Critical Materials for Climate Technologies in the EU

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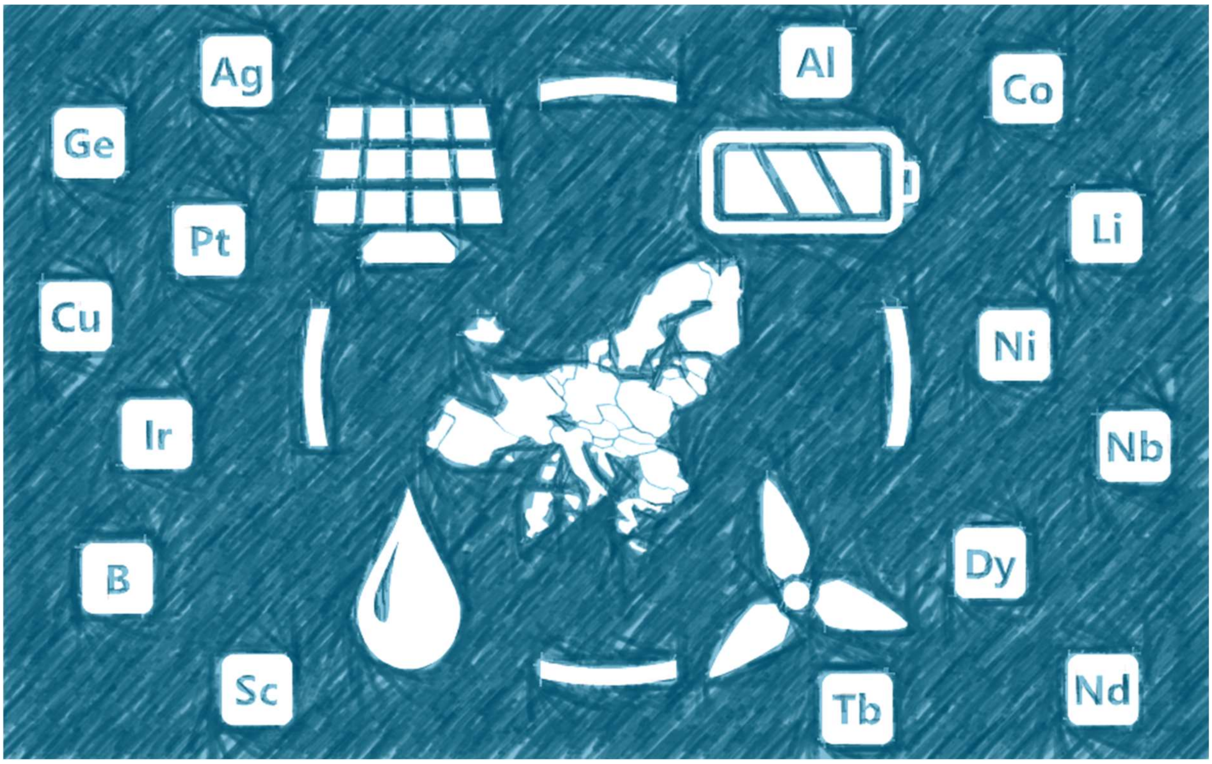
Abstract

Against the backdrop of the climate crisis, countries worldwide agreed in the Paris agreement to keep global warming below 2°C compared to the pre-industrial era, ideally below 1.5°C. The EU set out the goal to reach carbon neutrality by 2050 - a goal for which the energy sector will play a central role, as the production and use of energy is responsible for more than 75% of greenhouse gas emissions. To transition to low carbon energy production, photovoltaic and wind turbines, coupled with energy conversion technologies such as electrolysers, fuel cells, and batteries, are believed to be key solutions. But these technologies require substantial amounts of scarce raw materials with EU import dependency and environmental and social problems connected to extraction and refining. The vulnerability of the EU energy sector became apparent in 2022 at the example of its dependency on Russian oil and gas. The supply chain for clean energy technologies could be equally vulnerable and jeopardise the achievement of EU climate targets.

A plethora of studies dealing with resource scarcity has been performed. These studies, however, differ in their results regarding the most critical materials and often only provide vague recommendations on how to increase the resilience of the production and supply chains. Hence, it is of interest to synthesize the findings of major studies from renowned institutions, identify commonalities as well as differences, filter out areas with need for immediate action and create an overview of critical materials in climate technologies.



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Critical Materials for Climate Technologies in the EU

An overview of five renowned studies

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Background

Against the backdrop of the climate crisis, countries worldwide agreed in the Paris agreement to keep global warming below 2°C compared to the pre-industrial era, ideally below 1.5°C (UNFCCC 2015). The EU set out the goal to reach carbon neutrality by 2050 (European Commission 2019) - a goal for which the energy sector will play a central role, as the production and use of energy is responsible for more than 75% of greenhouse gas emissions (European Commission 2019). To transition to low carbon energy production, photovoltaic and wind turbines, coupled with energy conversion technologies such as electrolysers, fuel cells, and batteries, are believed to be key solutions. But these technologies require substantial amounts of scarce raw materials with EU import dependency and environmental and social problems connected to extraction and refining (Sovacool et al. 2020). The vulnerability of the EU energy sector became apparent in 2022 at the example of its dependency on Russian oil and gas. The supply chain for clean energy technologies could be equally vulnerable and jeopardise the achievement of EU climate targets.

A plethora of studies dealing with resource scarcity has been performed. These studies, however, differ in their results regarding the most critical materials and often only provide vague recommendations on how to increase the resilience of the production and supply chains. Hence, it is of interest to synthesize the findings of major studies from renowned institutions, identify commonalities as well as differences, filter out areas with need for immediate action and create an overview of critical materials in climate technologies.

Usage of the term *criticality*

We follow the definition of *criticality* (or *raw material criticality*) as "the field of study that evaluates the economic and technical dependency on a certain material, as well as the probability of supply disruptions, for a defined stakeholder group within a certain time frame" (Schrijvers et al. 2020). Therefore, we define *critical materials* as those on which the EU is highly economically and technically dependent, associated with a high risk of supply disruptions. In order to combine different studies using different terminologies and metrics, we follow a broad and to some extent qualitative understanding of *criticality*.

Analysis of renowned studies

Scope and approach

To gain insight into the critical materials for climate technologies, five renowned studies were selected and analysed. These studies were selected because they are recent, provide an in-depth analysis on the supply and demand situation of materials relevant to climate technologies, have been published by reputable institutions and are publicly available. These studies have not been published in scientific journals due to their length and level of detail (40 to 350 pages each), so they are unlikely to have undergone a formal peer review process. However, each study contains detailed information on the study design and results.

- **Study 1:** Critical Raw Materials for Strategic Technologies and Sectors in the EU (Bobba et al. 2020) conducted by the JRC.
- **Study 2:** Raw materials for emerging technologies 2021 (Marscheider-Weidemann et al. 2021) conducted by Fraunhofer ISI and IZM (commissioned by DERA).

- **Study 3:** Metals for Clean Energy: Pathways to solving Europe's raw material challenge (Liesbet Gregoir et al. 2022) conducted by KU Leuven (commissioned by Eurometaux).
- **Study 4:** The Role of Critical Minerals in Clean Energy Transition (IEA 2021) conducted by IEA.
- **Study 5:** Critical Materials for the Energy Transition (Gielen 2021) conducted by IRENA.

The analysis is intended as a short summary focussing on the following points: the authors and funding authorities, the methodological design, the scope of the technologies and materials analysed, the results, and the recommendations. We focus on four technologies that are critical for the decarbonisation of society: wind turbines, solar photovoltaic, traction batteries and electrolysers and fuel cells. Why those technologies? For low-carbon power generation, **wind turbines** and **solar photovoltaic** are key technologies and substantial volumes will be build up in the coming decades (IEA 2021). For the decarbonisation of the transport sector and especially passenger vehicles, **batteries** are crucial, but require substantial amounts of critical raw materials such as lithium, cobalt and graphite (IEA 2021). Hydrogen is needed as an energy carrier for reducing emissions in heavy industry, heavy duty road transport and shipping, and requires e.g. nickel and zirconium for **electrolysers** and platinum-group metals for **fuel cells** (IEA 2022).

After the brief description of each study according to the described criteria, we form a synthesis with an overview of all the assessed materials and their criticality classification according to the respective study.

Study 1 Critical Raw Materials for Strategic Technologies and Sectors in the EU

The first analysed study bears the title "Critical Raw Materials for Strategic Technologies and Sectors in the EU – A Foresight Study" (Bobba et al. 2020), created by the Joint Research Centre (JRC) of the European Commission in 2020. The 100-page long document has a global focus regarding the material demand and supply, and a European focus regarding the recommendations. To analyse necessary materials, the study distinguishes technologies and sectors. The eight technologies are Li-Ion batteries, wind energy, solar energy, fuel cells, robotics, electric traction motors, drones, and 3-D printing. The four sectors are renewable energies, e-mobility, defence, and aerospace.

In order to analyse the critical material requirements for the sectors and technologies, demand forecasts for 2030 and 2050 are made in combination with a low, middle and high demand scenario. The low and middle demand scenarios are in line with the EU Long-Term Strategy – "A Clean Planet for All" and the increase in material demand uses the EU's current consumption of materials as the baseline.

The supply chains of the technologies are divided into four process steps: raw materials, processed materials, components, and assembly. Each process step is evaluated regarding its risk potential for the EU supply chain. To evaluate the risk potential, six parameters are used: the global supply risk, the European production, material status regarding its level of criticality in the critical raw material list of the EU, import reliance, substitution and finally recycling.

The study finds that all process steps of Li-Ion batteries, robotics, electric traction motors, drones and solar energy are of at least moderate risk. Merely some process steps of fuel cells (processed materials and components), wind energy (assembly) and 3D-printing (processed materials) are of low to very low risk. The materials that are the most critical for the mentioned technologies are borate, cobalt, dysprosium, germanium, graphite, magnesium, neodymium, niobium, platinum, praseodymium, scandium, strontium, terbium, and yttrium.

The recommendations to prevent upcoming supply chain shortages are of general nature. The authors suggest for instance to increase the regional production capacities for the raw materials, processed materials, and assembly processes in combination with a higher recycling rate to cover part of the demand through secondary materials.

Link to study 1: Critical Raw Materials for Strategic Technologies and Sectors in the EU 2020

Study 2 Raw Materials for Emerging Technologies 2021

The study "Raw materials for emerging technologies 2021", published in August 2021, was commissioned by the German Mineral Resources Agency (DERA) at the Federal Institute for Geosciences and Natural Resources (BGR) and conducted by researchers from the Fraunhofer Institute for Systems and Innovation Research ISI and the Fraunhofer Institute for Reliability and Microintegration IZM (Marscheider-Weidemann et al. 2021).

The 350-page document is part of the DERA raw material monitoring that regularly assesses potentially critical raw materials that are needed for key and emerging technologies. Despite being commissioned by a German institution, the study uses global scenarios for technology development and material demands, utilising scenarios from the Shared Socioeconomic Pathways (5^{th} Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)), extended by other sources for sectors or technologies where information is missing in the IPCC scenarios.

By analysing 33 technologies (including the main climate technologies wind turbines, photovoltaic, electrolysis, fuel cells, batteries, electric motors and power grid) the authors compare the demand projections of 18 potentially critical materials for three distinct scenario pathways (sustainability, middle of the road, fossil-fuelled development) until 2040 against the primary production of each material in 2018 (the study does not include scenarios on future material production).

Materials with direct application in climate technologies for which future demand greatly exceeds current production are scandium (fuel cell, electrolysis), lithium and cobalt (batteries), iridium (electrolysis) and the rare earth metals dysprosium, terbium, neodymium, praseodymium (for electric motors and wind turbines).

The goal of the study is not to provide recommendations to reduce criticality of individual materials. For the technologies, material substitution potential and status quo of recycling are provided, but no long-term strategies to reduce criticality of a certain material is given.

Link to study 2: Raw materials for emerging technologies 2021

Study 3 Metals for Clean Energy

The study “Metals for Clean Energy: Pathways to solving Europe’s raw material challenge” (Liesbet Gregoir et al. 2022), published in April 2022 was commissioned by Eurometaux, the European non-ferrous metals association, and conducted by researchers of KU Leuven. The 117-page document has a global as well as European focus. Eleven clean energy technologies are considered in the study: solar photovoltaic, onshore-, and offshore wind, concentrating solar power, hydro, geothermal, biomass, nuclear power, electricity networks, battery storage, electric vehicles, electrolysers, and fuel cells. The reference scenario for upcoming resource consumption is the sustainable development scenario, which is in line with the Paris Agreement.

The process steps in focus are the mining and refining stage of the materials, and for each step the production capacities as well as the demand are shown. There is, however, no comparison between demand and supply to identify the actual material gaps. Results show that the transition from fossil fuels to renewable energies is highly material intensive. The main drivers are the electric vehicle production with 50-60% of the overall increase in material demand, followed by electricity networks, and photovoltaic production, which are responsible for 35-45%. The other technologies combined are responsible for the remaining 5%.

The materials that are most impacted by the energy transition will see the strongest demand growth. Those are the higher volume materials lithium, cobalt, nickel, rare earth elements and copper and the lower volume materials iridium, scandium, and tellurium. The main solution strategies that are presented are the extension of domestic value chains of the key technologies and the increase of the crucial material's recycling rates.

Link to study 3: Metals for Clean Energy: Pathways to solving Europe's raw materials challenge

Study 4 The Role of Critical Minerals in Clean Energy Transition

The study "The Role of Critical Minerals in Clean Energy Transition", was published in May 2021 (revised in March 2022) by the International Energy Agency (IEA) (IEA 2021) as a part of the World Energy Outlook.

The 287-page study is based on the IEA Sustainable Development Scenario (SDS) and the Stated Policies Scenario (STEPS) and calculates global demand from 2020 to 2040. The analysis includes the technologies solar photovoltaic, wind power (onshore and offshore), concentrating solar power, hydro, geothermal, biomass, nuclear power, electricity networks, electric vehicles, battery storage and hydrogen (electrolysers and fuel cells).

The focus materials of the study are cobalt, copper, lithium, nickel, and rare earths elements (neodymium, dysprosium, praseodymium, terbium, and others), all of which show a strong increase in demand until 2040. Fewer information is provided on the potential supply for each material, however, supply chain risks are identified. A large share of the material mining and refining activities is geographically concentrated in only a few countries, recycling rates of many materials (e.g. lithium or rare earth elements) are still low, material market prices are fluctuating, and mining projects show long project development times.

Based on their literature review, as well as expert and industry consultations including IEA Technology Collaboration Programmes, the authors provide several recommendations to improve supply chain resilience, including material substitution or reduction through technology innovation, scale-up of recycling, and clear signals of policy makers towards the climate goals to provide confidence of industry actors into long-term investments.

Link to study 4: The Role of Critical Minerals in Clean Energy Transition

Study 5 Critical Materials for the Energy Transition

The study "Critical Materials for the Energy Transition", published in May 2021, was conducted by the International Renewable Energy Agency (IRENA) (Gielen 2021).

In the 43-pages document, the authors make global demand projections from 2020-2050 based on the IRENA World Energy Transitions Outlook 1.5°C Pathway, and the study concentrates on the materials cobalt, copper, nickel, lithium, and the rare earth elements neodymium and dysprosium - all of which are considered critical due to supply risks. For five specific applications (EV batteries, permanent magnets for wind turbines, photovoltaic, permanent magnets for electric vehicles and the electricity grid), state-of-the-art, expected development and substitution potentials are examined.

The study suggests that future scarcity problems can be avoided with the right policy frameworks and design decisions today. Several mitigation strategies are proposed, including the diversification of supply, developing national production routes of the materials, substituting the critical materials, developing stockpiles, increasing material efficiency, increasing recycling (for long-term resilience, not for build-up of material stocks), and enhancing international governance for critical materials.

Link to study 5: Critical Materials for the Energy Transition

Synthesis

The five studies vary greatly in their scope (inclusion of technologies and materials). However, there are findings that are shared throughout all analyses. Table 1 provides an overview about the materials that are covered in the studies and their criticality assessment. Materials are excluded that are covered in the studies but are not used in the four focus technologies.

There is commonality in rating the battery materials cobalt and lithium as highly critical, and to a lesser extent copper and nickel. Rare earth elements are not in the scope of each of the studies, but for those that consider them the elements dysprosium, neodymium, praseodymium, and terbium are classified as highly critical (used in electric motors and wind turbines). Materials needed for solar photovoltaic (e.g. gallium, indium, silicon, and silver) are either not considered in the analysis or are classified as not highly critical. For the hydrogen technologies electrolyser & fuel cells, cobalt, iridium, lithium, scandium, and yttrium are the most critical materials.

There are differences in study results for copper and yttrium. Copper is needed across technologies and thus has a high economic importance, but the EU estimates its supply risk as low (Blengini et al. 2020). If only the need of climate technologies is analysed, then current global supply of copper would meet the future demand (Marscheider-Weidemann et al. 2021), but a whole market analysis might provide different results. The IEA study includes an analysis of current mining sites, and states that "mines currently in operation are nearing their peak due to declining ore quality and reserves exhaustion" and that "mines in South America and Australia are exposed to high levels of climate and water stress" (IEA 2021). Yttrium is only considered in two of the assessed studies, and our categorisation of study 2 results as not critical for this material is only based on the fact that the estimated demand for climate technologies will not exceed the current supply.

Nickel and copper have a special role since they have cross-technology character, needed in high quantities throughout several of the technologies. While for a single sector or technology, global demand is much higher than demand, due to the large demand throughout industry sectors material criticality is nonetheless an issue.

Despite different study design and background assumptions, the results of the studies are comparable. Batteries could be described as the most critical technology, due to the high criticality of cobalt and lithium and the usage of the critical cross-technology materials nickel and copper. Wind power is equally a focus area due to the rare earth elements - which are also needed for some types of electric motors in electric vehicles. Thus, the mobility sector can be understood as the key sector for material criticality and potential shortages. Electrolysers and fuel cells can contain to some degree critical elements but are still low in number and more technological (and material) change is happening compared to the other more mature technologies. Solar PV is expected to see strong growth in the coming decades, but the materials needed are the least critical compared to the other technologies.

The assessed studies either do not provide any solution strategies to reduce supply risks or they are of generic character (not supply chain or material specific), e.g. referring to material substitution, increased recycling, or the build-up of domestic material production. It is however crucial to give precise recommendations both on the supply chain level and on the process/technological level. The supply chains of individual materials must be analysed to give clear instructions on how to improve the supply chain’s resilience by diversification or by a ramp-up of local production and refining capacities. The process steps of individual materials need to be evaluated regarding the possibilities of reducing the necessary material amounts for a certain technology and regarding possible improvements in recycling rates.

Table 1: Critical materials for climate technologies

LEGEND
- 1 = Criticality group 1
- 2 = Criticality group 2
- 3 = Criticality group 3
- (empty) = Outside study scope

	Technology application				Criticality[i]				
	Wind turbine	Solar PV	Electrolyser / Fuel cell	Battery	Study 1	Study 2	Study 3	Study 4	Study 5
Aluminium	X	X	X	X	3				
Borates	X	X	X		1				
Cadmium		X			3				
Chromium	X		X		3				
Cobalt	X		X	X	2	1	1	1	1
Copper	X	X	X	X	3	3	1	1	1
Dysprosium	X				1	1	1	1	1
Gallium		X			3	3			
Germanium		X			1	1			
Graphite			X	X	2	3			
Indium		X			3	3			
Iridium			X			1	1		
Lanthanum			X	X		2			
Lithium			X	X	2	1	1	1	1
Magnesium			X		1				
Manganese	X			X	3				
Molybdenum	X				3				
Neodymium	X					1	1	1	1
Nickel	X		X	X	3		1	1	1
Niobium	X			X	1				
Platinum			X		2	2			
Praseodymium	X					1	1		
Rhenium						3			
Ruthenium						1			
Scandium			X		1	1	1		
Silicon		X			3				
Silver		X	X		3				
Strontium			X		2				
Tantalum						1			
Tellurium					3				
Terbium	X					1	1	1	
Titanium			X	X	3	3			
Vanadium			X	X	3	3			
Yttrium			X		1	3			
Zinc	X				3				
Zirconium			X		3				

[i] Since all of the assessed studies use different classifications for the evaluation of material criticality, we defined our own criticality scale and converted the results of the assessed studies into our metric. According to the likelihood that future demand exceeds supply, we classify materials into criticality group 1 (high supply risk), criticality group 2 (moderate supply risk), and criticality group 3 (low or no supply risk). Information on the conversion of the assessed studies into our metric is provided hereafter.

- Study 1: (EU JRC) We classify materials for which the materials are of very high and high supply risk according to the six evaluation parameters in the study as criticality group 1. A moderate supply risk is referred to as criticality group 2. Low and very low supply risk are referred to as criticality group 3.
- Study 2: (DERA) We classify materials for which demand for both the sustainability and middle of the road scenario exceeds the 2018 production as criticality group 1, materials where for only one of the two scenarios demand exceeds production as criticality group 2, and those where none of the two scenarios exceed the 2018 production as criticality group 3.
- Study 3: (KU Leuven) The classification for the criticality groups depends on the increase in demand. Materials with the highest acceleration in demand increase are in criticality group 1. This leads to all materials being in criticality group 1.
- Study 4: (IEA) Expected production only provided for three materials (cobalt, copper, lithium). No classification of materials into criticality classes provided. We classify the focus minerals of the study as criticality group 1.
- Study 5: (IRENA) All materials under consideration are classified in criticality group 1, since 2050 demand exceeds the 2020 supply.

Conclusions

Materials are the backbone of the energy transition. Due to a combination of supply risks and techno-economic importance, the level of criticality differs among them. To ensure the supply of relevant materials, technological and political action must be taken. Based on the discussed studies, we present the following key findings:

1. Breadth and depth of study design differs

The analysis of the five different studies shows varying level of details of the analysis and background assumptions. Main differences in evaluation of criticality levels are attributable to differences in the underlying methodologies. The scopes differ in terms of time, material demand scenarios and assessed technologies. The consideration of cross-technology usage can make a vast difference in the evaluation of material criticality; Materials such as nickel and copper are extremely relevant from a whole market perspective, even if for a single technology global supply greatly exceeds demand.

2. Resilience of EU supply chains for key climate technologies is low

Although the study's underlying methodologies are different, all presented studies agree that there are high risks for EU supply shortages for key climate materials. Especially cobalt and lithium for batteries and rare earths for wind power are highly critical. Materials needed for the uptake of solar photovoltaic are less critical, while the materials needed for electrolysers and fuel cells iridium and scandium could become critical under assumptions of strong hydrogen market expansion. For the materials rated as highly critical, most reserves and large parts of the supply chains are located outside of Europe.

3. Additional technology, material, and supply chain specific research is needed to improve supply chain resilience

The studies identify supply chain gaps or risks, but no in-depth solution strategies are developed to increase resilience; this will have to be done on a technology, material and supply chain specific level, work for which our overview can serve as the basis. Solution strategies that are mentioned are mainly technological, e.g., substitution or reduction of the most critical materials or the increase of recycling rates to partly satisfy the future demand. Besides technological solutions, policy makers and industry actors can support the build-up of domestic mining, processing, and production processes of the climate technologies within the EU.

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