions, and promoting energy security. In the last decades, researchers and industries focused their efforts on investigating new technologies or improving the existing ones with the aim of attaining energy efficiency and carbon emissions reduction. One of the most notable examples of this trend is the introduction of energy efficiency labels in the European Union (EU) with the EU Directive 92/75/EC, i.e., labels indicating the yearly energy consumption mandatorily applied on appliances such as refrigerators, washing machines, light bulbs, and televisions [1].

However, the energy transition is highly dependent on the availability and supply of innovative materials, precious metals, or rare raw materials. Among these, those showing the highest supply risk and the highest economic importance are known as critical raw materials (CRMs). Moreover, a subset of materials relevant to the green transition, digital transition, defense, and space applications, are collectively known as strategic raw materials (SRMs) [2]

These materials are selected and updated every three years by the European Union. Within the supply risk feature, the rate of substitution of a CRM with another raw material more easily available and the possibility of recycling the material at the end of the life of the technology [3] are considered.

Both the EU and the USA are heavily dependent on imports of CRMs. The European Commission has highlighted the vulnerability of European industries due to the lack of domestic supply of materials like lithium, cobalt, and rare earth elements [4]. The USA has recognized similar risks, implementing policies to secure supply chains by investing in domestic mining and fostering alliances with resource-rich countries. More in detail, three main supply risk categories can be identified as related to CRMs: (1) geopolitical risk, (2) environmental risk, and (3) social risk.

One of the major risks associated with the supply of CRMs is their geographic concentration in a few countries. For instance, over 74% of the world's cobalt mine production in 2023 came from the Democratic Republic of Congo (DRC) [5], while China dominates the production of rare earth elements, accounting for more than 90% of global output [6]. This concentration creates geopolitical vulnerabilities, as supply disruptions due to political instability, trade disputes, or regulatory changes can lead to shortages, price volatility, and increased costs for renewable energy technologies. The 2010 rare earths embargo by China on Japan, which triggered concerns about the reliability of supply chains, is a notable example of such geopolitical risk [7]. Economic factors exacerbate these geopolitical risks. The volatile nature of commodity markets, particularly for CRMs, leads to boom-and-bust cycles that create price uncertainty. For example, fluctuations in the prices of lithium and cobalt are influenced not only by market demand but also by the long lead times required to develop new mining projects and the high capital investment needed [7].

From the environmental point of view, the extraction and processing of CRMs are associated with significant environmental and social challenges, which pose additional risks to the supply chain. Mining for lithium, cobalt, and rare earth elements has been linked to land degradation, water contamination, and habitat destruction, particularly in developing countries where environmental regulations may be weak [4]. For instance, lithium extraction from salt flats in South America, a key region for global lithium production, has raised concerns about the depletion of freshwater resources, a critical issue in arid regions like Chile's Atacama Desert [8].

Moreover, social risks are also prevalent in CRM supply chains, including human rights abuses and labor exploitation. In the DRC, the mining of cobalt has been associated with child labor and hazardous working conditions. These issues not only pose ethical concerns but also introduce legal and reputational risks for companies that rely on these materials. The European Union's Conflict Minerals Regulation, which came into force in 2021, is an attempt to address these risks by ensuring that companies source CRMs responsibly from conflict-affected and high-risk areas [4].

Nevertheless, it is worth highlighting that not all the authors agree on the considerations here illustrated. For instance, with specific reference to renewable energy technologies, Overland pointed out in 2019 that the CRM supply risk fear started back in 2010 when China imposed an embargo on Japan concerning rare earth exports due to a territorial dispute. The author states that the widespread global diffusion of rare earths should discourage these fears, also because only a few rare earths are employed in a specific, not-so-common wind turbine technology [7].

Focusing on the energy sector, CRMs like lithium, cobalt, rare earth elements, and others play a crucial role in the manufacturing of renewable energy technologies such as wind turbines, solar photovoltaics, and battery storage systems, but the risks associated with CRMs create supply chain bottlenecks and delays, hindering the timely deployment of renewable energy technologies [9]. This aspect becomes of paramount importance in the context of the European Green Deal, a long-term path to reach a climate-neutral society by 2050 in a fair, cost-effective, and competitive way. To achieve this target, the provision of energy from zero-emissions sources is one of the main measures, but supply risks of technologies pose a possible threat to the green transition, and it is thus evident that these aspects should be included in energy systems planning. Nevertheless, as pointed out by Aljabery et al. in their review on multi-carrier energy systems [10], the most common objective functions that are generally used in the literature are costs and emissions reduction, while CRM supply risk is not even mentioned.

This literature review synthesizes the available studies concerning energy technologies containing CRMs. According to the main outcomes of this study, some criteria for optimally planning a power technology mix in regional or national energy systems are proposed. The document is structured as follows. Section 2 provides a recap on the most common CRMs used in the manufacture of energy technologies, describing their main uses and the reasons why these materials were listed among the CRMs. Complementarily, Section 3 lists the energy technologies mostly impacted by the CRM content, describing their main operating principles and their role in the energy transition. Section 4 describes the methodology adopted to carry out this literature review, which is illustrated in Section 5. The results of this review are discussed in Section 6, including a proposal for an optimal planning method for regional or national energy systems considering the availability and future supply of critical raw materials. Lastly, the conclusions of this paper are provided in Section 7.

2. Critical Raw Materials Used in Energy Technologies

CRMs are essential for the manufacturing of various energy technologies. Renewable energy technologies, such as wind turbines or solar panels but also energy storage systems, depend on materials like lithium, cobalt, nickel, rare earth elements, and other metals to function efficiently. Lithium and cobalt are critical for battery storage systems, while neodymium and dysprosium are essential for permanent magnets in wind turbines. In detail, the introduction of CRMs in energy technologies is essential to improve their performance, efficiency, and scalability. Their supply chain is vulnerable due to geopolitical factors, economic constraints, and environmental concerns. In this section, a brief description of the key CRMs used for the manufacture of energy technologies is provided. The ChatGPT GenAI software tool was used to generate a preliminary list of critical raw materials mostly used in the energy sector with enriched content included. Additionally, the map of all CRM mines, gathered from the website of the European Geological Data Infrastructure, is shown in Figure 1 [11].

2.1. Lithium

Lithium is a lightweight metal and has a high electrochemical potential, making it crucial for rechargeable batteries. In detail, due to their high energy density and relatively low self-discharge rate, lithium-ion batteries are widely used in energy storage applications, such as mobile phones, electric vehicles, and facility-scale storage systems. However, their increasing demand has led to concerns about future lithium supply since its extraction is geographically concentrated, primarily in Chile, Argentina, and Australia [6].

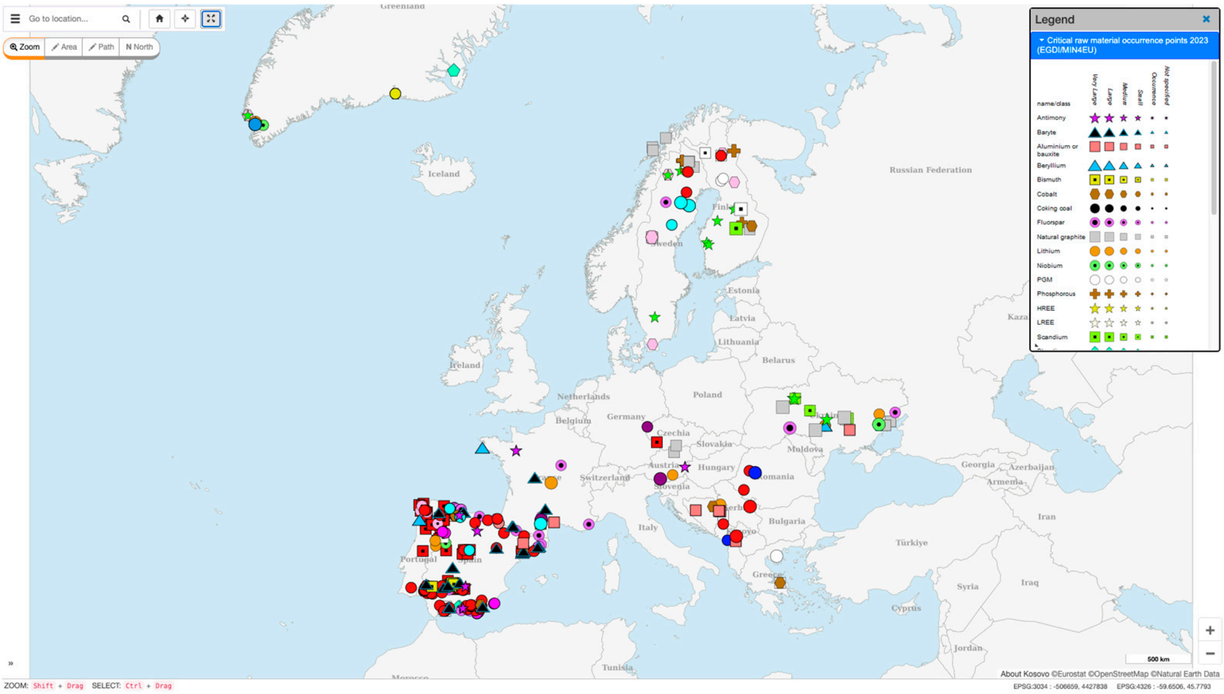

Figure 1. Map of the CRM mines in Europe [11].

2.2. Rare Earth Elements (REEs)

Rare earth elements, particularly neodymium, dysprosium, and praseodymium, are vital for high-performance magnets used in wind turbines (especially direct-drive systems), electric motors, as well as some advanced energy storage technologies. Despite the adjective "rare", these elements are actually not scarce but are difficult to extract and refine, often leading to significant environmental degradation. For this reason, China dominates global REE production, controlling over 90% of the share [6].

2.3. Cobalt

Due to its stabilizing properties, cobalt is predominantly used in the cathodes of lithium-ion batteries, especially in those designed for long-duration energy storage such as electric vehicles and large storage applications. This raw material is mostly mined in the DRC, where production is frequently associated with ethical concerns like child labor and unsafe working conditions [5,12]. Moreover, the political instability of this region creates geopolitical risks that could impact global supply chains, making cobalt one of the most supply-constrained CRMs.

2.4. Nickel

Nickel is used to increase the energy density of batteries, improving their performance. It is an essential component in advanced battery chemistries like nickel–cobalt-aluminum and nickel–cobalt–manganese batteries. Nickel mining is energy intensive and has significant environmental impacts, particularly when extracted from laterite ores. The high demand for batteries and increasing stainless steel production creates high pressure on the supply side [6].

2.5. Copper

Copper is widely used as the main component for electrical wires and is thus essential for conducting electricity because its high conductivity makes it a preferred material for electrical infrastructure. Although copper is widely distributed, the extraction process is energy-intensive and subject to environmental concerns. Increased demand from the installation of worldwide power infrastructures related to wide penetration of renewable energy sources and loads electrification is putting pressure on copper supplies [6].

2.6. Graphite

Graphite is used in the anodes of lithium-ion batteries, contributing to their ability to store energy. Synthetic and natural graphite are both critical for battery production. Although synthetic graphite production is technically feasible, it is an energy-intensive process, while natural graphite is primarily mined in China (79% in 2021 [13]). This leads to concerns about the sustainability and availability of this material as demand increases for energy storage solutions.

2.7. Platinum Group Metals

Platinum group metals (PGMs) are a group of five elements. The group comprises platinum, palladium, ruthenium, iridium, osmium, and rhodium. Platinum and palladium are the key elements of this group, and they are considered essential for the catalytic processes in hydrogen fuel cells, which are becoming increasingly important for energy storage and transport in a zero-carbon economy. PGMs are primarily mined in South Africa and Russia, making them vulnerable to supply disruptions due to political instability or trade sanctions [14].

3. Energy Technologies Dependent on CRMs and SRMs

The dependence of energy technologies on CRMs and SRMs varies significantly, influencing their deployment potential at the commercial scale. In this section, a list of key energy technologies that include CRMs and SRMs is provided, along with a description of how these materials are used. In this way, this section complements the view already given in Section 2. The ChatGPT GenAI software tool was used to generate a preliminary list of energy technologies mostly impacted by their critical raw materials content with enriched content included. In addition, a recap of the information provided in Sections 2 and 3 is provided in Table 1 [15].

Table 1. Recap of the main energy technologies with an indication of the relative importance of CRM content (1 is low, 2 is medium, and 3 is high) [15].

	Cobalt	Copper	Lithium	Nickel	PGM	REE	Graphite
BESS	3	3	3	3	1	3	3
Wind	1	3	1	2	1	3	1
Solar PV	1	3	1	1	1	1	1
Hydrogen technologies	1	1	1	3	3	2	1
Superconductors	1	1	1	1	1	3	1
Geothermal	1	1	1	3	1	1	1
Nuclear	1	2	1	2	1	1	1
Electricity networks	1	3	1	1	1	1	1

3.1. Battery Energy Storage Systems (BESSs)

Battery energy storage systems store electrical energy generated in a specific period to release it in another period. These systems are usually employed to store energy from intermittent renewable sources (such as solar or wind) when production is high and the load is low and release it when the load is higher, stabilizing the energy supply. Another main use of batteries is storing the energy used to power electric motors in electric vehicles, which are crucial for decarbonizing the transportation sector.

Lithium-ion batteries, currently the most widely used energy storage system, rely on many CRMs such as lithium, cobalt, nickel, and manganese. In detail, lithium is the primary material in this technology, cobalt enhances the energy density and stability in cathodes, graphite is used as the anode material, and nickel and manganese are used in some selected lithium-based batteries.

Nickel–metal hydride batteries are also commonly used in all-electric and plug-in electric vehicles, while alternative storage technologies such as sodium–sulfur and flow batteries are less CRM-dependent but currently less efficient or more expensive [16].

3.2. Wind Turbines

Wind turbines convert kinetic energy from wind into electrical energy using rotor blades connected to a generator. Direct-drive wind turbines, which eliminate the need for a gearbox, depend heavily on rare earth elements for their high-performance magnets like neodymium and dysprosium, while offshore wind turbines require significant amounts of CRMs due to their higher material intensity [17–19]. In addition, nickel is used in the manufacturing of some wind turbine components, especially in offshore wind turbines due to its corrosion resistance, while copper is essential for electrical wiring [16,19].

3.3. Solar Photovoltaics (PVs)

Solar PV systems convert sunlight directly into electricity using semiconductor materials. Silicon-based PV panels are the dominant technology among PVs. They rely on large quantities of silicon metal, used for cell manufacturing, but also on copper and silver for the electrical contacts. Although silicon is quite abundant, it is considered critical due to its growing economic importance in the electronics industry. Emerging PV technologies such as thin films use gallium as alloys (copper indium gallium diselenide cells) [16,17,19].

3.4. Hydrogen Fuel Cells and Electrolyzers

Hydrogen-based fuel cells generate electricity exploiting the chemical reaction between hydrogen and oxygen to produce water. On the opposite, hydrogen electrolyzers use electricity to break the chemical bond between hydrogen and oxygen in water molecules with the aim of obtaining hydrogen. PGM, mainly platinum and palladium, are used as catalysts in proton-exchange membrane fuel cells, while polymer electrolyte membrane electrolyzers commonly contain platinum in cathodes and iridium in anodes [14,20]. Additionally, nickel is commonly included in electrodes for solid oxide fuel cells [15,16,21].

3.5. Superconductors

Superconductors are used in power grids to transfer electricity with minimal energy loss, which is essential for efficient energy distribution. However, they depend on rare earth elements, mainly yttrium and neodymium, commonly used in high-temperature superconductors to improve their performance [22].

3.6. Electricity Networks (Power Transmission and Distribution Systems)

Power lines transport and distribute electricity from generations to final consumers, involving a complex network of transformers, substations, and lines. As is commonly known, copper is extensively used in wiring and electrical connections due to its excellent conductivity.

4. Methodology

The literature review illustrated in this paper was performed according to the commonly adopted scientific approach described by the following steps [23]:

1. Formulate the questions addressed in this review.
2. Describe the methods to find and select the best of the research relevant to answer those questions.
3. Identify the methods to compare and synthesize the disparate studies found.

4.1. Question Addressed in the Review

Regarding the first step, this review aims to discuss the existing approaches to assess the CRM content in energy technologies. Furthermore, if some research gaps can be clearly identified, the authors aim to highlight these gaps and propose a method to overcome the current barriers.

4.2. Methods to Find and Select the Research

The research relevant to address the aspects discussed in the previous section was performed consulting two main generic databases, Scopus and Google Scholar, and two publisher-specific databases, IEEE Xplore and MDPI. These databases were selected since they are commonly considered among the most comprehensive and reliable in scientific studies. The investigation was performed in the third quarter of 2024 combining the following keywords: critical raw materials, energy planning, energy transition, risk, supply chain, and sustainable development. Furthermore, in order to expand the number of documents collected, their references were also investigated. The analysis focused on any kind of literature studies, including journal articles, conference papers, books or book chapters, and technical reports. Nevertheless, since the specific topic of this review has been addressed only recently by academics, the final set of studies is limited and is actually composed of 13 documents, recapped in Table 2.

Table 2. List of documents analyzed for this review paper with their main details.

Ref.	Year	Study Focus	Technology/Sector	CRMs/Materials Assessed
[24]	2014	CRM consumption estimation for wind energy systems	Wind turbines (onshore and offshore)	13 materials from CRM 2023 list
[25]	2015	Comparison of CRM content in different wind turbine technologies	Gearbox vs. direct-drive wind turbines	Neodymium, dysprosium, copper, strontium
[26]	2017	Material flows for multi-terawatt PV installations	Photovoltaics	Silicon, gallium
[27]	2019	Lithium market assessment in the energy transition	Electric vehicles	Lithium
[28]	2020	Optimal design under fossil fuel scarcity	Multi-energy systems	No direct CRM focus
[29]	2024	Energy hub optimization with hydrogen integration	Multi-energy systems	CRMs mentioned but not assessed
[30]	2024	CRM demand assessment for achieving climate targets	Energy system model (TIMES-VTT)	7 materials from CRM 2023 list
[31]	2022	Economic approach to optimal energy transition under mineral scarcity	General energy transition	No specific CRM mentioned
[4]	2023	Ranking CRMs using Euclidean distance	CRMs	All
[17]	2021	CRM indicators for energy system modeling	Wind and photovoltaic systems	8 materials from CRM 2023 list
[32]	2024	Security of energy systems based on CRM content	General energy systems	4 materials from CRM 2023 list + REE
[33]	2022	Comparative assessment of energy technologies	Renewable and non-renewable systems	30 materials from CRM 2020 list

4.3. Compare and Synthesize the Studies

The studies included in the final set of this bibliometric research may be categorized according to the following criteria:

1. CRM content assessment in specific energy technologies.
2. Optimal long-term planning/design studies on a regional/national scale considering CRMs.

3. Development of indicators for CRM content in energy technologies.

The final set of research studies was analyzed and compared with the others belonging to the same category. The comparison allowed for identifying common trends and research gaps.

5. Literature Review

In this section, the studies subject to review were collected and compared according to their category, highlighting research trends and gaps with respect to the main topic of this literature review.

5.1. CRM Content Assessment in Specific Energy Technologies

In this category of studies, the authors focused on assessing, for specific technologies, the quantity of precious materials, most of them being CRMs. The most notable examples are described here below.

In [24], current and future critical and valuable materials consumption in EU27 for wind energy systems were estimated based on the wind energy production scenarios and roadmap by country. The analysis was based on 13 materials, most of them being in the CRM 2023 list, comparing turbines with different rated sizes and distinguishing between onshore and offshore technologies, according to the bill of materials gathered from the Ecoinvent database.

A similar analysis was performed by Habib and Wenzel in [25], focusing on two different wind turbine technologies (gearbox against direct drive) rather than on the rated size and comparing the content of five raw materials, including two rare earth elements, namely neodymium and dysprosium, and two metals, copper and strontium, all of them being CRMs.

Davidsson and Höök, in [26], investigated the growth rates and material flows required to sustain long-term strategies on multi-terawatt photovoltaics installations, focusing on seven raw materials, including the CRMs silicon and gallium.

Although the studies belonging to this category assess and highlight the relevance of the criticality of some raw materials, they disregard including these considerations in energy systems modeling or planning. Furthermore, the references for the CRM content usually are manufacturer-confidential data, making this information hard to compare with other databases.

5.2. Optimal Long-Term Planning Studies

In this category of studies, the authors developed energy system models to assess final demands or installation of renewables according to national targets. The most notable examples are described here below.

Hache et al., in [27], propose a decision-making tool for assessing the future raw material market in the context of energy transition with particular attention to the electric vehicles market and lithium supply. A Times Integrated Assessment Model (TIAM-IFPEN) for the transportation sector was considered for the modeling, including a projection on the growth of lithium demand in the year 2030 for each vehicle category (it is not explicitly stated how the authors estimated the lithium content). This assessment model is constrained by the lithium supply, based on the extraction data from 2017. The interactions between the widespread of electric vehicles and the lithium supply were analyzed. The lithium sector and a detailed representation of the transportation sector were then implemented into the TIAM-IFPEN processes constituting the global energy system. Energy supply, demand, and market dynamics were modeled in order to represent energy dynamics over a long-term, multi-period time horizon at the local, national, multi-regional, or global level.

In [28], an optimal design under fossil fuel scarcity was considered. The authors formulated the problem considering the uncertainty about fossil fuel provision in a geographical island. Although this study does not deal with CRMs, a similar approach might be used for optimal energy planning considering strategic dependencies and critical raw materials scarcity. The study developed a copula-based interval full-infinite programming method for a multi-energy complementary power generation system under multiple uncertainties. According to the authors, this method has the following advantages with respect to the existing literature: (a) deals with different forms of uncertainty such as probability distribution or crisp interval values; (b) handles the joint distribution of any edge distribution; and (c) model the dynamic features of the system.

Massaro et al. [29] developed a multi-carrier multi-component energy hub optimization model to simulate regional-scale energy systems based on the inclusion of hydrogen as an energy carrier for electricity storage or mobility. The study includes several final demands, such as electricity, high- and low-temperature heating, cooling, freshwater, natural gas, and hydrogen, all of them being assessed under uncertain conditions through a probability distribution function. Furthermore, the inclusion of renewable energy systems was also included in the study, assessing the availability of solar radiation under uncertain conditions. Although CRMs are mentioned in the study, no objective function or constraint was included in the mathematical model.

In [30], the authors describe the use of the TIMES-VTT IAM energy system model to assess the demand for critical minerals and metals (including several CRMs) under the assumption of attaining the 1.5–2.0 °C mitigation targets. Their results show how the availability of cobalt and dysprosium for battery manufacturing might result in a constraint for the energy transition.

Lastly, Pommeret et al. address the problem of optimal energy transition under mineral scarcity from an economic point of view, focusing on climate policies but disregarding explicit references to any specific energy technology [31].

This category of studies is quite heterogeneous, both in terms of objective functions, i.e., the target of the optimization, and in terms of the variables to be evaluated. Nevertheless, the approaches here appear promising for an integrated optimization model for long-term energy systems planning aimed at reducing critical raw materials supply. Regarding the treatment of CRM content, these studies generically base their simulations on projections on technologies installation or on economic optimizations and then use average data from the literature on the CRMs' intensity (kg/MW) for the various technologies resulting from the simulations [15,19].

5.3. Indicators for CRM Content

A part of the literature is also focused on identifying an indicator for comparing technologies based on the content of CRMs. This kind of study starts from the calculation method developed by the European Commission to assess whether a raw material is critical, involving two main indicators named "economic importance" (EI) and "supply risk" (SR), both of them ranging between 0 and 10. According to the current methodology, these indicators are evaluated for several candidate raw materials (54 in 2014, 78 in 2017, 83 in 2020, and 87 in 2023 [34]), and an arbitrary threshold was set for these two indicators. Starting from 2017, a raw material is critical when $EI \geq 2.8$ and $SR \geq 1$ [35]. Nevertheless, according to this method, there is no material that is "more critical" than another, although a quantitative value is assigned to both indicators. This aspect makes it difficult to compare CRMs among them with the aim of selecting a technology with a "low criticality" index.

For these reasons, the authors in [4] combined the two indicators EI and SR using the Euclidean distance method, suggesting that other methods might also be used in future studies. In this way, a ranking of the first five more critical CRMs was presented in the study. Furthermore, the authors noticed that the overall criticality of CRMs increased from 2017 to 2020 and from 2020 to 2023.

Using a different approach, Talens Peiró et al. proposed using a combination of the four indicators easily usable in energy systems modeling as a support to decision-makers [17]. These indicators combine the approach used by the European Commission in terms of supply risk with more classical data from the Life Cycle Assessment (LCA) method. In detail, the set of indicators chosen by the authors is made up of (a) Global Warming Potential, indicating the equivalent carbon emissions over the lifecycle, (b) the Cumulative Energy Demand, quantifying the equivalent use of energy resources over the lifecycle, (c) the supply risk, and (d) the EOL-RIR rate, indicating the percentage rate of recyclability of the raw materials. The study also employs these indicators to compare four wind turbine technologies and four photovoltaic technologies.

Vai et al., in [32], assess the security of energy systems in terms of CRM content and evaluate seven indicators. These indicators calculate the supply risk and the reliability of the energy system both in terms of technology capacity and technology activity. Nevertheless, due to the high number of indicators, the authors are forced to aggregate these indicators in a synthetic index in order to compare the results.

Martin et al. also assessed supply risk together with other indicators for energy technologies, comparing the performance of several renewable and non-renewable electricity production systems [33].

These studies provide significant results in terms of comparison and ranking among CRMs, helping in the development of a methodology for identifying an energy technology mix with a low content of CRMs. As a critical comment, on the one hand, with reference to [17], it is evident that the economic aspects cannot be disregarded in energy systems modeling and planning. On the other hand, with reference to [32], the use of a limited set of indicators is recommended since the use of many indicators causes two well-known issues in the literature on multi-criteria analysis: (a) the risk that each material can outperform the others according to one criterion, thus making all the candidates good and, consequently (b) the aggregation of the indicators in an index, causing loss of precious details and information related to the main indicators.

6. Discussion

According to the main approaches illustrated in the previous section, in order to develop a method to plan a technology mix in regional or national energy systems using an optimization model, the following main criteria should be considered:

1. Regarding the quantification of CRM content in each technology, the bill of materials might be gathered from reliable sources provided by third parties such as IEA reports [15] or life cycle inventory (LCI) databases, as already performed in [33,36]. On this topic, there are several existing LCI databases such as Ecoinvent [37], the Environmental Footprint (EF) database of the European Commission [38], and EXIOBASE [39]. The most common LCI database, Ecoinvent, covers more than 20,000 datasets for various processes. These datasets contain the inputs (and outputs) of the products/processes, including the raw materials used for energy technologies. According to a recent announcement on their website, the next version of Ecoinvent will update several datasets related to energy and power system planning such as the consumption mix of crude oil petroleum, methane emissions from coal mining, new electricity mixes, Li-ion chemistries, Na-ion electrolytes, and new data on metals [40]. While Ecoinvent provides global data, the EF database focuses on EU products and processes, for example, the Product Environmental Footprint (PEF) data for some representative

products and the organizational environmental footprint [41].

The first two databases consider the technologies in detail from a bottom-up approach, i.e., the materials, energy, and other inputs to manufacture the technologies, and the emissions and other outputs being originated from these processes. In contrast, EXIOBASE is an example of an LCI database considering the whole economy from the top-down approach. This database estimates the emissions, materials, and resource extraction (including 662 materials and resources) by industries at the global scale [42]. Although it is not suitable for the optimization of one sector, it is useful to simultaneously examine several energy production and consumption sectors such as transportation, electric power, chemistry, etc. In addition, it will be interesting to combine several databases to obtain the most effective results.

2. Regarding the selection of CRMs, a preliminary ranking among the materials should be introduced in order to focus on the most critical raw materials and technologies.
3. Regarding energy system modeling, a comprehensive multi-carrier, multi-component model should be developed, including reliable methods to assess the uncertainty related to the various aspects of real systems.
4. Regarding the comparison among different technologies, a proper list of indicators should be selected, including economic, energy, and environmental aspects together with a CRM assessment, limiting the list to no more than four or five indicators to avoid the need for aggregation in synthetic indexes. Additionally, since both EI and SR are concerned with macroeconomic aspects, the CRM content might be limited using constraints.
5. Regarding the inclusion of a specific technology, since there exist several options for each category of technology (e.g., silicon-based or copper indium gallium diselenide cells for photovoltaic systems), a preliminary comparison might be introduced.
6. Regarding the size of the energy system, to properly consider macroeconomic aspects deriving from the selection of a specific material/technology, a regional or national scale should be selected. Nevertheless, this should also be accompanied by further analyses such as consequential LCA studies.

The integration of such methodologies into the energy system planning model could greatly increase awareness about critical raw materials provision and supply chain vulnerabilities and guide policies that maximize the compatibility between resource availability and decarbonization goals achievement. The following Figure 2 provides a recap of the main findings discussed in this section.

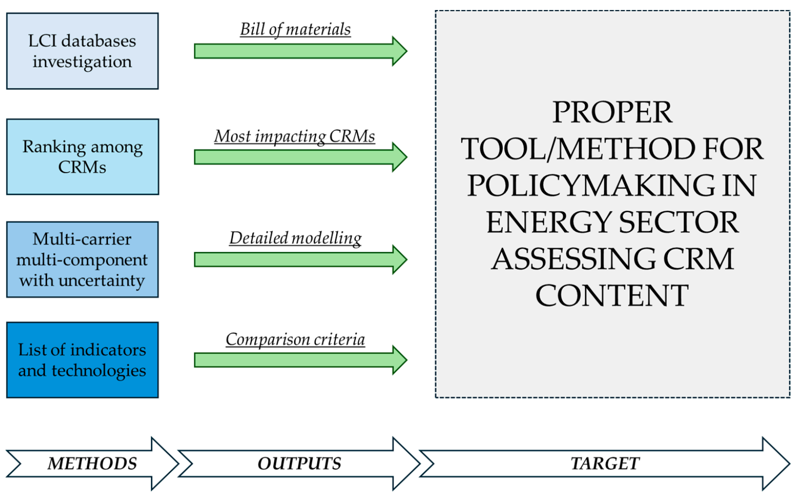

Figure 2. Flow diagram of the proposed methodology.

7. Conclusions

This paper illustrates the most common approaches adopted in the existing scientific literature about the CRM content in energy technologies. First, an overview of the most common CRMs employed in the energy sector was provided, followed by a description of the technologies mostly impacted by the CRMs' supply risks. Subsequently, the main criteria adopted for the present review study were illustrated, and the analysis of the available literature according to categories was presented, identifying main ideas and research gaps. In the discussion section, the authors summed up the considerations emerging from the literature review and proposed an integrated approach for the optimal planning of large-scale energy systems considering the CRM supply risk as a constraint for the optimization problem.

According to the outcomes of this review study, we further recap some recommendations for the policymakers to include a CRM assessment in energy system planning. In detail, assessing CRMs in energy technology policies will support the sustainable development of the energy system and ensure regional and national energy security, with considerations of material shortage, as well as the long-term economic feasibility of the system. At the same time, it is necessary to link the energy system planning of a country to those of its energy or input supply partners. The transboundary energy system will partly tackle the problem of material shortage, especially the limited deposits of critical raw materials. For energy practitioners, it is suggested that the traditional research, development, innovation, and investment in the supply–demand balance of energy systems need to extend to include several factors of environmental aspects such as carbon footprints and critical raw materials. These factors not only impact the environmental profile but also contribute to the economic sustainability of the energy projects through carbon credits and the investment costs of energy technologies.

Future research should focus on developing proper indicators or indexes and collecting data for the comparison of energy technologies in terms of their CRM content without disregarding more common approaches such as cost reduction, primary energy saving, and carbon emissions abatement, useful also to help develop advanced tools for assisting policymakers in making proper aware decisions.

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Abbreviations

Abbreviation	Meaning
BESS	Battery energy storage system
CRM	Critical raw material
DRC	Democratic Republic of Congo
EI	Economic importance
EF	Environmental footprint
EU	European Union

LCA	Life Cycle Assessment
LCI	Life cycle inventory
PEF	Product Environmental Footprint
PGMs	Platinum group metals
REEs	Rare earth elements
SR	Supply risk
SRM	Strategic raw material

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