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Critical raw materials for the green energy transition: a comparative analysis of the US and the EU strategies

BY

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Introduction

Human-induced climate change has already led to widespread impacts on ecosystems, people, settlements, and infrastructure. The frequency and intensity of climate and weather extremes -including hot weaves, heavy precipitation, drought, and fire weather-go beyond the natural climate variability (IPCC,2022).

At the 2015 United Nations Climate Change Conference (COP 21) closing, 196 parties signed the first binding agreement for international cooperation on climate change, then defined as the Paris Agreement. It commits all parties to limit global warming to well below 2°C and pursue efforts to limit it to 1.5°C, as breaching these thresholds would prove disastrous for humanity (Climate Council,2022).

With the COP26, held in November 2021 in Glasgow, there has been a rapid and irrevocable turn in global politics and climate actions (Climate Council, 2022). Several developed countries, including the United Kingdom (UK), the European Union (EU), and the United States (US), have updated their nationally determined contributions (NDCs), committing to net zero emissions by 2050 and strengthening their 2030 targets. Despite these new pledges and substantial momentum, there remains a significant shortfall between the ambitions and the pace of the required actions.

In alignment with the IPCC report, limiting global warming to 1,5° C by 2050 demands a 45 percent reduction in greenhouse gas (GHG) emissions by 2030 (compared to the 2015 level). Nevertheless, energy-related carbon dioxide (CO_2) emissions increased by 1.3 percent annually, on average, between 2014 and 2019. Global warming has reached 1°C above preindustrial levels and is rising at approximately 0.2°C per decade (IPCC,2022). The window of opportunity to reach the 2030 milestone defined is small, and the actions taken in the next eight years will determine whether a 1,5°C future remains reachable (IRENA,2022).

Most of the technical solutions required to decarbonize the energy sectors are already available. These involve renewable energy systems, electrification of sectors heavily dependent on fossil fuels (e.g., space heating and transportation), energy efficiency measures, green hydrogen, and bioenergy combined with carbon capture and storage. To ramp up the development of such technologies, they should be made even more competitive through cost reduction, incentives, and innovations. Other prerequisites are targeted policies and measures, including phasing out coal and fuel subsidies, adapting market structures, and investing in social funds for a fair and just transition (IRENA,2022).

As the clean energy transition progress, countries will require to evolve their energy security strategies, moving beyond the unidirectional energy value chain (from generation to consumers) to a more complex decentralized system with more players involved. This evolution will bring challenges such as higher cyber-attack resiliency (through physical and digital infrastructure), adaptability to climate change, and securing a steady supply of critical raw materials (CRMs). The latter requires particular attention since disruption in the supply can directly hamper the progress towards carbon neutrality.

Research Methodology

This master thesis aims to analyze the role of CRMs in the clean energy transition. The research will be performed as a comparative analysis of the strategies adopted by two major forces, the EU and the US. The research question is understanding to what extent the challenges posed by the CRMs supply might hinder the pace of the clean energy transition and, ultimately, the achievement of the net-zero energy goals in these two blocs.

Firstly, the commitments of the EU and the US to the green energy transition are introduced (Chapter I). In this section, the qualitative and quantitative data are primarily extracted from official documents and reports of the European Commission (EC) and the White House. Considering the role of other countries in the current energy scenario, the situation in the rest of the world is also briefly analyzed with data from the Organization for Economic Co-operation and Development (OECD) and the International Energy Agency (IEA). The second chapter analyzes the role of CRMs in the energy transition, analyzing, for some of them, their supply chain and their application in selected technologies. In this chapter, the methodology followed is a qualitative and quantitative analysis with data extracted mainly from the EU assessment of CRMs and the IEA.

The strategies currently adopted by the EU and the US are brought as a case study in Chapter III. The author focuses on the most recent actions by the blocs in the field of

CRMs supply. Therefore, the data collection covers the maximum of the last five years (2017-2022). Considering that energy is a shared competency, the research incorporates the analysis of two member states (MSs): Italy and Germany. The selected countries are net importers of fossil fuels and have adopted a strategy for the green transition which includes the supply of the required CRMs. The primary sources used in this section are official documents from the European and US institutions, such as reports of the European Commission, the German and Italian governments, and the White House with its departments.

In Chapter IV, the current strategies of the EU and the US are analyzed and compared to identify common ground and differences. This section did not provide any new data, but it is developed on the ones already extrapolated in the previous chapters; the discussion is built following a similar methodology to Barteková & Kemp, which compared the global strategies for raw materials back in 2016. Their methodology is updated considering the changed political and energy scenario with a more substantial commitment of countries to the green transition. Finally, the conclusions are drawn, summarizing the main findings of the thesis, and answering the research question. Further recommendations in developing the blocs' policy frameworks are offered based also on the work of the IEA.

Literature review

Definition of critical raw materials

In literature, the definition of CRM is not unique as the methodologies on criticality assessment have evolved in the last years. Most studies follow a standard security assessment addressing the potential risk and vulnerability (e.g., the importance of the specific raw material for the industry, absence of substitutes, or the negative impact on the economy if the raw material is unavailable) in the supply (Hoffman M., 2018).

In the US, the National Research Council (2008) performed one of the first analyses of CRMs. A material was considered critical if it was both important in use and subject to potential supply restriction. Graedel et al. (2016) integrated the analysis by considering the environmental implications and defining the term "critical" for the raw materials that are essential, important, or influencing external factor as the economy, the society, and the environment. The "Amendment of the US Stock Piling Act" (2019) identified as critical any materials "needed to supply the military, industrial, and essential civilian needs of the United States during a national emergency and not found or produced in the United States in sufficient quantities to meet such need." The Energy Act of 2020 definition specifies that the definition of critical applies for "non-fuel mineral or mineral material essential to the economic or national security of the US and which has a supply chain vulnerable to disruption" (US Congress,2020).

In Europe, Angerer et al. (2009) analyzed emerging applications in several industrial sectors to assess raw materials' current and future requirements. They concluded that industries need a reliable supply of technology metals to progress, namely the access to specific metals with science and technology applications. In Europe, the Commission's "Ad-hoc Working Group (WG) on Defining CRMs" established the first methodology for the assessment considering the economic importance and supply risk in 2010. In the analysis, the WG considers several factors such as the socio-economic stability of the producing country, concentration of production, presence of substitute materials, and recycling rate (see Chapter III). According to the current definition provided by the European Commission, CRMs are a set of raw materials which are, at the same time, economically and strategically important for the development of the European economy and associated with a risky supply (European Commission,2021).

Criticality is a complex concept that cannot be unambiguously defined in the literature. Moreover, it should be emphasized that the term "critical" is strongly linked with a specific timeframe and a given economic system: an element can be crucial for one economy and not for others and in short/medium periods but not in the long run (Hoffman M.). This thesis will consider the definition made by the European Commission due to a more consistent and defined research framework. Although the US 2020 Energy Act refers to "critical minerals" and not materials, the framework and definition are similar to the one of the CRMs by the EU (The White House,2022b).

Strategies for the supply of CRMs

In the last years, few scholars have analyzed political raw materials strategies in different countries. Barteková & Kemp (2016) compared how national interests, presence of resources, and historical experience reflect the raw material strategies in different world regions (the US, the EU, China, Japan, and Australia). The authors identified a link between mining and environmental regulation and how the national interests have shaped the policy framework in the mining sector.

Andersson (2020), Biedermann (2018), Shen, Moomy, & Eggert (2020) focused their attention on policies on strategic and critical raw materials in China. In particular, the work of Anderson analyzed how sub-categories of raw materials are subject to different regulations and policies. The author identified circular feedback loops where industrial demand influence raw material assessments and categorization and thus the coordinated policy actions.

The role of competition for raw materials between certain countries was analyzed in the work of Gulley et al. (2018), Schmid (2019), and Vekasi (2019). Gulley et al. focused on the competition between China and the US, identifying eleven minerals as potential sources of competition between the two forces, especially in South Africa, Brazil, and Chile, where these materials are geographically located. Bekasi investigated the geopolitical consequences of the export restriction of rare earth elements (REE) carried out by China against Japan in 2010. The author emphasizes how the decision allows Japan to prioritize the supply of CRMs in the national interest, diversifying its supply and developing international trade agreements beyond the dependency on China. Some scholars also investigated corporate raw material strategies due to their relationship with national policies. (Lapko, Trucco, & Nuur, 2016; Schmid, 2020). Lapko et al. analyzed the different approaches to materials criticality in five EU manufacturing companies emphasizing the importance of companies' vision in the assessment of critically.

The most recent effort in the field comes in the work of Schmidt (2021). The author offers a structured, qualitative analysis of raw materials strategy for Germany, considering the current global political and market development. He emphasized how the German private sector's engagement will be fundamental to securing a stable supply of raw materials.

The author of this thesis is not aware of an up-to-date comparative analysis of raw material strategies that consider the current trends in the global market nor of a study regarding CRMs specifically. This work represents a novelty, providing a structured comparison of two main blocs, the EU and the US, in their commitment to the energy transition.

1. The energy transition: state of play

The World Economic Forum (2020) defines the current energy transition -from fossil fuels to low-carbon technologies- as "*a timely transition towards a more inclusive, sustainable, affordable and secure energy system that provides solutions to global energy-related challenges while creating value for business and society*." In other words, an effective energy transition considers, at the same time, environmental sustainability, energy security, and economic development.

This section will discuss the current commitment of the EU and the US to the energy transition in terms of domestic policies and the international scene. The state of play in the rest of the world is briefly analyzed before discussing the issue of energy security in a changing energy scenario.

1.1. The European Union

The EU is a significant contributor to global emissions. Since the industrial revolution, the EU's MSs (EU-27) have accounted for almost 18 percent of global GHG emissions (Tiseo,2021). Petroleum products still have a significant share of the energy mix in the EU: in 2020, renewable energy accounted for only 17 percent of the total energy production. THE EU is also a net energy importer, producing domestically 42 percent of the total demand (Eurostat,2022) and covering the remaining part with imported fossil fuels (20 percent of global crude oil demand comes from the EU) (ibidem). The commitment of the bloc to the energy transition is defined both domestically and on the international scene.

In the domestic arena, the aim "to be the first climate-neutral continent by becoming a modern, resource-efficient economy" is one of the six priorities for the European Commission for the 2019-2024 period under the presidency of Ursula Von der Leyen. The European Climate Law (Regulation (EU) 2021/1119 amending Regulations (EC) No 401/2009 and (EU) 2018/1999) made the carbon neutrality goal legally binding. The EU Green Deal is the instrument to achieve the target of shaping a "carbon-neutral, fair, and prosperous society with a resource-efficient and competitive economy" (European Commission, 2019). The Climate Law also set a midterm reduction target of GHG emissions of 55 percent by 2030. Achieving this result will require a revised and updated legal framework: the Fit for 55 Package is a set of thirteen proposals (eight reviews of existing legislation and five new initiatives) to align the environmental, energy, and transportation legislation with climate actions. It includes a revision of the Renewable Energy Directive to increase the current EU-level target of at least 32 percent of renewable energy sources (RES) in the overall energy mix to at least 40 percent by 2030 (European Council,2022).

Following the Russian invasion of Ukraine, the EU strengthen its overall energy strategy with the RePower EU, a plan to make Europe independent from Russian importation of natural gas "well before 2030" (European Commission,2022a). REPower EU aims to diversify gas supplies, accelerate the roll-out of renewable gases and replace gas in heating and power generation. Therefore, the action plan can accelerate renewable energy installation in the EU (ibidem).

In the international arena, the EU has been acclaimed as a global frontrunner in climate change, promoting environmental cooperation through bi- and multilateral summits, diplomacy, and creating transnational panels of experts. However, such position has been attained only in the last few years (Torney, 2008). At the COP15, held in Copenhagen in 2009, the EU failed to achieve a binding agreement to tackle climate change as was initially expected before the event. Before the following UN summit, the COP21 held in Paris in 2015, the European External Action Service and the Directorate General (DG) for Climate Action performed extensive preparation, including drafting two joint papers and a climate diplomacy action plan (ibidem). The latter defined the main elements of the diplomacy actions for the upcoming Paris climate summit. On that occasion, all 28 MSs could speak with one voice and advocate for higher ambition in the fight against climate change.

The EU delivered a strong message of ambition: from 1990 to 2014, the EU was able to reduce its emission by 27 percent while, at the same time, growing its economy by 43 percent. This fact resonates at high- and low-level meetings, especially with developed countries that perceive climate action as opposed to economic development. In the negotiation at the COP21, the EU was one of the main actors behind the definition of intended nationally determined contributions.[1] (INDCs) as a binding commitment to emission reduction from developed and least developed countries (LDCs). The EU committed to an ambitious reduction target (40 percent by 2030, then updated to 55 percent) to challenge China and other reluctant countries to do the same (ibidem).

In the recent COP26, held in Glasgow at the end of 2021, the EU strengthened its position in climate diplomacy. Firstly, the EU pledged EUR 23,4 billion (23,4 percent of the total global pledge) to finance climate actions in LDCs and small island developing states (SIDSs). This amount will be paired with an additional EUR 4 billion coming from the multiannual EU budget. Other results include new partnerships for the decarbonization of South Africa and the completion of the Paris Agreement rulebook.[2].

1.2. The United States

The US is the second biggest polluter in the world and ranks 13th as the country with the highest emissions per capita (WPR,2022). In 2019 the US became a net total energy exporter for the first time since 1952. Since 2014, the gross exports of natural gas have increased yearly due to a continuous increase in domestic production and investment in the export of liquified natural gas (EIA,2021). Renewable energy accounts for nearly 20 percent of utility-scale electricity generation in 2020, coming from hydropower (7.3 percent) and wind power (8.4 percent). Renewables (solar photovoltaics and wind turbines) are the fastest-growing energy source in the US, with an increase of 42 percent from 2010 to 2020 (C2ES,2022).

The US is committed to achieving a net-zero emissions economy by 2050. Following the end of negotiations in Paris, the Obama administration drew the first long-term strategy to reduce GHG emissions between 80-90 percent by 2050 (compared to 2005 levels) (The White House,2022a). The following Trump administration (January 2017-2020) decides to withdraw from the Paris Agreement due to an overall skepticism on human responsibilities on climate change. Further climate actions were deprioritized, regulations

[1] A country's INDC becomes a Nationally Determined Contribution (NDC) when it formally joins the Paris Agreement.

[2] The Paris Rulebook defines the details for the operation and monitoring of climate actions for the signatory countries of the Paris Agreement (191 countries). It also contains provisions for developed countries for climate action financing to developing countries.

for climate polluters relaxed, and new investments in the oil industry were financed (Gibbens,2019).

On his first day in the office, President Joe Biden rejoined the Paris Agreement and put the fight against climate change a top priority of his administration. In 2021, a new ambitious goal of net-zero emissions by 2050 was agreed upon. The US long-term strategy was updated to define the macro areas of intervention in the pathways to carbon neutrality. The US also established a 2030 NDC of 50-52 percent reduction below 2005 levels, covering all sectors and gases, and a goal for 100 percent carbon pollution-free electricity by 2035.

The plummeting costs of renewables and enhanced policies have already supported the sector's decarbonization with increased consumer demand for clean and affordable power systems. The process will be further enhanced with the support of incentives and higher environmental standards for power plants, together with continuous research and development (R&D) in the sector. The long-term strategy also provides critical actions for the other sectors mainly contributing to climate change, namely transportation, building efficiency, and industry sectors (The White House,2022a).

On the international scene, the Biden administration is restoring the US's role in climate diplomacy. At the COP26 in Glasgow, the US engaged in intensive diplomacy, bonding new partnerships with countries worldwide. Together with the EU, the US proposed the "Global Methane Pledge," a commitment of more than 100 countries (including six of the world's top10 methane emitters) to reduce methane emissions by at least 30 percent by 2030, eliminating over 0,2°C of warming by 2050 (methane emissions alone accounts 0,5°C increase of the current observed warming of 1°C [3]) (The White House,2021a). Another key result was the President's Emergency Plan for Adaptation and Resilience (PREPARE), the first-ever response to the US to address the increasing impact of the global climate crisis, especially in developing countries. Biden will now work with Congress to provide USD 3 billion in adaptation finance annually for PREPARE by 2024 (ResilienceLinks,2022).

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[3] GHG emissions have contributed 150 percent of the observed warming of 1.0 ºC, but emissions of cooling aerosols have compensated for them.

1.3. Rest of the world

According to the Energy Transition Index[4] 2021, three European countries, Sweden, Norway, and Denmark, are leading the energy transition. Among the world's top 10 economies, only France and the UK appear in the top 10 countries leading the green transition. Considering that such countries represent only 3 percent of the energy-related GHG emissions and 2 percent of the world population, countries with a higher emission per capita and GDP should pursue a more substantial and consistent commitment.

G20 countries account for about 75 percent of global GHG emissions (OECD,2022). Their climate actions can limit global temperature rise at the end of the century to 1,7° C (ibidem). At the COP26, the United Nations Framework Convention on Climate Change (UNFCC) asked all 193 parties to update their NDCs, setting reduction targets for 2030. Among G20 countries, Indonesia and Australia submitted an identical NDCs target to the one sent in 2015. Brazil, Mexico, and Russia submitted less ambitious plans with higher emissions levels than the previous one presented in 2015. Although other G20 members updated their NDCs, estimation shows that the current NDCs and legally binding net-zero targets are still putting the world on a trajectory to 2,1°C, well far from the threshold of 1,5°C set in the Paris Agreement (Fyson,2021).

G20 emerging economies, such as China and India, have improved their green strategies, although it might not be enough. China, the country with the highest GHG emissions, is the world’s largest coal producer and consumer, accounting for over 50 percent of all coal burnt globally (Koons,2022). Despite that, China is the biggest wind and solar energy producer and the largest domestic and outbound investor in renewable energy (Chiu,2017). In India, the third country for the level of GHG emissions, over 80 percent of energy demand is covered by coal, oil, and solid biomass, with coal being the most significant single fuel in the energy mix and the primary source of the rapid economic expansion of the country (IEA,2021).

[4] The Energy Transition Index is a WEF proposed tool to measure the national energy transition progress. It is built as a benchmark of 115 countries, providing a value between 0 to 100 based on their current energy system performance and preparedness for the ongoing transition (Koons,2022)

At the COP26, China updated its previous NDCs stating that the country will reach peak carbon emission before 2030 and carbon neutrality before 2060. By 2030 the government pledged to increase the share of non-fossil fuels in primary energy to 25 percent and reduce the emission per unit of gross domestic product (GDP) by 65 percent compared to 2005 levels. In 2021, China reached the highest level of coal production in its history and registered a year-to-year growth in coal consumption by 4,7 percent. The country also plans to add 30 GW of coal by the end of 2022 and 180 GW by 2030 (Climate Action Tracker, 2022).

In Glasgow, India pledged carbon neutrality by 2070 without submitting any 2030 NDC target to the UNFCC. Following the outbreak of COVID-19, the Indian government allocated several stimulus packages for the country's economic recovery. The most recent one, defined in 2021, dedicates two-thirds towards a green recovery, including around USD 3 billion for battery and solar photovoltaics (PVs) development in the country (Climate Action Tracker, 2022). While much effort is a good step, the Indian finance institute continues investing in new thermal power projects. Based on current coal expansion plans, India’s coal capacity would increase by almost 70 GW by 2030, with 35 GW of new coal capacity in the upcoming five years, translating into a 17,5 percent increase in power (ibidem).

Achieving the goals of the Paris Agreement's 1,5°C also requires ambitious climate actions from non-G20 countries and a common strategy to deal with the emissions from international aviation and shipping. Mobilizing LDCs and SIDSs requires a cohesive commitment from developed countries to climate finance to fund policies, mitigation plans, and adaptation measures (Climate Analytics, 2022). In 2015, advanced nations pledged USD 100 billion to finance climate actions yearly. In 2019, only USD 79 billion were mobilized (OECD,2021), a negligible fraction of almost USD 6 trillion, to fund 40 percent of the climate actions listed in the NDCs of developing countries (UNSFC,2021).

1.4. Energy security during the energy transition

Energy security is defined as “the interrupted availability of energy sources at an affordable price” (IEA, 2021). In the short term, that means guaranteeing a certain level of flexibility in the energy system to react promptly and adapt to an unexpected shift in the supply-demand curve. In the long term, energy security requires allocating investment to supply energy accordingly to economic developments and environmental needs (ibidem).

In the past, energy security mainly focused on managing a steady supply of oil (Egenhofer,2019). With global mass motorization and the role of oil in national security, countries were cyclically worried about "running out of oil", especially during demand surges or few discoveries of reserves. With the beginning of the cold war, the US and the Soviet Union needed a reliable oil supply to guarantee their capability to conduct war and defense their supremacy in their respective area of influence (ibidem). The issue became even more crucial with the creation of the Organization of the Petroleum Exporting Countries (OPEC) in 1960, the 1973 Arab oil embargo, and the resulting oil shock. Such an oil crisis led to the International Energy Agency (IEA) creation in 1974 to define regional and global energy governance between like-minded countries. Ultimately, the stabilization of oil prices in the late 80s and 90s, together with the end of the cold war and the beginning of globalization, helped reduce attention on energy security (ibidem).

The situation changed at the beginning of the 21st century with the rising hostility of petrol states following the Afghanistan and Iraq wars and the 2008 economic crisis. The demand eventually recovered through the development of China and other emerging countries in the global economy (ibidem). Fears of supply shortage, resource competition, and political tensions are still present, but they are increasingly reducing. Nowadays, energy security can be enhanced through several measures, including diversifying the energy mix, promoting trade agreements with like-minded countries, and ensuring adequate domestic reserves to address shortages or peak demand. Technological progress and innovation can also strengthen energy security for more efficient use of domestic resources (IEA,2021).

The clean energy transition is bringing a significant structural change in the energy system and thus to the security of the supply. Moving from fossil fuels to renewables means moving beyond the generator/consumer dichotomy with a more decentralized system in which users become an active part of the energy market through PV solar panels and small-size wind turbines. Moreover, the electrification of end uses as one of the main pillars of the energy transition will gradually increase the share of electricity in the primary energy mix. IEA (2020) states that electricity will surpass oil and become the primary energy source (40 percent of the global energy mix) by 2040.

In the process of green transition, countries will have to adapt their energy security strategy considering three main aspects:

1. Renewable power generation requires higher digital support to forecast and manage the unsteady output of RES and deal with its more decentralized nature. The increased digital and physical infrastructures needed for the clean transition might raise the risk of cyberattacks. Policymakers, regulators, and utilities play a crucial role in assuring a more robust level of cyber resilience in the energy value chain.
2. The energy sector is undergoing continuous pressure from climate change in extreme and variable weather conditions. Appropriate policies and investment allocation can improve the climate resilience of energy infrastructure (especially transmission and distribution networks). However, significant countries are falling short in addressing this issue, with a limited number of countries addressing it in their climate actions.
3. The energy sector is emerging as a significant force in the raw materials market due to the demand for renewable systems (PV panels, wind turbines, and batteries, among others). Due to an increased share of renewable energy systems, the amount of minerals needed to generate a new power unit has increased by 50 percent since 2010 (IEA,2021). The uneven distribution and geographical concentration of mining and processing represent a primary risk to energy supply, especially for net-importers (as EU member states and the US). The outbreak of COVID-19 has exacerbated these issues highlighting the excessive dependence on areas of the world that suddenly become more difficult to reach due to trade and physical restrictions.

2. The role of Critical Raw Materials in the energy transition

The clean energy transition will be a material-intense process. As countries progress in their climate actions, the demand for renewables technologies and batteries (for storage and electric cars) will rapidly increase. The manufacturing of these technologies involves more materials than their fossil counterparts (Figure 1): a typical electrical vehicle needs six times the mineral inputs of a conventional car, wind farms nine times more mineral resources than a gas-fired power plant (IEA,2021). Therefore, the energy sector is expected to become a leading consumer of raw materials as the clean transition advances (ibidem).

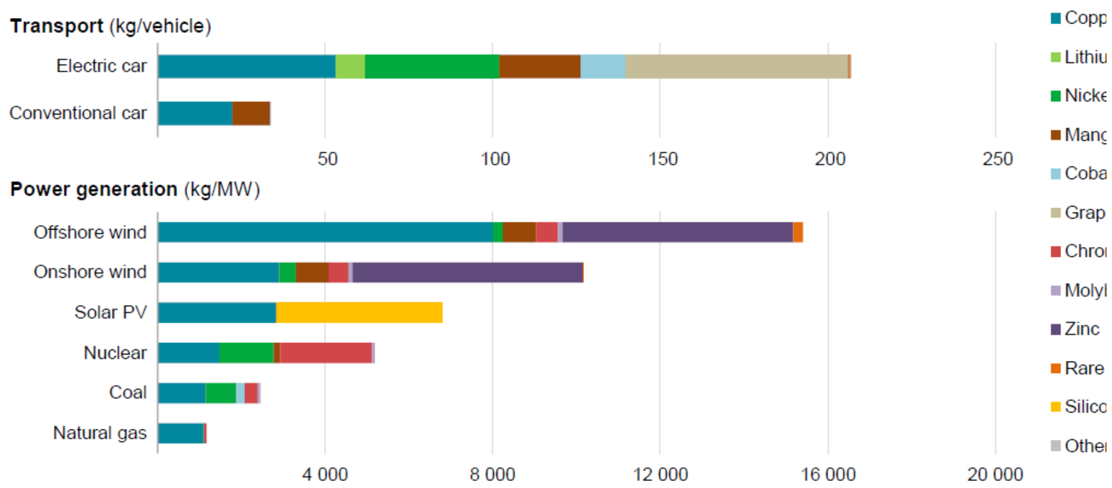

Figure 1 Minerals used in selected technologies (IEA,2021)

The types of mineral resources vary by technology: rare earth minerals are essential for permanent magnets (PMs) in wind turbines, while lithium, manganese, and nickel are crucial for batteries. The increase in demand will put the metals and mining sectors under stress as they will need to guarantee a resilient supply for the green transition to progress. The supply of CRMs introduces new challenges since the production and natural reserves of many materials for the green transition are more concentrated than that of oil or natural gas. Other challenges include the longtime development of new projects, higher exposure to climate change, and environmental and socially sound governance. This chapter will discuss the supply chain of CRMs and their role in selected technologies in the green transition, together with the main challenges in procurement.

2.1. The supply chain of critical raw materials

CRMs found applications in environmental technologies, digitalization and electronic devices, the health sector, steelmaking, defense, and space exploration. The supply of CRMs is fundamental not only for the specific domain but for the functioning of the economic system since a shortage in one sector can impact the others (CRM Alliance,2022).

It is necessary to underline that CRMs are not classified as critical because they are scarce (although some of them suffer from relative scarcity in nature). Three main aspects mark raw materials as critical:

- They have significant importance for crucial sectors of a country's economy.
- They have a high-supply risk due to a strong dependence on imports and a higher concentration in specific countries.
- There is a general lack of viable substitutes due to their unique and reliable properties in current and future applications.

As part of the Action Plan for raw materials (see Chapter III), the EC defined a list of 30 raw materials to be considered critical for the European economy's sustainable development. According to this inventory, CRMs are antimony, barite, bauxite, beryllium, bismuth, borate, cobalt, coking coal, fluorspar, gallium, germanium, hafnium, heavy rare earth elements (HREE), indium, light rare earth elements (LREE), lithium, magnesium, natural graphite, natural rubber, niobium, phosphate rock, phosphorus, platinum group metals (PGM), scandium, silicon metal, strontium, tantalum, titanium, tungsten, and vanadium (CRM Alliance,2022).

Although the supply chain of CRMs has structural differences based on their specific properties, the process usually begins with the extraction/mining from the open pits or underground mines, and it ends with the delivery of the final product in which the material is used. The supply chain can be divided into upstream (extraction of the mineral ores, processing) and downstream (manufacturing of components and assembly of product) operations. The main steps (Figure 2) are:

Extraction

The mined ore is sorted and smashed into smaller particle sizes to be used in the following processing operation. The extraction (or beneficiation) can be a simple method such as hand-picking and sorting with the mechanical or chemical process. It can also consist of air bubbles injection into an ore-chemical mixture to separate the ore particles from residual rocks. REEs are usually extracted in this way, producing a "mineral concentrate" with a total content of REEs ranging from 40 to 60 percent (White House, 2022c).

Processing

The mineral is further separated from trace elements and impurities using multiple liquid-to-liquid solutions (hydrometallurgy). The most common techniques are ion exchange or the use of solvent extraction.

In some cases, further refining is required to achieve ultra-high purity metals, using heat (pyrometallurgy) or electricity (electrolysis)[5]

Component manufacturing

Processed materials are then used to manufacture the main components for the end technology. Typical procedures include melting and alloying different minerals, casting, milling to fine powders and machining.

End-use technologies

The several components are finally assembled to commercialize the end-use product. In the energy sector, finalized technologies include solar cells and generators for wind turbines.

Recovery and recycling

In general, metals can be recycled indefinitely, but they must be separated from one another. The process of recovery and recycling starts with the sorting of the main components of the end-of-life products. The process is reversed with the components separated mechanically or chemically (including metallurgy) and the recovery of the CRMs.

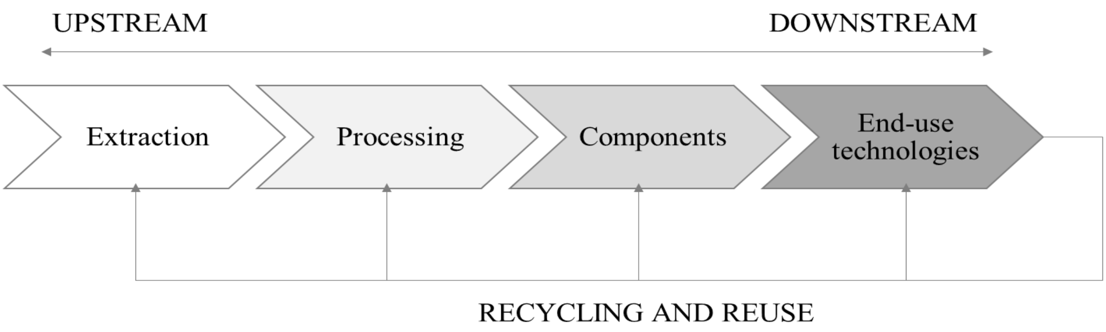

Figure 2 Critical material supply chain (own work)

2.2. Critical raw materials required for the green transition

Based on the assessment of the EC, Dolega et al. (2021) defined the relevance of the 30 listed CRMs as enabling sources for the green transition. Table I reports the current applications for the 15 CRMs considered with high or medium importance for the clean energy transition. Their relevance for other sectors (scored between very high to very low) is also included.

Table I List of CRMs important for the green transition with their selected applications and relevance for other sectors (Dolega et al.,2021)

Critical Raw Material	Selected applications	Importance for the green transition	Relevance for other sectors
Cobalt	Batteries, super alloys, catalysts, magnets	High	Medium
Lithium	Batteries, glass and ceramics, steel and aluminium metallurgy	High	Low
Niobium	High-strength steel and super alloys for transportation and infrastructure, high-tech applications (capacitors, superconducting magnets, etc.)	High	High
Tantalum	Capacitors for electronic devices, super alloys	High	High
Heavy rare earth elements		High	Medium

Light rare earth elements	Permanent magnets for electric motors and electricity generators, lighting phosphors, catalysts, batteries, glass, and ceramics	High	Medium
Borate	High performance glass, fertilisers, permanent magnets	Medium	Very high
Phosphorous	Mineral fertilizer, phosphorous compounds	Medium	Very high
Silicon metal	Semiconductors, photovoltaics, electronic components, silicones	Medium	Low
Gallium	Semiconductors, photovoltaic cells	Medium	Medium
Germanium	Optical fibres and infrared optics, satellite solar cells, polymerisation catalysts	Medium	High
Indium	Flat-panel displays, photovoltaic cells and photonics, solders	Medium	High
Natural graphite	Batteries, refractories for steelmaking	Medium	High
Scandium	Solid oxide fuel cells, lightweight alloys, 3D printing	Medium	High
Platin group metals	Chemical and automotive catalysts, fuel cells, electronic applications	Medium	High

<u>Lithium</u>

Lithium is one of the most crucial elements for the green transition. It is a soft metal extracted from ores through mining or brines through evaporation and processing of the salts. The main application of lithium is in batteries for battery energy storage systems (BEES) and electric vehicles (EVs). The battery market has grown exponentially in the last decade: the lithium demand in this sector has increased from 23 percent in 2011 to 70 percent of global production (Dolega et al., 2021). Other applications, such as ceramics and greases, have become negligible (ibidem).

The increasing demand in the battery sector has been the main driver of mine production growth (from 28.100 tons to 82.000 tons per year from 2010-to 2020). The mining processing (including both ores and brines) is led by Australia (46,3 percent) and Chile (23,9 percent) (Visual Capitalist,2022). The two countries represent more than 70 percent of global identified lithium reserves (Chile 48 percent, Australia 25 percent) (ibidem). China is the leading producer of lithium compounds (57 percent), followed by Chile (23 percent) and Argentina (13 percent) (IEA,2021). Lithium compounds represent the most marketed form in global trading (86 percent of the global lithium market) (European Commission,2020a).

Rare earth elements

REEs indicate a family of 17 different metals obtained through mining, leaching, and chemical separation. The four most important REEs are the neodymium and praseodymium (light REEs) and the heavy REEs dysprosium and terbium. Their primary demand is a key component for neodymium-iron-boron alloy used in wind power generators and electric motors (in EVs). Other applications include their role as a catalyst in glass and ceramic manufacturing. For this reason, their importance for the green transition is vital (high in Table I), and they have medium importance also in other sectors (Dolega et al., 2021).

China leads in REEs' production, covering 60 percent of global annual production (240.000 tons in 2020) (Dolega et al. ,2021). The US, Myanmar (Burma), Australia, and Madagascar (ibidem) are other producers. Chinese market share is even higher for processed oxides, metals, alloys, and magnets, ranging between 85-90 percent of the global market (European Commission,2020a). The country established a monopoly through production controls, export restrictions, quotas in foreign sites, and mine closings (ibidem).

Cobalt

Cobalt is a hard metal usually produced as a by-product of nickel and copper processing or from mining. Therefore, its production is directly linked with these materials' industry (and supply) (European Commission,2020a). Cobalt mining, especially in the Democratic Republic of Congo (DRC), has been widely criticized and at the center of international concerns for the low health and safety standards and involvement of child labor (ILO,2019). The role of cobalt in the upcoming future is less predictable than the one of lithium. Possible substitutes (e.g., nickel) characterized by fewer environmental and social hazards might come from continuous R&D (The White House,2022a). Today, its importance for the green transition as an element for batteries is high, and its importance in other applications (especially for small electronic devices) is medium (Dolega et al.,2021).

In 2020, DRC will cover almost 70 percent of the global production (estimated at around 140.000 tons) (IEA,2021). While China is a net importer of cobalt ores, it leads the processing market for cobalt intermediates and refined cobalt (62 percent), followed by Finland and Belgium (IEA,2021).

Silicon metal

Silicon metal is the second most abundant element in the earth's crust (European Commission,2020a). It can be extracted by high silica content ores such as quartz veins and pebbles. Processed silicon is used in metallurgical grade silicon (in metallurgy and the production of silicones) and polysilicon. The latter finds application as a semiconductor in PV applications or microelectronics. In the energy sector, silicon is also used in wind turbine generators and as an anode component in Lithium-ion (Li-ion) batteries (ibidem).

China dominates the global market producing 66 percent of the share, followed by the US (8 percent) and Brazil (7 percent). Since the 90s, the US, the EU, and Canada have imposed anti-dumping duties[6] on silicon metal coming from China (ibidem).

2.3. Selected technologies for the green transition

Within the scope of this document, only the CRMs required in the green transition will be discussed, and the ones essential for three technologies, PV solar panels, wind turbines (generators), and Li-ion batteries for energy storage and e-mobility.

PV panels

To meet carbon neutrality by 2050, solar PV panels will have a predominant role in the global energy scenario. Solar PV requires modules, inverters, trackers, and mounting structures. Crystalline silicon (c-Si) modules are the most common, followed by "thin-film" alternatives which require more glass but less mineral overall (European Commission,2020a). Some of the main components of PV panels use raw materials listed in the 2020 EU CRMs analysis, such as silicon metal, indium, gallium, germanium, and

[6] An anti-dumping duty is a protectionist tariff that a country can impose on the import of goods that are priced below fair market value

borates. The continuous progress in R&D has avoided possible shortages of raw silicon metal and processed material due to a continuous material intensity reduction and thinner and more efficient solar cells. Other components, such as copper, cadmium, selenium, and silver, do not suffer from possible scarcity in the supply (IEA,2021). The main issue with raw materials in the solar energy system is mainly related to the concentration of the global supply chain in China. The country leads the market from the early stages of extraction of raw materials (53 percent of the total market), manufacturing of processed materials (50 percent) and components (89 percent), and final assembly (70 percent) (Bobba S.,2020).

According to the IEA (2021), the global capacity additions have to grow three times by 2040 (compared to the 2020 added capacity of 107 GW) to meet the carbon neutrality goal. Cooper demand as strategic raw materials is expected to grow at the same rate. R&D and material intensity reduction help limit the growth of silicon and silver demand, which are both estimated to be lower in 2040 than in 2030 and only 18 percent and 45 percent higher than in 2020, respectively (IEA,2021). Thin-film technologies remain a market niche over the coming twenty years, although IEA estimated further efficiency gains and cost reductions.

Wind turbines generators

Together with solar power, wind energy represents the leading solution to mitigate climate change through cost-effective renewable technologies. The Global installed capacity of wind power (744 GW with an added capacity of 93 GW in 2020) almost quadrupled over the past decade due to falling costs and policy support (ibidem). It is also a steadily growing market and a vital sector in global R&D. Current research focus on enhancing performance, energy output, and reliability while reducing capital cost and transportation. The main components of wind turbines are the tower, generation, drive train, rotor, and blades. While the overall wind technology is mature, innovation offers new frontiers for manufacturing blades and generators. The first is usually produced with glass-fiber composite, although carbon fiber might soon become the new production standard. Generators can be more heterogeneous, although permanent magnet synchronous generators (PMSGs) are the most commercial due to their high power density and low mass. PMSGs manufacturing high amount of REEs such as neodymium, praseodymium, and dysprosium. These elements and boron are recorded among the CRMs identified by the EC.

China alone covers 54 percent of the total production of raw materials demanded by wind turbines, followed by Latin America (29 percent). China is also leading the production of process materials and final components, covering 41 percent and 56 percent of the global supply chain, respectively (ibidem).

Annual added installed capacity for wind power is expected to double by 2040 (reaching 160 GW on average) due to falling costs in the offshore wind industry, which will become more mature, and continuous political support. Installations will be primarily located in China, Europe, and the US. However, the IEA expected growth in emerging countries and regions such as Southeast Asia, India, Latin America, and the Middle East (ibidem).

Batteries

Fluctuating power supply by solar and wind power will require an appropriate storage system to cover the energy demand when it is more needed. Moreover, batteries have a crucial role in the functioning of EVs and thus in the electrification of civil transportation. This research will focus on and discuss the lithium battery system among the different types and technologies in the battery sector. The demand for Li-ion batteries has been rocketing in the last five years due to several benefits of this technology compared to other types of batteries (such as lead-acid), such as higher energy density, voltage capacity, and lower self-discharge. The steady increase of lithium batteries has been driven by their use in portable electronic devices, BEES, and EVs. The specific materials used in lithium batteries can vary depending on the specific technology used in the anodes, cathodes, and distinct components. Battery manufacturing usually includes at least six out of the 30 CRMs listed by the EC, including cobalt, natural graphite, and lithium (ibidem). Current market trends, focusing on higher energy density and durability, will lead to higher use of silicon metal, titanium, and niobium.

The production of CRMs required for batteries is primarily concentrated in Asia. China, Japan, and South Korea represent 86 percent of the global demand for processed material and components required in Li-ion batteries (ibidem). China hosts almost 50 percent of the refining of cobalt and lithium. In comparison, mining and extraction are diversified:

for cobalt, the global mine production is concentrated in DRC (54 percent), China (8 percent), and Canada (8 percent). Lithium coming from brine and spodumene sources is processed in Chile (40 percent), Australia (29 percent), and Argentina (16 percent) (ibidem).

Battery demand for electric vehicles is expected to grow by almost 40 times between 2020 (160 GWh) and 2040 (6.200 GWh). The demand for CRMs grows 30 times in the same period (ibidem). The demand for nickel and cobalt grows by 40 and 20 times, respectively (compared to the 2020 level). Lithium demand is estimated to increase by 43 times. This scenario considers growth in the nickel-rich cathode with the industry shifting to massive use of nickel rather than cobalt (due to the social and environmental implications of this material) and fast uptake of ASSBs (all-solid-state batteries) and thus higher demand for lithium from 2030 (ibidem).

For utility-scale batteries, the demand rises by 11 times between 2020 (37 GWh) and 2040 (420 GWh). The demand for associated raw materials will grow by 33 times in twenty years due to the higher use of Lithium iron phosphate (LFP) batteries which are more mineral intense than nickel manganese cobalt (NMC) ones.

2.4. Challenges in the supply of critical raw materials

The increasing demand for CRMs raises the issue of availability and reliability of their supply. In a scenario aligned with the 1,5°C global warming threshold, the expected supply based on current mining and ongoing projects is estimated to meet only half of the lithium and cobalt demand (IEA,2021). Several challenges can make the supply of CRMs more vulnerable and thus undermine the path toward the clean energy transition:

Geographical concentration of production

The supply chain of raw materials is more concentrated than fossil fuels (Figure 3). Such a concentration level raises the problem of reliable supply chains in case of trade restrictions, physical disruption, or geopolitical tensions. For lithium, cobalt, and some REEs, three-quarters of the global demand is covered by three importers, and for some materials, a single country is responsible for more than half of the supply (Table II). Since the end of the Cold War, China’s supply chain of CRMs expanded to fuel the development of the national and global economy. Although several countries conduct the initial mining of the raw materials (e.g., DRC cobalt), China is leading the remaining phases of the supply chain, controlling the entire flow of CRMs through state-owned enterprises. Especially in the processing and manufacturing of the product, the concentration of the supply chain in China is even higher than the beneficiation step. Chinese quotas on foreign companies in resource-rich countries have helped the country achieve this controlling position.

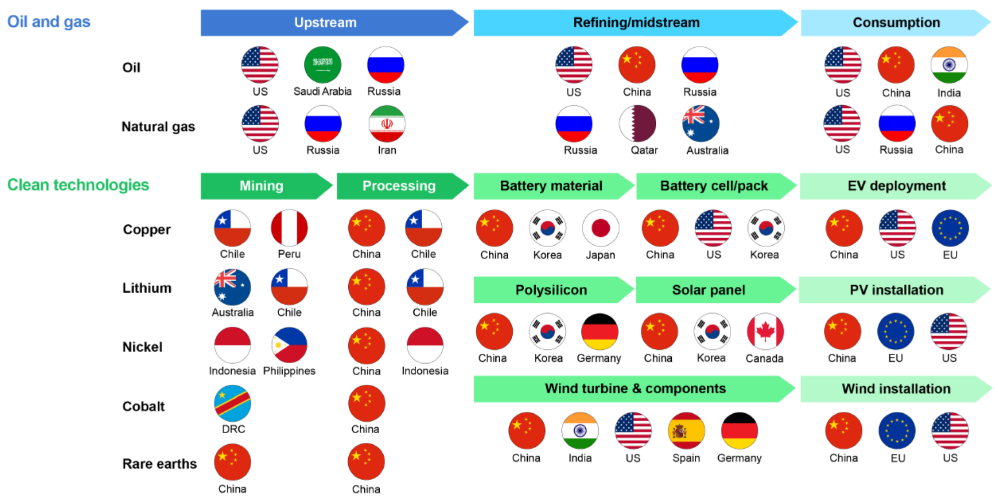

Figure 3 Indicative supply chains of oil and gas selected clean energy technologies (IEA, 2021b)

Table II Market Concentration of Some of the Most CRMs (Schmidt,2021)

Critical Raw Material	Major Producer	Share of World Production
Gallium	China	95 percent
Niobium	Brazil	88 percent
Magnesium (metal)	China	82 percent
Tungsten	China	82 percent
Bismuth	China	81 percent
Beryllium	US	74 percent
Rare Earths	China	71 percent
Antimony	China	71 percent
Platinum group metals	South Africa	69 percent
Natural Graphite	China	68 percent
Cobalt	DR Congo	64 percent

Fluorspar	China	60 percent
Vanadium	China	55 percent
Rhenium	Chile	55 percent
Phosphate rock	China	52 percent

Declining resource quality

Several CRMs are relatively abundant in the earth's crust and thus do not suffer from physical resource scarcity. However, the overall quality of the extracted ore and its metal content might raise issues about their quality. For instance, the average quality of copper extracted in Chile has declined by 30 percent over the past five years (IEA,2021). Extracting from low-quality ores requires more processing and thus more energy, GHG emissions, and waste volumes. The mining sector already accounts for between 2 and 11 percent of global emissions (Hund,2020)

Difficulties in the recovery and recycling

Recovery of common metals has already become a reality due to the relative simplicity of the process and mature technologies. Secondary metals cover part of the demand, reducing the need for primary extraction and energy consumption (recovered materials require around 5 percent of the energy need of the primary supply from mining) (Seabra and Caldeira-Pires,2020). However, the recovery of CRMs from Electrical and electronic equipment (EEE) and alloyed components is more complicated. It requires the physical, chemical, and metallurgical separation of over 50 materials with different properties (IEA,2021).

Higher exposure to climate change

Today, 70 percent of mining operations performed by the six largest mining firms are in water-stressed countries in Africa and Latin America (ibidem). Lithium production is particularly critical due to the high requirements for water. Moreover, primary operations in the supply chain occur in LDCs particularly vulnerable to climate change-related events such as extreme heat or flooding. The increase of extreme weather events can undermine the reliable speed of operations.

Long-lead time investments

Mining projects- from first explorations to running operations- take an average of more than 16 years (IEA,2021). The private and public must be resilient to accommodate the increasing demand and avoid possible deficits. The ultimate risk is persistent price volatility and marketing tightness for some materials.

Stricter environmental and social standards

The mining surge represents a threat to the ecosystem and local communities if high environmental and social standards are not respected during the operations. While the mining sector in industrialized countries is well regulated and relatively safe, activities in LDCs are more challenging to monitor, especially in remote regions (acatech,2018). Environmental concerns include soil and water contamination, air pollution, the release of wastewater (ibidem). Social standards should guarantee the respect of human rights, health and safety for workers and surrounding communities and the enforcement against child labor (ibidem).

Failing to respect these standards might lead to supply disruption when production sites are shut down due to disputes (e.g., clean water access or regulatory actions to enforce human rights violations). In the long run, not compliant companies can be excluded from a country's portfolio, eventually reducing available suppliers[7] (IEA,2021).

Social acceptance

Globalization and easier access to information have provided local communities the means to fight unwelcomed and impactful investments. The phenomenon of NIMBY (Not in My Backyard) [8] is widespread in the mineral industry and can affect resource exploitation due to social opposition of such impacting activities (Badera,2014). For instance, in January 2022, the Serbian government decided to withdraw exploration

[7]An example of a recent import ban is the one imposed by the EU and the US on solar panels produced in Xinjiang (China) due to allegations of forced labor.
[8] The NIMBY phenomenon is the resistance of inhabitants (as individuals or organized in groups) towards the realization of an investment that aims is to serve not only local purposes

licenses of Anglo-Australian mining company Rio Tinto following weeks of protests over plans for lithium exploration (De Launey,2022).

Despite these challenges, which can lead to potential shortages, supply will always be able to equal the demand. As the clean energy transition progress, each CRM will face specific supply-demand balances with a constant loop between supply, demand, and market prices. Individual commodity markets can experience three main paths:

- Supply responds to the demand: growth in demand is met by the industry able to respond relatively quickly with new supply. In such cases, the clean energy transition will not face disruption because the technology development will bear the expected growth. However, a limited/short-lived price reaction can occur.
- Demand acceleration meets with materials substitution: a new supply does not cover the high demand. The commodity's price increases until the industry can provide an alternative solution to meet the demand. A bottleneck can be avoided through innovation leading to materials substitution: raw material is substituted with another having higher availability and similar performance. This scenario requires, in some cases, compromises in the overall performance.
- Demand acceleration meets with technology substitution: when materials substitution is not possible, a technological substitution might be required to meet the acceleration in demand and avoid bottlenecks.

An example of a feedback loop has occurred in the battery sector. In the first application, batteries contain a high share of cobalt. When their usage accelerates, the price for cobalt rockets in 2018 at USD 100.000 per metric ton (Azevedo,2022). The price spike was followed by material substitution with nickel as an alternative cathode material. Eventually, the substation pushed by the price volatility led to better performance and lower costs. The loop continued with commonly used nickel batteries and several issues in the supply chain, such as capital-expenditure overruns, delays, and market failure. As of today, manganese is becoming the main frontier in battery innovation due to the higher availability of reserves than nickel and cobalt (ibidem).

With the evolution of clean energy transition, such loops are expected to occur more frequently and widely. In the power generation, a similar cycle can happen in the tellurium market for PV panels and with REEs in the wind power generation (ibidem).

The evolution in the supply of some materials needs to be watched more closely. CRMs used in electronics and PV panels such as indium, germanium, and gallium are extracted as by-products in the supply chain of other metals. In such cases, a feedback loop will work only to a certain extent since the quantity processed by these CRMs depends on the extraction rate of the primary metals. As a rule, producers will not increase the primary metal production only because the by-product is becoming scarce.

In conclusion, there is still an unclear image on how the market of CRMs will evolve in the future due to a differentiated number of actors involved and less price transparency. As the ecological (and digital) transition progresses, countries will have to adopt ad hoc strategies to manage the supply of differentiated materials and to engage the different stakeholders.

2.5. Security of critical raw materials and their other applications

A reliable and steady supply of CRMs is becoming one of the main priorities for national and supranational energy security. Typical strategies address the supply of crude oil as the primary commodity of the global energy system, especially in case of unexpected supply disruption and price spikes. However, there are fundamental differences between oil and mineral security.

An oil supply crisis has broad repercussions for all actors involved in the supply. Consumers, for instance, driving gasoline or diesel cars, are directly impacted by higher prices of such commodities. By contrast, a shortage of CRMs will not impact end-use: the scarcity in the supply or spike in price will affect only manufacturers producing renewable technologies, while consumers already using such technologies will not be affected. Therefore, mineral security does not deal with short-time consequences in the value chain but instead with the overall energy transition delays and increased costs (IEA,2021).

Crude oil is a single commodity with a broad and well-defined global market. By contrast, each CRMs has its commodity market and supply dynamics which involves a restricted number of countries. Therefore, a different strategy should be adopted considering each trade partner's different positions and roles in the value chain.

Finally, the supply security of CRMs adds another layer of complexity because of a vaster number of applications and thus sectors involved. Crude oil is used chiefly in four main sectors with all mature technologies: transportation, industrial, heating and power generation. In comparison, CRMs are crucial not only for these sectors but also for defense, aerospace, and digital (information and communication technology). Considering that different applications share the same type of CRMs, there will be increasing competition (domestic and international) between industries to have priority access to the market for CRMs, processed materials, and components. Digital technologies and the solar panels industry, for instance, compete for the same CRMs as germanium, indium, gallium, and silicon metal. Wind power generation, electric traction motors (used in EVs), and the robotic industry contend for the supply of the borate and REEs.

Finally, the defense and aerospace define a particular case in the overall demand for CRMs. Although the need for materials is limited compared to civil uses, both sectors require alloys with specific requirements that cannot be easily substituted in case of a shortage in supply. If the supply-demand balance becomes tight, the defense sector will not accept production stops and will prioritize the supply of CRMs (especially in the case of rising geopolitical tensions). These and other factors make the demand for CRMs in defense and aerospace less elastic compared to civil sectors. However, it should be emphasized that both sectors are the primary enablers of innovation. New applications are then usually scaled up and made available for others (e.g., solar panels were first used in space exploration).

3. Strategies for the supply of Critical Raw Materials

3.1. The United States

The role of CRMs has been historically recognized in the US as crucial for national security and the development of military and defense sectors (Barteková & Kemp, 2016). In the early 1950s, under President Truman, an ad-hoc Material Commission (Paley Commission) provided recommendations on increasing the supply of CRMs with domestic exploitation on public lands and improving extractive technology and recycling procedures. In the late 70s, two oil price shocks and the interruption of Zairian cobalt production lit up the political debate about reducing US reliance on imports (ibidem). The 1980 National Materials and Minerals Policy and Research and Development Act created a coherent environment for the REEs industry to flourish. Between 1965 and 1995, through production in California, the US became the global supplier of REEs. In the 90s, unable to compete with the low prices of the emerging Chinese market, the industry became rapidly irrelevant. Today, the US covers only 4% of the global supply (USGS, 2019).

Since the late 80s, the United States has increasingly relied on imports to meet its demand for CRMs. The end of the Cold War and the stabilization of the relationship with foreign suppliers (especially in Africa) lead to a loss of strategic perception of non-energy minerals. Today, the number of non-fuel metal commodities for which the US is dependent on import for a percentage higher than 25 percent has grown from 21 products in 1954 to 58 raw materials. In the supply of CRMs, the US is a leading producer only of beryllium which, however, has applications only in the military, aerospace, and nuclear sectors (The White House,2022b).

Recognizing the challenges posed by the critical minerals supply, President Donald Trump issued two Executive Orders (EO 13817 and EO 13953[9]). With the EO 13953, issued in 2020, the department of energy (DOE) received the mandate to update the previous 2010 Critical Materials Strategy, developing an ad-hoc action plan for energy-related CRMs (DOE,2020). The DOE strategy is based on three main pillars: diversifying

[9] EO 13817: A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals and EO 13953: Addressing the Threat to the Domestic Supply Chain from Reliance on Critical Minerals from Foreign Adversaries and Supporting the Domestic Mining and Processing Industries

supply, finding substitutes, and improving reuse and recycling. To support the three areas of intervention, the 2020 Strategy listed four strategic goals:

- Promote scientific innovation and new technologies for the resilient and secure supply of CRMs reducing the need of imports.
- Catalyze and support private investment, building capacity for domestic supply.
- Build a long-term innovation ecosystem with a specific focus on finding new substitutes.
- Coordinate with international trade partners, allies, and other federal departments and agencies to diversify the global supply and adopt best practices for sustainable mining (ibidem).

With the new Biden-Harris administration, the US is undergoing a significant evolution toward an energy-oriented CRMs strategy (Schmidt, 2021). In February 2021, the President signed the EO 14017 on America's Supply Chains. In the document, the President orders the necessity for the US to build a "resilient, diverse and secure supply chain" to ensure economic growth and national security. The Administration also gives the order to:

- the DOI to identify a list of CRMs essential for the economic or national security and vulnerable to disruption (The White House, 2022b)
- the Assistant to the President for National Affairs (APNSA) and the Assistant to the President for Economic Policy (APEP) to complete a comprehensive review of the supply chain risks within one hundred days (ibidem)

3.1.1. The federal list of critical minerals

The 2022 Federal list of critical minerals, published in February 2022, aims to support the federal state, private and public sectors to prioritize investments and strategies based on the role that specific CRMs will play in the green transition and other priority areas. The list was defined by the DOI acting through the Director of the US Geological Survey (USGS). It is an update of the 2018 list with 50 minerals (35 considering the grouping of LREEs and HREEs) considered critical, such as cobalt, lithium, graphite, and REEs. The assessment will be reviewed after three years, reflecting the current data, supply-demand balance, production concentration, and policy updates (Federal Register,2022).

Based on the available data, the methodology built by the USGS considered three different evaluations with different levels of accuracy: a quantitative one related to the supply risk, a semi-quantitative assessment of possible single point of failure [10]in the value chain and a qualitative evaluation in case no quantitative data were available. The qualitative assessment uses a net import reliance indicator of the dependence of the US industries for the specific raw material, an enhanced production concentration indicator to assess the production concentration outside the US, and a weight indicator to consider the products in foreign countries (ibidem). According to the study, of the 35 mineral commodities identified, the US lacks domestic production of 14[11] and is more than 50 percent dependent on imports for 31 of them.

3.1.2. 100-Day Review under Executive Order 14017

In June 2021, The White House published the 100-day review of the American supply chain, identifying four critical areas: semiconductor manufacturing and advanced packaging, large capacity batteries (for EVs and BESS), critical minerals and materials, and pharmaceuticals and active pharmaceutical ingredients. The review underlined structural weakness in domestic and international supply chains, which can threaten the American economy and security. In particular, the lack of investment, poor policy support, unfair trade practices, and market distortion were recognized as hazards. At the same time, the US still has a leading position and can use its technological and scientific advancements to adopt innovative solutions in a future-proof supply chain (The White House,2022c).

Regarding the two sectors of interest for this study, the batteries and CRMs, the White House identified several actions to be implemented:

<u>Secure domestic supply for batteries</u>

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[10] A single point of failure is a potential risk posed by a flaw in the supply chain that can affect the optimal functioning of the system

[11] Aluminum, antimony, arsenic, barite, beryllium, bismuth, cesium, chromium, cobalt, fluorspar, gallium, germanium, natural graphite, hafnium, helium, indium, lithium, magnesium, manganese, niobium, platinum group metals, potash, the rare earth elements group, rhenium, rubidium, scandium, strontium, tantalum, tellurium, tin, titanium, tungsten, uranium, vanadium, and zirconium

A larger storage capacity will be required as the US proceeds in the energy transition. Without policy intervention, US storage capacity is expected to increase by around 220 GWh in the next three years without covering the expected annual demand for storage by 2025 (ibidem). The current strategy aims to develop an end-to-end supply chain. Regarding the downstream operations, the Biden administration aspires to reduce reliance on foreign importers investing in domestic extraction and refining CRMs. For instance, the US holds 4 percent of the known global reserves for lithium, which could cover 2020 domestic demand for this raw material for the next eight years (ibidem). National funding and investment will also be required for refining and processing the CRMs due to the total reliance on imported processed materials.

The US carries less than 10 percent of the global market share in the upstream operations for the main battery components and cell fabrication. For battery pack manufacturing, the bloc has established an industry to support EV domestic production but lacks in sustaining the global demand covering around 12 percent of the total (China and the EU have reached around 40 percent of the share) (ibidem). Regarding the recovery and recycling of end-of-life batteries, the Administration recognizes their importance in reducing the demand for primary raw materials. However, a general waste legal framework is still missing (ibidem).

The current Administration has already taken several actions. The DOE is defining a National Blueprint for Lithium Batteries, a 10-year plan to develop a domestic end-to-end lithium battery supply chain to electrify consumption and reduce unemployment across America. The Loan Programs Office of the DOE has already financed USD 17 billion to support manufacturers in the battery sector to relocate, expand or establish their processes within the US. Moreover, the DOE has launched a USD 273 million worthy call to support energy storage projects for federal sites interested in expanding their mining industry (The White House,2021b).

In February 2022, Biden announced a new partnership with the private sector. Redwood Materials is conducting several lithium explorations in geothermal brine as part of a five-year plan to investigate new reserves (at the Imperial Valley in California, one of the largest deposits of lithium in the world) to be exploited in a new sustainable value chain. If successful, the plan will bring a path to commercial-scale production of lithium batteries by 2026. Redwood Materials is currently working on a partnership with Ford and Volvo for the recovery of end-of-life li-ion batteries to extract secondary CRMs such as lithium, cobalt, and nickel (The White House,2022b).

<u>Invest in domestic production and processing of CRMs</u>

The DOE and the Department of Interior (DOI) are currently working on identifying national sites in which CRMs can be extracted and processed in respect of the highest environmental, social, and labor standards. The WG, which includes members of the DOI and the Environmental Protection Agency (EPA), seeks to collaborate with the private sector, tribal nations, and civil society to reinvigorate the mining sector through an open dialogue with the business and the local communities (ibidem).

Moreover, the Biden administration established an interagency working group (IWG) to examine current regulation and legislation framework with a particular focus on permitting and environmental law. The legal framework, especially the Mining Law of 1872, should be updated considering stricter environmental criteria, consultation with local communities, and engagement of tribal nations during all the value chain. The IWG also committed to public sessions to avoid the NIMBY phenomenon, looking for continuous inputs from the affected communities in new mining operations (ibidem).

Regarding financial aid, the DOE has already allocated USD 3 billion in the form of loans to sustain projects in the mining industries, including recovery and recycling implementation. The Department of Defense (DOD) stipulated a public-private partnership with MP Materials to extract and process heavy REEs in California, intending to establish an end-to-end domestic permanent magnet supply chain. The partnership, with an allocated budget of USD 35 million and a further USD 700 million announced, will bring new jobs (350 according to estimation) to the magnet supply chain by 2024. MP Materials has also announced the construction of REE facilities in Texas and an agreement with General Motors to produce magnets for EVs (ibidem).

<u>International relations with allies and partners</u>

The US has built robust relationships with allies to cooperate intensely in the defense and civil supply chains. Since the EO 13817 ("A federal strategy to Ensure Secure and Reliable Supplies of Critical Minerals”), the US has sought broad interagency cooperation to coordinate diplomatic channels with third countries. Under the National Technology and Industrial Base [12], the US has signed solid bilateral agreements with Canada and Australia. The USGS is also part of a three-way collaboration with Geoscience Australia and the Geological Survey of Canada in the Minerals Mapping Initiative to build a diversified supply of CRMs and identify new sources in the three countries (ibidem).

Canada

The robust relationship between US and Canada also encompasses the trade of CRMs. After China, Canada is the second-largest importer of CRMs and other raw materials needed for the green transition in the US. Trade in strategic and critical materials exceeds USD 76 billion (ibidem). The primary traded commodities include high-purity aluminum and gallium. The latter is becoming more and more critical due to its application in the industry of semiconductors, LEDs, and solar cell technologies. Moreover, Canada has the potential to support the US demand for cobalt, tantalum, antimony, and twenty other CRMs through available reserves, all listed as "domestic sources" under the Defense Production Act (DPA) (ibidem).

Australia

Like Canada, Australia is a member of NTIB through which the two countries cooperate in R&D, innovation, and industrial development in CRMs (such as the joint ventures for processing light and heavy REEs). Building cooperation with Australia is fundamental to cover the demand for raw materials. Australia is a mineral resource-rich country, with the mining industries covering almost 11 percent of the GDP in 2020. The country has natural reserves for more than 20 CRMs and is one of the more significant investors in global mining exploration (ibidem).

Japan

Japan is another important ally for the US within the Asia-Pacific region. Although it is not a member of NTIB or considered a domestic source under the DPA, Japan has agreed with the US for reciprocal defense procurement to remove trade barriers in the sector. In

[12] The National Technology and Industrial Base (NTIB) comprises people and organizations engaged in national security, R&D, production, maintenance, and other activities within the US, Canada, the UK, and Australia.

2010, following a territorial dispute with China and the resulting Chinese embargo on REEs export, Japan adopted a new strategy in the supply of CRMs. National policy focuses on diversifying the procurement of such materials, especially REEs, investing in continuous R&D (to improve efficiency and find possible substitutes), and end-of-life recycling. In less than a decade, Japan has become a powerful R&D hub source of project finance and downstream manufacturing. The trilateral critical materials cooperation with Japan and the EU is an essential platform for the US to share best practices, technical data, and approaches (ibidem). The three forces also cooperate in reducing market distortion and ensuring fair global competition. In 2014, they filed a formal complaint to the World Trade Organization (WTO) in response to China's decision to insert export restrictions on REEs, which was eventually found incompatible with WTO rules (European Commission,2014)

3.2. The European Union

Historically, the EU has sustained experience in extracting and processing raw materials. Modern, efficient, and more eco-friendly technologies are becoming a reality in the main mining sites in the EU. However, the industry and economy are heavily reliant on international trade. Especially in the field of CRMs, the EU is entirely dependent on imports from third countries and covers only 3 percent of the total production in the world (Barteková & Kemp, 2016).

To launch concrete actions in securing supply and global competitiveness, the EU launched the Raw Materials Initiative (RMI) in 2008 (consolidated in 2011). The strategy lays on three main pillars (European Commission,2022):

- Ensure a fair and sustainable supply of raw materials from global markets
- Foster a sustainable supply of raw materials within the EU
- Boost resource efficiency and supply of “secondary raw materials” through recycling.

Within this strategy, CRMs represent a focus for the EU as an enabler for many industrial and economic sectors. In 2011, the EC published the first list of CRMs with 14 raw materials. The list is updated every three years; the last version was published in 2020 with a gradual increase of CRMs. The 30 materials, which made the latest version of the list, consider the rising importance of CRMs in the new frontiers of the EU economy, especially green and digital transition, defense, and aerospace.

The EU has focused on bringing private and public sectors together to cooperate in a standard set of actions. For instance, the European Innovation Partnership on Raw Materials is a platform bringing together stakeholders of the private sector, public service, academia, and non-governmental organizations (NGOs) to reinforce the RMI. The European Institute of Innovation and Technology (EIT) Raw Materials, with more than 120 members, is the largest consortium in the field. It has the mission to enable competitiveness of the EU industry through innovation, education programs, and entrepreneurship. Since 2017, the European Battery Alliance (EBA) and the European Raw Materials Alliance (ERMA) were established to build resilience and strategic autonomy for batteries, REEs, and magnet value chains. The ERMA also helped define the last version of the CRMs list in 2020.

The EU funds several projects through the EIT and Horizon Europe: the EURARE aims to develop a sustainable exploitation scheme for the ore deposits of REEs in the EU. The project FRAME (Forecasting and Assessing Europe's Strategic Raw Materials Needs) aimed to deepen the knowledge of CRMs and create synergies for common strategies among several sectors.

3.2.1. 2020 list of Critical raw materials in the European Union

Building on the RMI, the EC published the updated list of CRMs and an Action Plan to increase the bloc’s resilience and autonomy in the field of CRMs. The inventory was constructed following the same methodology as the 2017 previous version (European Commission, 2017). The assessment takes into consideration 83 raw materials determining two main parameters for each one:

- economic importance (EI) in terms of end-use applications is calculated considering the share of end-use in a specific sector[13], the manufacturing sector’s added value

[13] The economic and industrial sectors following under the Statistical classification of economic activities in the European Community (NACE rev.2) by Eurostat (2008)

in the EU economy and the substitution index as a reducing element for the economic importance[14]

- supply risk (SR) reflects the disruption possibility in the EU supply by analyzing the performance of trade partners. The calculation considers the concentration of primary supply from importers adjusted with indexes for their governance and trade performance. SR also considers the share in the production that the importers have in the global supply and the presence of recycling and substitutions as risk-reducing factors.[15].

The assessment is performed using a set of data prioritizing official EU data when available, MSs authorities' public data, and in some cases, public data from international organizations or non-EU authorities. An average of the last five-year period is used in the computation. The resulting list contains 30 CRMs, introducing lithium, titanium, and strontium from the previous 2017 list (European Commission,2020c). The EC reserves the close monitoring of nickel due to its overall importance in the batteries production.

The 2020 list is a powerful tool to guide negotiations and diplomatic work in the field of trade and cooperation for CRMs. It is also used to define research and innovation under the Horizon Europe and national research programs, especially for new mining technologies, substitution, and [16] as much as possible.

Together with the revised list of CRMs, the EU published the first foresight report estimating the required demand of CRMs (pre-COVID-19 scenario) to meet the 2030 and 2050 targets. According to the report, climate neutrality in the EU will require:

- for batteries (both EVs and BEES) up 18 times more lithium and five times more cobalt in 2030, almost 60 times more lithium and 15 times more cobalt in 2050.

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[14] the presence of substitutes reduces the dependence of a specific sector on the analyzed raw material. It is calculated considering three main sub-factors: the substitute cost performance, the use in the sector, and the sub-share of each substitute within the same application

[15] For more details: European Commission (2017) METHODOLOGY FOR ESTABLISHING THE EU LIST OF CRMS [online] https://op.europa.eu/en/publication-detail/-/publication/2d43b7e2-66ac-11e7-b2f2-01aa75ed71a1

[16]circular economy approach (ibidem).

A circular economy refers to a production and consumption model which involves an extension of the life cycle of a product through sharing, leasing, reusing, repairing, refurbishing, and recycling. The main goal is to reduce the use of primary (virgin) resources and the amount of waste

- for permanent magnets (EVs, ICT, and wind generators), the demand might increase tenfold by 2050 (ibidem).

3.2.2. The European Union Action Plan for Critical Raw Materials

Together with the revised 2020 list of CRMs, the EU identifies the main challenges in the supply of raw materials and a set of ten actions to be developed by 2025 at the supranational and national levels to assure a secure supply and global competitiveness. The EU Action Plan can be summarized in the following areas of intervention:

Develop a resilient value chain for CMRs

The EU seeks to reduce the vulnerability of existing raw materials supply chains. For instance, lithium extracted in the EU is then processed in foreign countries. The EU wants to invest in closing similar gaps and creating a resilient supply chain to prevent unexpected disruption through domestic sourcing of substitute materials. Through the EBA, the EU has already set a goal to cover 80 percent of European lithium demand by internal sources by 2025 (ibidem). Moreover, the European Investment Bank has already updated its new energy leading policy, prioritizing investment in CRMs (European Commission, 2021). Finally, the green taxonomy, currently under adoption, will help guide public and private investments toward sustainable activities in respect of high environmental and social standards.

Reduce dependency through circular economy, innovation, and sustainable products

Within the EU Green Deal, the Commission has already defined an Action Plan for Circular Economy as a strategy to promote circular design and the use of secondary raw materials.[17]. The Waste Electronic and Electrical Equipment (WEEE) Directive and the Batteries Directive provide the general framework for recovering secondary raw materials in two material-intensive sectors. The EU is already leading the circular economy approach, with more than 50 percent of commonly recycled metals (iron, zinc, and platinum) covering 25 percent of the domestic consumption (ibidem). However, more can be done to recover and use secondary CRMs (like REEs, gallium, and indium) since they represent only a marginal contribution to the current consumption. For instance,

[17] Secondary raw materials are recycled materials that can be used in manufacturing processes instead of together with virgin (primary) raw materials.

permanent magnet recycling projects are still not commercialized, and the possibilities offered by urban mining[18] are not fully exploited in any MSs (Barteková,2016).

<u>Enforce the sustainable and responsible domestic production and processing of raw materials.</u>

Creating a more resilient and autonomous supply chain means exploiting the possibilities offered by domestic production to the maximum. The EU has been successful in developing the mining sector for base metals such as copper and zinc, but it is less successful for what regards CRMs. Considering the geographical distribution of CRMs (Figure 4), the EU can achieve more autonomy in the battery sector, covering part of the demand with lithium, nickel, cobalt, and graphite reserves. Moreover, many resources are in countries heavily dependent on coal or carbon-intensive industries (Figure 5), such as Poland and Romania. The EU is seeking to accompany the green transition with the "Just Transition Mechanism ", aiming to alleviate the socio-economic impact of such a process in regions depending on coal. Many of the hard skills required in the coal industries can also be transferred to CRMs through the reskilling and upskilling programs within the EU Skills Agenda [19]Plan.

[18] Urban mining is the process of recovering CRMs from WEEE through mechanical and chemical treatments and within the urban context

[19] The EU Skills Agenda is a five-year plan to promote reskilling and upskilling of individuals and businesses by promoting sustainable competitiveness, ensuring social fairness, and building higher resilience after COVID-19 and in the face of future crises.

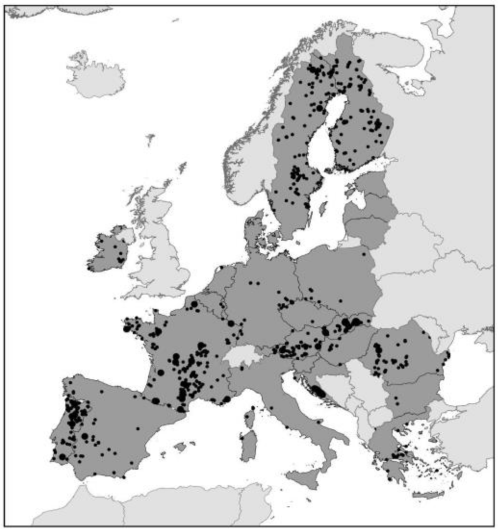

Figure 4 Deposits of Critical Raw Materials in EU-27 (European Commission, 2021)

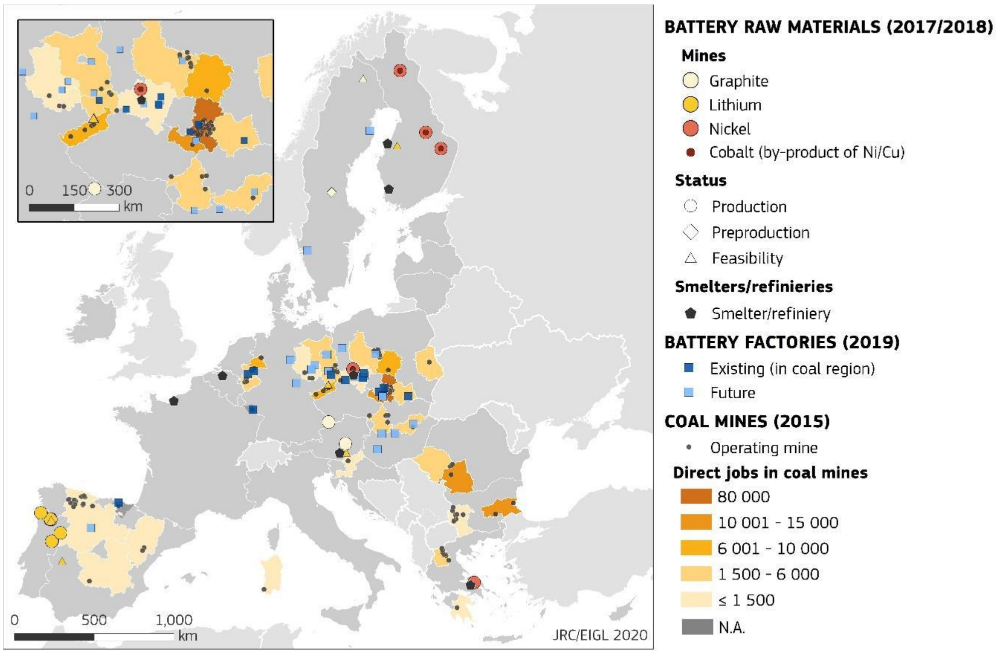

Figure 5 Battery raw material mines, battery factories and coal mines (European Commission,2021)

Regarding high standards, the European and national legislative framework is currently in place to guarantee that mining activities occur under environmentally and socially sound conditions. The main issue is not enforcing such criteria but more the capacity of the EU (and its MSs) to speedily transform projects. In the EU, environment and energy are shared competencies between MSs and the EU. Both can legislate on these matters and adopt legally binding acts. Consequently, the authorization process for infrastructure projects is differentiated between countries regarding actors involved and required stages.

Under the Better Regulation Agenda, the EU seeks to map out the main obstacles to a more efficient permitting procedure in the MSs.

Diversify supply from third countries, guaranteeing high environmental and social standards.

Due to a small concentration and the underdevelopment of the European mining industry, imports will still cover the demand for primary CRMs in the medium and long term. In its external actions, the EU committed to a well-diversified and undistorted access to the global trade markets of raw materials.

First, the EU is reinforcing trade policy tools (such as new Free Trade Agreements) and cooperating in internal fora to create new partnerships. The EU's requirements for high environmental and social measures will help promote green transition in third countries committed to decarbonizing their industry. Moreover, it will create a leveling playing field for EU industries suffering from unfair competition from polluting importers.

Current diplomacy actions and cooperation includes:

- the annual EU-US-Japan trilateral on CRMs to discuss supply risks, fair competition, trade barriers and international standards.
- the OECD, in which the EU deals with using conflict minerals and responsible sourcing.
- the UN, in which partners define the global framework for resource management and mineral governance.
- the WTO for discussing market access, technical barriers, and export restrictions.
- the G20 for resource efficiency and fair competition.

The EU aims to exploit diplomacy instruments to enhance strategic partnerships with resource-rich third countries. The EU is looking to countries with highly developed mining sectors, such as Canada,[20]Australia and developing countries in Africa and Latin America. The EU also cooperates with net-importers to share best practices in the R&D

[20] See EU and Canada's strategic partnership for raw materials, https://ec.europa.eu/growth/news/eu-and-canada-set-strategic-partnership-raw-materials-2021-06-21_en

and the use of secondary CRMs from recovery and recycling. Through the trilateral dialogue with US and Japan, the EU exchange ideas and collaborate in defining legislation and policy actions. One of the examples is the new EU regulation on "conflict minerals", a subcategory of CRMs, also analyzed in the US for the due diligence required under the *Dodd-Frank Wall Street Reform and Consumer Protection Act* (The White House,2022c).

Following the EU-Western Balkan Summit, held in Zagreb on the 6th of May 2020, the EU is working to integrate Western Balkan countries into the EU industries with a specific focus on primary raw materials (e.g., Serbia is rich in borates and lithium, Albania in platinum reserves). With Ukraine, the EU signed a strategic partnership in July 2021 with a specific focus on the battery industry and mining activities that can benefit both industries and improve global competitiveness. Although the Russian invasion stopped such an agreement, the EU remains committed to broader cooperation in the following years through a reconstruction platform that will help build back the Ukrainian industry and mining sector in the country (European Commission, 2022c).

3.3. Member states of the European Union

In the EU, environment and energy are shared competencies between MSs and the EU. In implementing EU directives, the MSs can define national strategies and bilateral and multilateral trade agreements with a certain level of freedom. In this section, the case of Germany and Italy are brought as case studies to analyze current actions for green transition and whether the countries are considering raw materials in their strategies.

3.3.1. Germany

Germany is the top polluter among the EU-27 and the seventh country worldwide (EIA,2020). The countries rely mainly on imports to cover their energy demand (63,7 percent of the total), especially with crude oil and natural gas (Wettengel,2021). Leading suppliers are Russia (34,1 percent and 55 percent of crude oil and natural gas imports, respectively), the US and Norway (IEA,2022b). Due to the rich reserves of coal, Germany was the fourth-largest consumer of coal till 2016 (Worldometer,2022). In 2018, the German government decided to phase out coal mining and power plants due to global competitiveness and an unprofitable market. Today only lignite is still mined in Germany (ibidem). Renewable energy share in electricity consumption is constantly increasing. In

2020, it reached a share of almost 51 percent in the total electricity production through the wind (27 percent) and solar power (10,5 percent) (IEA,2022b).

In 2010, Chancellor Angela Merkel initiated the process of green transition [Energiewend] with an ambitious plan for a low-carbon, reliable and affordable energy supply by 2050 (Clean Energy Wire, 2022). The plan includes a complete phase-out of nuclear power by 2022 and existing coal powerplants by 2038, specific targets related to RES (60 percent of primary energy by 2050 and 80 percent of electricity generation by 2050), and GHG reduction target (80-95 percent by 2050 compared to 1990 levels) (ibidem).

Germany's domestic production of raw materials includes clay sand, gravel, natural stones, and gypsum. The country produces brown coal, gas, and crude oil as energy raw materials. The extraction and processing of minerals are negligible and restricted to copper, silver, and minor gold. Considering the 2020 EU list of CRMs, the only material produces locally is fluorspar which does not have any applications in the green transition (Schmidt,2021). Moreover, its production is only 1 percent of the global market (ibidem).

In 2010, the German government adopted its first raw material strategy to address supply risk, environmental concerns, and social costs in production. The strategy aims to achieve more accessible access to raw materials, market transparency, material efficiency, recycling, R&D, and innovation (mainly to find new substitutes). Within the strategy, Germany implemented various programs such as the German Resource Efficiency Program (ProgRess I in 2012 and ProgRess II in 2016) and founded the German Raw Material Agency (DERA) (ibidem).

The 2010 Raw material strategy failed to deliver the expectations of either the government or the private companies (ibidem). The exploration support program was launched twice before being discontinued in 2015 due to a lack of demand. The Alliance for a Secure Raw Material Supply, founded in 2012 by the Federation of German Industries, was also closed in the same year. There are several reasons behind these failures, but the main one can be tracked in the German government's general lack of support for enforcing the mining sector in Germany (acatech,2018). The strategy document emphasizes how it is a matter for the companies to ensure their own supply of raw materials (Schmidt,2021). However, the mining sector is well-known to be risky and capital-intensive. Without financial support and incentives from the government, private investments in costly and long-term mining projects were not profitable for the German industries (acatech,2018).

Also at the international level, Germany was unable to achieve consistent results. Although some bilateral agreements were stipulated with Kazakhstan, Mongolia, and Peru, no one of these partners proved to be a reliant supplier of CRMs. The agreements were also criticized due to the government's lack of political courage to address issues such as sustainable aspects and market failures with the partners (Schmidt,2021).

Following the pressure of several stakeholders (e.g. environmental and social NGOs, Federation of German Industries-BDI), the Federal government is working on an updated raw materials strategy. The new version will consider the increased need for raw materials due to digital and ecological transition, market distortion, higher production concentration in Asia, and sustainability concerns. It lays on three main pillars: increase domestic production, support the import of raw materials, and increase recycling activities (BMWi,2022).

Regarding domestic production, the German government is seeking exploration within the national territory to increase energy security and reduce dependency on foreign countries. Compared to the previous strategy, the federal government recognizes the role of the public sector in financially supporting mining projects. The domestic strategy will be coupled with an enforced import of raw materials through long-term and more secure contracts. Regarding high environmental standards and human rights, Germany is willing to make untied loan guarantees available for the private sector in their partnership with foreign mining companies. Moreover, the strategy stresses the necessity of a level playing field for the German industry addressing unfair competitiveness by producers who do not respect high standards and stressing the WTO's role in settling trade disputes (ibidem).

Finally, the third pillar regards the recycling of end-life products to increase the availability of secondary raw materials, especially CRMs. The German raw materials strategy addresses the issues of recovery of CRMs which are usually found in small amounts and combined with other materials by setting research funding. Other commitments regard setting ambitious reuse and recovery rates in line with the latest EU Circular Economy Action Plan and intensifying the relationship between science, industry, and Administration (ibidem).

3.3.2. Italy

Italy is the third-largest energy consumer in the EU, after Germany and France (Statista, 2020). Primary energy consumption is covered mainly by fossil fuels (73,9 percent), especially oil (34,5 percent) and natural gas (34,0 percent). Renewable energy represents around 20,5 percent of the total demand. Imported electricity (5,6 percent) closes the energy balance (IEA,2022). The country covers its energy needs through imports (74 percent), especially with imported oil (88,7 percent of domestic consumption) and imported natural gas (92,9 percent of the country's gas consumption). The demand is covered by four major countries, with Russia leading the overall importation (of petroleum, natural gas, and coal) with a share of 25 percent (IAC,2022).

As a member of the EU, Italy has implemented European GHG reduction targets in the National Plan, defining specific objectives. The Integrated National Plan for Energy and Climate 2030 [PNIEC] sets a 30 percent share of renewable energy in the final gross consumption, a 40 percent reduction in GHG emissions (compared to 1990 levels), and an energy efficiency improvement of 43 percent by 2030. The Italian government is currently working on updating the PNIEC and national objectives in line with the EU Fitfor55 Package. According to estimation, meeting the update target will require RES to cover 40 percent of final energy consumption by 2030 (The European House Ambrosetti, 2021).

The National Recovery and Resilience Plan (NRRP) [Piano Nazionale di Ripresa e Resilienza] will play a crucial role in achieving these objectives. It is a set of investment and structural reforms to address the weakness of the Italian economy exacerbated by the COVID-19 (MEF,2021). The PNRR will accompany the country on the path of ecological and digital transitions with a total amount of EUR 248 billion,[21] (ibidem). For the ecological transition, one of the three main pillars, the country allocated EUR 68,6 billion in investment and structural reforms that will accompany the effort toward the green economy (ibidem).

[21] of which EUR 191.5 billion comes from the Next Generation EU, EUR 30,6 billion financed internally by the Complementary Fund, and EUR 26 billion from the EU Development and Cohesion Fund

Italian government recognizes the relevance of a steady and secure raw material supply for the success of the green transition (MiTE,2021). Italy is working towards adopting the actions envisaged in the EU action plan (ibidem). Since January 2021, together with other MSs, Italy has been part of the second Important Project of Common European Interest (IPCEI) on batteries, with a net contribution (private and public investment) of over EUR 1 billion (ibidem). The goal is to create a sustainable and innovative value chain to produce a new generation of raw materials, cells, modules, and battery systems and the reconversion and recycling of existing batteries at the end of their life.

At the national level, the National Working Table for CRMs was established in January 2021 to bring together various national stakeholders along the entire CRM value chain (ibidem). The table is attended by actors from the world of universities and research, as well as small and medium-sized enterprises, consortia, and trade associations (ENEA, ISPRA, ISTAT, ERION, Confindustria).

The main contribution of Italy to the overall EU strategies for raw materials might come from the recovery of secondary raw materials. According to estimation, the Italian industry relies upon 90 percent of imported raw materials due to a historical lack of natural reserves in the national territory (erion,2021). Conversely, the country has become a front-runner in the circular economy, especially regarding recycling and recovery of end-life products (ibidem). Italy has one of the lowest domestic material consumptions among the G7 countries and EU-27 (around 10 tons per capita) (ibidem) and net import has decreased constantly since 2005(Eurostat,2021). This trend is partly related to the economic recession and the substantial improvement in the efficient use of resources. In 2020, the EU average utilization rate of recycled material was 12,8 percent. Italy was the second country with the highest rate (21,6 percent), following France (22,2 percent) (Construcia, 2022).

Within the PNRR, the Italian government incorporates the enhancement of waste recycling as one of the main actions of the ecological transition. Among other objectives, the PNRR sets a 55 percent recycling rate for WEEE by 2026. WEEE contains up to 69 periodic table elements, including precious metals (such as gold, silver, copper, and platinum), CRMs (cobalt, palladium, indium, germanium, bismuth, and antimony), and base metals, such as aluminum and iron. Considering the fundamental role that these materials will have in the ecological and digital transition, Italy is committed to enforcing their recovery as the main driver for reducing the national reliance on foreign suppliers (MiTe,2021).

4. Discussion

This section will analyze and compare the strategies for the supply of CRMs adopted by the US and the EU to identify possible convergences and discrepancies.

In 2020, the EU updated the list of CRMs identifying thirty raw materials that can be considered critical for developing the EU economy for their economic importance and risky supply. More recently, the USGS performed a similar analysis for the US context, identifying 35 minerals.[22] through a quantitative and qualitative assessment based on the supply risk. The two assessments recognize that 20 raw materials are critical for both economies (Figure 6). For instance, lithium and cobalt, for battery systems, and REEs, for permanent magnets, appear in both analyses. Both blocs are net importers of these CRMs. Due to their role in the green transition in the digital and defense sectors, the expected substantial growth in the demand might lead to supply disruption.

A total of 12 elements appears in the EU list but not in the one proposed by the USGS. Among them, silicon metal is perhaps the one with an essential role in the green transition due to its application in silicon solar cells. While both blocs rely on imports of silicon, the EU is more dependent on China (17 percent) than the US (European Commission,2020a). The US natural reserves of silicon are abundant, and several companies produce ferrosilicon and silicon metal domestically (USGS,2020). The country covers the rest of the demand through imports coming from Russia and Brazil (Statista,2020).

The elements documented in the US federal list but not in the EU are 15 out of 35. Among them, nickel found application in the battery and solar power sectors. It is not considered critical for the EU due to the low supply risk. The bloc has a limited dependence on imports (in 2020, imported nickel ore accounted for 28 percent of the total supply), and post-consumer recycling is a mature practice within the EU, supplementing the primary supply. The recovered nickel represented 43 percent of overall nickel consumption in 2020 (European Commission,2020b). However, the EU reserves to closely monitor the

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[22] Unlike the EC, the USGS listed the rare earth elements individually and not under the light or heavy REEs. The REEs are grouped for both assessments to compare the list proposed by the EC and the USGS. The official number of critical minerals in the 2022 Federal list equals 50.

evolution of nickel supply due to the increasing demand as a substitute for cobalt in batteries (European Commission,2022b).

Conversely, the USGS decided to add nickel in the 2022 revision of the critical minerals. The country is a net importer of nickel by allies such as Canada (42 percent of total supply) and trade partners (Norway,10 percent and Finland, 9 percent). There is only one domestic mining site in the US (located in Michigan), and the refining process is almost wholly located in foreign countries (USGS,2020). The 100-day review by the Biden administration also underlined the necessity to invest in a new nickel refinery as a top priority for a secure supply (The White House,2022c). The combination of a single point of failure in the domestic supply and the expected growth in the demand due to the new applications in the battery directed the USGS to consider nickel as critical (USGS,2022).

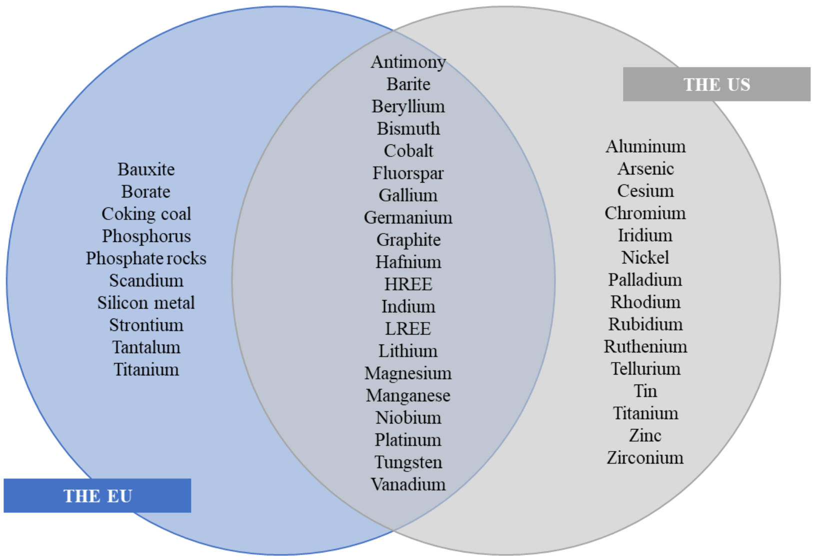

Figure 6 Comparison between CRMs listed in the 2020 EU list and 2022 Federal list of the US (own work)

Common grounds and discrepancies can be identified regarding the strategies adopted by the two blocs. As far as the US is concerned, the strategy focuses primarily on reducing the dependency on foreign importers and thus investing in the domestic dimension, especially in the diversification of the internal supply and R&D to promote materials efficiency, reduce the use of minerals and discover possible substitutes. The debate on raw materials has deep roots in the American political scene, with the concept of criticality already mentioned in the 1939 Critical Material Stock Piling Act. The well-established regulation facilitates the development of REEs industries in the 80s. Although the industry was eventually overshadowed by Chinese competition, innovation in raw materials continued to have a predominant role in the R&D of the country, and today's activities cover all the three pillars of the US Critical Materials Strategy. It is also important to emphasize the strong correlation between CRMs and national security in the US. The DOD has direct control over the stockpiling of raw materials (such as heavy REEs from China), and it received the mandate to analyze the supply of CRMs in the 100-days review ordered by the Biden-Harris administration. In this assessment, the role of CMRs in the energy transition is shortly discussed, while the primary considerations remain in the defense and aerospace sectors. Finally, the US strategies reflect the liberal-pluralist and market-driven approach of the US. The industry has a significant role in policymaking. Several times in history, the American industrial associations were able to lobby for their interest and address concerns directly to Congress. Even in the current effort for mining exploration and domestic supply, the Biden administration is seeking a public-private partnership with the private sectors covering a significant part of the funding.

Conversely, the experience of the European Union is more time-restricted, considering that it was established only in 1993 and is composed of sovereign states which follow differentiated strategies. The comparison of two MSs, Germany and Italy, emphasized this aspect. Due to their heavy import dependency, the countries will likely be the most impacted by the phase-out of Russian imports following the Power EU initiative. Germany is developing a harmonized response for the CRMs supply considering its significance for a successful energy transition. The country’s strategy includes private-public partnerships, bilateral agreements with foreign producers, and securing domestic supply. By contrast, Italy shows a more limited approach: the procurement of CRMs is briefly mentioned in the national circular economy strategy within the NRRP without proposing possible domestic supply or enhanced international cooperation. The country seeks to improve the well-established experience in recovery and recycling, especially of WEEs, to increase the supply of secondary raw materials. Differences between MSs can be attributed to their distinct regulatory style, or the given priority and concerns governments place on the topic. This choice ultimately led to a lack of an integrated approach within the EU-27.

With the RMI and the most recent Action Plan for CRMs, the EU is trying to overcome the limits in the differentiated position of its MSs. The Action Plan was developed through the typical European consensual style creating a platform for broad public consultation with a collaborative effort of various DGs, the EC, private and public stakeholders, and NGOs. The main element of the EU strategy is resource diplomacy in the context of international fora and agencies such as the UN and WTO. Similar to the diplomatic actions in the context of the Paris Agreement, the EU is looking for multilateral and bilateral trade agreements with foreign importers and cooperation in R&D and innovation with resource-poor countries. The trilateral partnership with the US and Japan is an example of cooperation with three forces heavily dependent on importers but being front runners in improving technologies and recycling secondary raw materials. Through the Circular Economy Action Plan, within the general context of the EU Green Deal, the EU is willing to share best practices and expertise in the field, especially for recovering REEs from WEEEs.

Table III summarizes the blocs' position towards the different elements that composes their supply strategies. Considering the upstream supply, both are heavily or entirely dependent on imports of raw materials, especially the EU; they perform better in the secondary steps of the supply chain, namely the manufacturing of components and end products in which their only competitor is China. Regarding the diversification of supply, both countries are engaged in domestic exploration through public and private investment. Both powers emphasize the creation of new jobs provided by the sector, with the EU stressing the importance of upskilling and reskilling processes in resource-rich regions (e.g., Poland). The diplomatic action is where the EU is more active, building from the experience of the Paris Agreement and, most recently, the COP26 in Glasgow. The Biden administration seeks more vital but limited cooperation, remaining in the defense and allies' framework. At COP26, both countries signed a multilateral agreement with South Africa, a resource-rich country, to develop the green transition in the region and resource exploration. The forces will likely use similar cooperation with other foreign importers and like-minded countries in the upcoming future.

Regarding stockpiling, it has been used in the US for national security reasons (Chappell et al., 2008). This possibility cannot be applied in the EU due to the historical failures to build a supranational and common defense framework. Another element of contrast regards the role of recycling. Both net importers and developed countries recognize the importance of recycling to cover part of the demand with secondary raw materials from recovered end-of-life products. However, the EU has already established a coherent legal framework with specific directives for sectors such as EEE and batteries that use a consistent number of CRMs. However, both blocs lack concrete and structure measures such as diffuse recycling facilities and sizing the potential of urban mining. Finally, the role of R&D in improving efficiency, reducing material intensity, and finding substitution are crucial in both strategies. Due to a more deregulated legal framework, the US can scale up innovative applications and has already become a front runner in the industry.

Table III Summary of the main actions in the strategies for CRMs supply in the EU and the US

	Industrial Supply Chain		**Diversification of Supply**		**Resource diplomacy**	**Stockpiling**	**Recycling**	**R&D**
	Upstream (extraction, processing into metals, alloys.)	Downstream (manufacturing of components and assembly of end products)	Domestic (mining, exploration and permitting, skilled workforce)	Foreign (financing projects abroad)	(policy dialogue, e.g., financing, development aid, international collaboration)	public defense	established recycling operations, waste management policies	substitution, efficiency improvement, collaboration with academia and institutes
US	*	**	**	o	*	*	*	**
EU	o	*	*	*	**	o	**	*

o absent or not applicable * work in progress ** well established

Limitations

Considering the constraints posed by a master thesis project, the study was limited to two major political forces, the EU and the US, which have taken concrete actions toward defining a CRMs strategy. However, it is recognized that China has a leading role in the CRMs market, controlling the highest share of the supply chain, both in terms of upstream and downstream activities. China has established a solid policy framework for the industry of CRMs, especially REEs, considering them under "protected and strategic materials" and thus stringent state regulation. This strategy is unlikely to change and adapt to the current challenges posed by the clean transition. Moreover, China is an emerging economy and thus difficult to compare with two solid realities as the EU and the US, with clear and binding commitments to carbon neutrality. The country still placed national interests at the center of its growth strategy, neglecting its development's social and economic costs. This choice can be seen clearly in the mining industries, especially REEs, where excessive mining through polluting techniques leads to high environmental and social costs.

A second limitation in this study is related to the selection of technologies in which raw materials are used, namely PV panels, wind turbines, and batteries for BES and EVs. The clean energy transition will require raw materials in different applications, such as electricity networks and hydrogen. However, electricity networks (transmission and distribution grids) require exclusively copper and aluminum. Neither raw materials are included in the EU CRM list nor the Federal list of critical minerals of the US. Moreover, the two materials do not suffer from possible scarcity or challenges in the supply even if the demand is expected to increase exponentially to support the installation of renewable energy systems and the electrification of end-use. Finally, the industry is mature, and the process of recovery and recycling of both materials are well-known and widespread worldwide.

Regarding hydrogen production, electrolysis represents the most promising and sustainable process to increase the use of hydrogen as an energy carrier in the transportation sector and as a storage source. The IEA (2021) has emphasized uncertainties about which three main types of electrolysis (alkaline, proton exchange membrane-PEM, and Solid oxide electrolysis cells-SOECs) will dominate the market.

The alkaline and PEM electrolyzes involve several CRMs such as nickel, zirconium, and lanthanum, while the SOECs have a lower material cost, although they are less developed. The IEA expected a slight increase in the demand for the CRMs required in electrolysis due to R&D and innovation that will drastically reduce the demand for the material. Therefore, no criticality in the supply of these materials is envisaged; thus, hydrogen applications were not considered in this master thesis.

Conclusion and recommendations

This master thesis investigated whether the challenges in the supply of CRMs might hinder the pace of energy transition and net-zero energy ambition of the EU and the US. CRMs are characterized by a high geographical concentration with few players controlling the upstream and downstream supply chain. Domestic supply might not always represent a feasible option due to scarcity of natural reserves or the need for long-term and risky investments. The EU and the US seem to recognize the role of CRMs in the clean transition and the need to address them in their political actions. The Action Plan in the EU and the 100-day review in the US defined a first response to the issue. They propose multi-level and diversified strategies, which include the enforcement of the supply chain, procurement diversification, diplomatic actions, and R&D. To meet the 2030 reduction targets, it is now crucial to transform these ambitions into concrete actions. The remaining eight years require bolder solutions, also considering the recent Russian invasion and the changed geopolitical and energy scenario. In particular, the policy actions taken by the EU and the US should also consider:

<u>Establishing a level playing field in respect of environmental and social standards</u>

The EU and the US have a long-time experience in the regulation of mining activities. In their diplomatic actions, the blocs should pursue trade agreements and cooperation only with countries seeking to improve their legal and regulatory practices providing them with the technical and political support. The blocs can incentivize producers to adopt more sustainable practices and enforce due diligence processes to identify, assess and mitigate risk related to mining operations. Setting and respecting high standards is a fundamental step for a just and inclusive transition in which the environmental and social costs of the clean transition are distributed and not only paid by vulnerable communities in resource-rich regions.

<u>Strengthening international cooperation to ensure reliable and sustainable mining activities</u>

The UN Environmental Programmer’s International Resource Panel has highlighted the lack of an international governance framework to inform policy strategies and coordinate international efforts on mineral security. Building from the diplomatic experience in the

COPs, the blocs can be the frontrunner in addressing these gaps in international fora. A coherent multilateral framework will provide clear market signals, de-risk investment, mobilize public funds, accelerate global R&D and innovation efforts, and promote knowledge and capacity transfer to various countries, especially LDCs and SIDSs.

Supporting the development of recovery and recycling of CRMs

The EU and the US have set overall recycling rate targets for consumer products, with the EU also focusing on end-of-life cars, batteries and WEEE. However, a product-specific approach is unlikely to encourage recycling materials required in the energy transition. Current targets are weight- and volume-based, meaning that companies and local authorities can meet the recycling target by focusing on high-volume materials and common metals that are more recyclable than those found in small quantities. Specific policies such as a minimum recycled content requirement, tradeable recycling credits, and taxes on virgin materials can incentives recycling operations and drive the growth of secondary raw materials. The success of such policies, coupled with financial aid and subsidies, will depend on the market evolution and dynamics (e.g., how a specific tax on primary raw materials will impact the uptake of secondary CRMs). Also, in this field, bilateral cooperation between the blocs can leverage the policy framework to have a standard response in the global market.

In conclusion, the strategies adopted by the EU and the US, if correctly implemented, will provide them with enough resiliency to face the challenges posed by the critical raw materials supply. The evolution of the market, moving beyond the supply-demand dichotomy of the energy commodities, might represent the highest level of uncertainty due to a differentiated market for each critical raw material. Through WTO and other supranational fora, international cooperation and global governance will become even more fundamental in dealing with market distortion and unfair competition of monopolistic powers.

List of acronyms

BEES Battery energy storage systems

CO_2 Carbon dioxide

COP United Nations Climate Change Conference

CRM Critical Raw Material

DG Directorate General

DOD Department of Defense (of the United States)

DOE Department of Energy (of the United States)

DOI Department of Interior (of the United States)

DRC Democratic Republic of Congo

EBA European Battery Alliance

EC European Commission

EEE Electrical and electronic equipment

EIP European Innovation partnership

EU European Union

GHG Greenhouse Gas

GDP Gross Domestic Product

HREE Heavy rare earth elements

IEA International Energy Agency

INDC Intended Nationally Determined Contribution

LDC Least Developed Country

LREE Light Rare Earth Elements

MS Member State

NDC Nationally determined contribution

NGO Non-governmental organization

NIMBY Not In My Back Yard

NRRP National Recovery and Resilience Plan

OECD Organization for Economic Co-operation and Development

OPEC Organization of the Petroleum Exporting Countries

PM Permanent Magnet

PMSG Permanent Magnet Synchronous Generator

PV Photovoltaic

R&D Research and Innovation

REE Rare Earth Elements

RES Renewable Energy Sources

RMI Raw Materials Initiative

SIDS Small Island Developing State

SR Supply Risk

UK The United Kingdom

UN United Nations

UNFCC United Nations Framework Convention on Climate Change

US The United States

USGS US Geological Survey

WEEE Waste Electrical and Electronic Equipment

WG Working Group

WTO World Trade Organization

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