Rare Earth Elements: Trade-off for Environment, Energy Security and Policies

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***Abstract*—The green technologies are dependent on critical materials and rare earth elements (REE) which are seen to be linked with the energy security in Europe. Disruptions in the REE supply chain can heavily impact the rhythm of green energy transition. The REE are abundant in nature despite their intriguing name, but capabilities for mining and refining are rather limited with environmental and geopolitical concerns. This paper aims to identify and discuss lessons from REE mining and processing around the world in an environmental and social impacts perspective. Furthermore, this paper discusses existing REE projects and policies in European and Nordic context. Technologies and technological changes can trigger paradigmatical shifts in energy system, but technology needs to be supported by sound policies. Innovative solutions for offshore wind need to aim for design optimization with REE reduction or substitutions as a part of green circular economy.**

***Index Terms*—Rare Earth Elements (REE), Environment, Energy policies, Energy security, Offshore wind**

I. Introduction

Technology is evolving faster and modern societies are becoming more reliant on a cohort of minerals. The pressing reality is that the whole world is powered by critical minerals: rare earth elements for wind turbines, medical devices, and electric and hybrid cars; cobalt and graphite for batteries; silicon and tin for electronics and these are just a few examples from a long list. In 2040, as per estimates, the world will need at least four times more critical minerals than what clean energy technologies demand today [1], [2].

The global demand for the metals, particularly critical materials, needed for the green transition and for digital technologies is increasing rapidly. Large quantities of critical minerals are required for production of mobile technology, wind turbines, electric motors, and solar cells [3], [4]. Demand for the Rare Earth Elements (REE) is going to rise through 2030 and beyond and is driven among others, by the usage of permanent magnets in wind turbines and hybrid and electrical vehicles. Nowadays, the global competition for critical materials, specially REE is increasing. REE are seen to have an increased geopolitical and strategic significance [3], [5].

The development of offshore wind is highly important to the European de-carbonization goals. However, offshore wind turbines require large amounts of critical materials and REE as the rare earth (RE) permanent magnets are used in generators. According to estimations, the EU demand for RE permanent magnets to be used in the wind energy will increase from 7,000 tonnes in 2020 to more than 21,000 by 2030 [6].

The present study aims to identify and analyse major lessons from the REE mining and processing around the world, with emphasis on China and lessons about environmental and social impacts of REE. The study will offer insights into the REE mining in the Nordic countries. Learning from the existing landscape of policies in China and European countries with regards to the critical materials and REE will also be outlined. As for research approach, the present study analyses academic studies, experts and industrial views, and harmoniously combine a historical perspective, with a present analysis and future estimations. A critical analysis and a problem-driven learning with regards to trade-off for environment, policies, and energy security linked to REE is also applied.

II. Critical raw materials and Rare Earth Elements

Critical raw materials are those raw materials/ metals/ minerals which are seen as vital for the European economy. Critical raw materials are highly concentrated at extraction, processing or refining stages. They are linked with high supply risk as their supply chain disruption can negatively impact the European industries and economy [7]. Critical materials are produced in relatively small volumes, have low recycling rates and are non-substitutable in their applications. The UK Government vowed to evaluate the list of critical minerals on annual basis and this will be implemented by a new organization, the "Critical Minerals Intelligence Centre (CMIC)" led by the British Geological Survey (BGS) [1], [8].

According to the International Union of Pure and Applied Chemistry (IUPAC), the REEs comprise a group of 17 elements, more precisely, 15 lanthanides plus scandium and yttrium. The REEs are classified in light REEs (LREEs) which are found relatively more in geological ores compared to the

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heavy REEs (HREEs) [9]. Despite their name as “rare”, REE are not geologically rare, but their extraction and processing are difficult, expensive, complex and presents serious environmental impacts. REE have a lot of usage, notably, in energy, medicine, defense industry in terms of permanent magnets, catalysts, and lasers [5]. REEs are also referred to as rare earth oxides (REO) and Rare earth metals (REM)s, but there are fundamental differences among them, and also different prices on the market. REE are linked to geological ore, while REO are those REE which are separated, purified and sold in their oxide form. In industry, REE are commonly expressed in the oxide form as this is the common nature of the traded product on the market. REM term refers to REE following the oxidation step (REO) and are found in a form which meets specific downstream technology applications [9], [10].

REE ores are highly variable in their chemistry and mineralogy, thus, the processing techniques which are required to isolate and refine the REEs need to be designed particularly for each deposit [5].REE occur in many geological settings like for example, in the alkaline plutonic rocks, particularly, carbonatites (the case of the Bayan Obo mine in Inner Mongolia, China and the Mountain Pass mine in California, USA). REE can occur also in rocks such as laterites and bauxites (the case of Zhaibei deposit in southern China and the case of the Mount Weld mine, Australia). Japan has discovered REEs in deep seabed mud. There are proven REE reserves all over the world, in countries such as China, Russia, Vietnam, Brazil, and many deposits were identified in Africa. As per estimations, the scale of REE proven reserves worldwide is over 400 times more than the current annual production [11].

Worldwide China has dominated the RE market, and is the global supplier besides being the global consumer [11]. In 2022, China accounted for 70 % of global production. USA accounted just with 14.3 % and Australia with 6.0 %. Thailand, Vietnam, and Myanmar together produced 7.7 % of the total REE world production [5] . As for the REE processing in the world, there are currently only two countries with such capacity: China and Malaysia. In 2019, China accounted for 90 % of REM as most of companies sent their ores to China for processing. Malaysia receives its REE ore from the Lynas mining company and its Mount Weld mine in Australia. In Europe, Estonia has a small facility for REE processing, and France a REE recycling plant [5].

III. REE Mining and Environment

China is the worldwide hub for the REE mining, processing, and manufacturing. Moreover, the majority of the REEs which are mined outside of China are again sent to China in order to be processed and enter the REE value chain [12]. An analysis of the project pipelines and various estimates for the next decades indicates the geographical concentration of the REEs mining will remain high, and also the REEs refining will remain highly concentrated, see Fig.1 and 2 [13] in Appendix.

Regarding the heavy REE (HREE), particularly, Dysprosium and Terbium, about 50 % of raw materials are provided by Myanmar. The mining of HREE in Myanmar developed relatively recently, in 2016-2017, after suspension of the HREE mining in the Southern China in the context of tough environmental inspections. In the recent years, the HREE mining shifted from China to Myanmar, and Myanmar has become an important location for the HREE mining [12].

China achieved its current status of global dominance in the REE mining and processing because of strong and continuous governmental investments, subsidies and support along the whole supply chain, research, incentives, low labor costs, weak environmental regulations, existence of illegal mines and processing plants. Moreover, China started to develop the REE industry more than half century ago [5]. Nowadays, the Bayan Obo mine is the largest REE mine in the world. At the end of 1980s, China became a major producer of REE in the world [5]. In the early of 1990s, China considered the REEs as protected and strategic minerals of country. Thus, the foreign companies were excluded from the REE mining and could be involved in the REE processing only in joint ventures with Chinese companies and subject to governmental approval. In the period of 2000s, China introduced governmental quotas for the REE export, and introduced production quotas, ban on export of the RE concentrate, and export tax on the RE oxides and metals [5]. In 2010, within the context of great concerns about excessive capacity in mining and processing, illegal mining and trade of REEs within China, poor resource management and great environmental impact and serious health matters, the Chinese authorities took important measures in order to reform the REE industry in China. As a note, from 2011, for the first time, the heavy REEs were distinguished from the light REEs [5]. In addition, the Chinese government has started to build REE strategic reserves, and to increase taxes on exports of rare earth ores, oxides, and compounds. Moreover, China introduced an export tax on the REE end products. In addition, the Chinese government reformed its resource tax in order to extract more fiscal revenues from the REE industry. Initially, the Chinese resource taxes on REE were based on the quantity of mineral extracted. Starting from 2015, the resource tax was to be based on value, and in this way, China followed the international practice [5]. On the reform path of REE industry, in 2016, a Rare Earth Industry Development Plan (2016–2020) was issued by the government. The REEs were considered by China as strategic minerals which required a careful monitoring and strategic actions. Many mining and processing REE enterprises were integrated by six REE industrial groups, and a large number of illegal mines and processing plants had been closed. Environmental protection measures were implemented in Bayan Obo and in the southern China [5]. Further on, in December 2021, the number of major players in the REE mining and processing was reduced from six to four, and the new China Rare Earth Group would control around 70 % of China’s REE production. As per forecasts, the Chinese imports of REE ores are going to increase as the processing industry outside of China cannot cover the rising demand. The Chinese REE exports will not rise and even may decrease, as the priority is to cover the Chinese domestic REE demand [5].

With regards to major REE geological deposits and their mining over the years, the Mountain Pass deposit in California, near Las Vegas, Nevada USA is considered to be the second largest RE deposit in the world discovered in 1949, and operations started in 1952. Between 1960s and mid 1990s, the Mountain Pass deposit was known as the largest LREE resource in the world, despite the Neodymium depletion [11]. However, in 1998, due to environmental concerns, the REE operations were suspended and later on in 2002 were ceased. The operations were re-opened in 2012, but terminated in 2015, due to bankruptcy of owner and the low prices of REEs in China. However, due to heavy geopolitics among China and USA, the REE operations were again reconsidered in 2020 [11]. Another example of REE geological deposit and mining is offered by the Mount Weld deposit situated in Western Australia, which is known to be one of the richest RE deposits in the world [11]. Other RE deposits and mining took place at Lovozero deposit on the Kola Penisula in Russia which operations started as early of 1951 for Neodymium and other REEs [11]. Another example of REE mining is Araxà complex in Paranaiba Province, Southern Brazil which is known for a high production of Neodymium for the global market.

The Nordic countries offer illustrative examples for the mining of critical materials, including REE. The CEO of LKAB company highlighted that within the next 10 years "at least something between 10 till 15 new mines, maybe an exponential increase" can take place [14]. However, the investments in the REE mining in Europe require huge resources in terms of finance, skilled workers, regulations and a considerable amount of time [5]. One case study in the Nordic countries is the Kiruna mine in Sweeden which is located more than 1,300 m under the ground, and is considered to be the largest deposit of REE in Europe. There are environmental matters linked to Kiruna mine as "the mine gives and the mine takes". The mountain landscape was dramatically changed, the city of Kiruna is sinking, people are reporting that they experience " shake every night and day", there is impact on structural integrity of houses and this required relocation of more than 6, 000 people (one third of population) [14]. Kiruna mine and the "mining, but not in my back yard" brought to attention social, cultural and ecological matters expressed by the indigenous sami populations which do not support further development of mines in Kiruna. The Sami culture and their reeindeer culture is considered to be under threat from mining development. Responsible mining means minimizing environmental impact, safe working conditions, and respecting local communities [14]. Critical mineral resources, including REEs are highly correlated with being on or near indigenous land, and local communities and Indigenous Peoples are directly impacted by mining projects [15].

Serious environmental problems and health issues related to RE mining and processing, transportation, waste disposal and decomposition are known [5], [11]. The REE mining and processing produce large quantity of waste and hazardous materials. As per estimations, the production of one REE tonne is producing 2,000 tonnes of waste. The nature and scale of pollutants varies along chain production, from REE mining until RE metals. For example, the REEs in clay deposits are leached in situ with very large quantities of ammonium sulphate, which can contaminate soil and ground water. High concentrations of REEs in tailings can leak into rivers and soils [5]. At Bayan Obo mine, the releasing water contained 5 % of radioactive thorium and high concentrations of other pollutants. In addition, many workers suffered from serious health problems. The environmental damage took high proportions in the southern China, and demanded governmental actions [5]. There are different environmental concerns linked to usage of reagents (chemicals needed for recover metals), impact from operation on nature and landscape, soil and water, and biodiversity loss. Moreover, there is an immense waste production caused by the tailing ponds for decades. [14]. At a particular attention are the environmental and health concerns linked to the radioactivity of the associated elements, such as thorium and uranium. Regulations introduced by the International Atomic Energy Agency (IAEA) and the US Environmental Protection Agency (EPA) are currently used in the REE mining and processing worldwide. However, there are still many and serious concerns about the radioactivity linked with REE mining and processing [11].

IV. REE and Energy Security

Currently China dominates the REE mining and processing, and around 70 % of REE mining and 90 % of REE processing are linked with China. In addition to the REE mining and processing, China has also developed its domestic industry such as manufacturing of magnets, wind turbines, and EV batteries. Therefore, at present China has a dominance of the full REE supply chain [5]. Past and present rising tensions among China and USA, and on going conflicts in Europe and Middle East brought high uncertainty and serious concerns about the supply chain fragmentation and resource supply security [5], [16]. An export ban on REE to Japan was enforced by China in 2010 during a dispute over the East China Sea. In the last years, China imposed export controls on germanium and gallium as a response to the US restrictions on export of advanced chip and other critical technology to China [17]. In April 2025, China offered tough answer to the imposed US tariffs by enforcing export controls on seven REEs, and its export control is not limited to US, but all countries [16].

Recently, the energy security linked with the REE is dramatically challenged by heavy geopolitics among USA, Ukraine and Russia. As a form of payment and exchange for the USA military support to Ukraine during the war with Russia, Ukraine is summoned to supply the USA with rare earth minerals and other critical materials. The European countries have criticized the USA stance towards Ukraine and warned of long-economic burden for Ukraine. The situation became even more complex and has sparked intense diplomatic tensions when USA has shifted to direct negotiations with Russia and Ukraine has been excluded from participation and direct negotiations. Ukraine detains very rich resources in terms of critical raw materials - has 25 of 34 from EU list and 22 of 50 from USA list. Ukraine has significant deposits of REE and as per estimations, the REEs deposits may account for about 5 percentage of the world's reserves. The REEs are known to exist in at least 6 deposits in Ukraine; one of them is the Novopoltavske deposit, in Zaporizhzhia region, and is assessed to be one of the largest deposit in the world [18]–[22].

EU regards Ukraine as important for the European energy security and the European Commission [23] made also clear its position about the potential of Ukraine and possibility to sign up agreement on cooperation in the field of critical raw materials. "I think Ukraine has everything what we need and what we've been getting from Russia. So I see the potential for critical raw materials, but also potential for low-carbon energy in Ukraine as huge, as very, very, very complementary to us", cited by European Commission [23].

Another matter linked to energy security and geopolitics is linked to the critical raw materials and REEs of Greenland. The Kvanefjeld deposit in south Greenland is famous for many resources, including REEs. According to 2011 estimations, this particular deposit has more than 6.6 million tonnes of RE oxides [11]. The race for Greenland's mineral wealth, particularly REEs, among USA and China, has brought strained dialogue and relations between Denmark and USA. USA emphasized its clear claims on the Arctic island because of "economic security" [24].

Regarding the current energy security situation in Europe, Maroš Šefčovič, Executive Vice-President for the European Green Deal, European Commission offered a clarification: "Because if it comes to critical raw materials, we in Europe are much more dependent on China that we've ever been on Russia, if it comes to the fossil fuels " [23]. The Fig. 3 in Appendix illustrates the major EU suppliers of CRMs in 2023; it can be observed that China is a major CRMs supplier for EU [25].

V. REE and Policies

Many political discussions and reports were produced over the years about the China and the role of REE. However, concrete policy actions have been accelerated in Europe in more significant way just in recent decade; the list of CRM was issued in 2011. These policy actions have included and are not limited to the followings: to designate REEs as critical materials; to support and ease of approval processes for REE extraction; to offer subsidies and facilitate loans for REE processing; to encourage reduction of the REE content for various devices; to increase information sharing; to form coalition with countries interested to develop production and process of REE outside of China [5], [26].

Policy activity has accelerated over the course of 2022-2023 in USA and Europe. In 2022, the Inflation Reduction Act (IRA) in USA was a policy step which encourage diversification away from the REE Chinese market [5]. In 2023, in Europe, the draft of Critical Raw Materials Act [27] was released. Moreover, in 2024, the regulations aiming to establish a framework in order to ensure a secure and sustainable supply of critical raw materials were issued. According to this policy measure, the critical raw material supply chain is monitored over Europe. A coordination of the strategic raw materials stocks need to take place among the EU Member States. Auditing of strategic raw materials supply chains for large companies is also required to take place. A threshold of 65 % for the maximum annual consumption from any stage of production or processing which might come from a single third country was also stipulated. Specific benchmarks of 10, 40, and 15 % were stipulated for the amount of mineral extraction, processing, and recycling that should take place in the EU [27].

As a partial response to the risk posed by security supply linked with REE, the UK government announced the UK Critical Minerals Strategy in 2022 [1]. Through this strategy, the UK Government has targeted to accelerate the domestic capabilities and to collaborate with international partners. Moreover, the strategy aims to contribute to enhance international markets by championing London as as the world's capital of responsible finance for the critical minerals [1]. Nevertheless, on the ground, UK presents many challenges with the REE supply chain [28].

In 2024, the former European Central Bank (ECB) president Mario Draghi presented a report [29] which was commissioned by the European Commission about the future of European competitiveness. His main proposal is to actively mobilize investments sourced from both public and private funds of up to 800 Euro billion per year (this is equivalent to about 4.5 % of the EU's GDP). These investments which could be supported by a new issuance of joint debt, would be considered as a key tool in regaining the European ground lost to the both United States and China in terms of economic growth, innovation, and productivity [29]. This might be seen as a solution for supporting also the development of critical rare material supply chain in Europe. Furthermore, in Oct 2024, the European Commission released a report authored by a group of 15 experts led by the former Portuguese science minister Manuel Heitor. This report has highlighted the current EU approach to funding research and innovation is not effective, and draw attention to strategies which can shape the future of European research and innovation landscape. Among the analyzed matters, is the position of EU versus key systemic competitors, notably, the US and China [30].

VI. Discussions

The green energy development is very much linked to steadiness of the RE supply chain. The road map of offshore wind, particularly, floating offshore wind [31] seems to be highly influenced by the trade-off among environment, policies and energy security with regards to REE. Alternative technologies are seen capable to reduce the REE consumption in offshore wind. Enhancing the performance of low REE permanent magnets, expanding processing capabilities outside of China, and recycling are few examples [5], [6].

Energy security concerns pointed out in the near future may be a shortage of raw materials such as REE required for the green energy technology developments. The periods such as "Rare Earth Crisis" (2010-2013) when the RE prices were impacted by the Chinese export policies might become again in picture due to heavy geopolitics among USA, China and other players. REE have become instrumental as " a diplomatic weapon" in the trade wars between China-Japan, China-USA and China-Europe [11]. In the present context of energy security and dynamics of geopolitics, the World Economic Forum (WEF), asked an important question "Are critical minerals the new oil?" [5].

Learning from the Japanese success in reducing REE dependency on China - from 82 % in 2010 to 60 % in 2020 is important for Europe. Over more than a decade, Japan has made investments in countries which are hosting REE and concluded many fruitful partnerships such as followings: in Australia the Japan Organization for Metals and Energy Security (JOGMEC) invested in Lynas's mine; in India, in Vietnam, in Namibia; in Kazakhstan, where Sumitomo has invested in REE processing plant [5]. It seems that Germany has looked out of the Europe by developing partnerships focused on REEs with Kazakhstan and Mongolia. The Inflation Reduction Act issued in USA in 2022 included a tax credit of 10 % of the production cost for those "critical components " which includes REE [5].

The new REE mining and processing capabilities are taking many years to be in place in Europe. Moreover, both REE mining and processing are linked with serious environmental, social, and governance concerns. Other regulatory constraints are very unlikely to scale up in Europe or in UK at path speed or scale in order to reduce the disruption of REE supply chain. Nevertheless, some scale-up took place in Australia, Canada and USA. However, the mining requires a big and long term investment, and for the REE processing, capital costs and know-how and skilled workforce are critical and require support, incentives and policies on long run [5]. On other hand, in the last years. China is focused to improve the management of its domestic REE mining and processing facilities and to ensure adequate rare earth materials supply for its own manufacturers [5].

The World Economic Forum [17] strongly recommends a more balanced narrative about China. The main aim is to minimize disruptions and uncertainties in global supply chains of REE. The prevailing narrative based on geopolitics which regards China as the main source of risk can bring more tensions and uncertainties worldwide.

The green technologies, such as offshore wind and green hydrogen are dependent on critical materials. The development of offshore wind as a part of the green transition can be critical raw materials intensive, notably REE intensive. Therefore, innovative projects and products in offshore wind need to aim a reduction usage for REE, efficiency improvements, optimization of design, and material substitutions, and other alternative technologies as a part of the green circular economy.

VII. Conclusions

Nowadays, the mining, and particularly, the processing of REE is highly geographically concentrated, and China holds a dominant role for decades being the world supply leader. It seems that China will hold a global dominant position in both REE mining and processing for next coming decades. The targeted new mining and process facilities for REE as well as transportation, and waste disposal in Europe need to take in account high environmental and social impacts, as well as a strong cultural resistance, and require stringent environmental enforcements.

Learning from the Chinese experience of more than half century in the REE mining and processing and how China achieved its current status of global dominance in the REE mining and processing can offer valuable learning for Europe. Non exhaustive examples of lessons are as follows: China started to develop the REE industry more than half century ago; current focus of China is to meet first its domestic REE demand; local communities are directly impacted by the mining projects; there is an immense waste production caused by the REE tailing ponds for decades.

Critical raw materials, and particularly, the REE are seen to be linked with the energy security in Europe. Uncertainties and disruptions in the REE supply chain can heavily impact the rhythm of green energy transition. The road map of offshore wind in Europe seems to be highly influenced and at crossroad by the trade-off among environment, policies and energy security with regards to REE.

The existing landscape of policies in the European countries with regards to the critical materials and REE was also outlined and investigated. As a part of the European energy security, the Critical Raw Materials Act was released as a path towards making EU to be more self-reliant in terms of mining,processing, recycling, and consumption of critical raw materials,including REE. Technologies and technological changes can trigger paradigmatical shifts in energy system, but technology needs to be supported by coherent and sound policies. The Nordic REE strategy and the European REE strategy requires a sound synergetic roadmap and with the necessary adaptations to the existing and upcoming geopolitics.

The success of China about the production and processing of REE has behind many decades of consistent governmental support and policies for supporting the whole supply chain for REE. This came along in China also with low labor cost, health matters and environmental degradations in the mining and processing regions, week environmental regulations, illegal mining and processing, export controls, heavy geopolitics and conflictual situations with other players around the world.

China seems to remain critical to the REE supply chains through 2030 and beyond. Diplomacy tools need to be used in a wise and consistent way and taking in account mutual interests linked with the worldwide REE supply chain. A balanced approach among geopolitical players can reduce geopolitical tensions and foster a long term and sustainable REE supply chain and viable solutions.

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APPENDIX

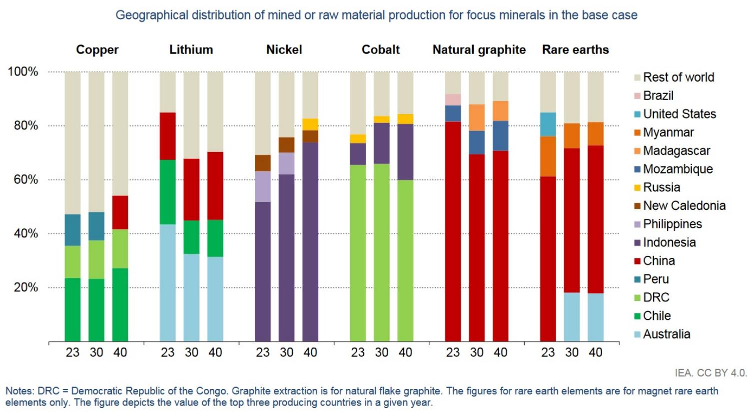

Fig. 1. High Geographical Concentration of Mining for Critical Raw Materials (REE)s [13].

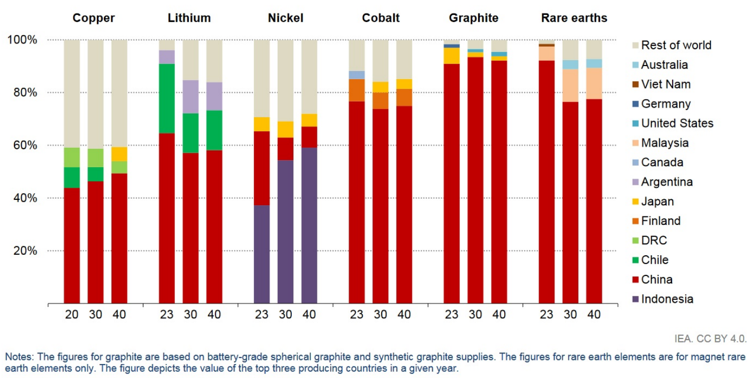

Fig. 2. High Geographical Concentration of Refining for Critical Raw Materials (REE)s [13].

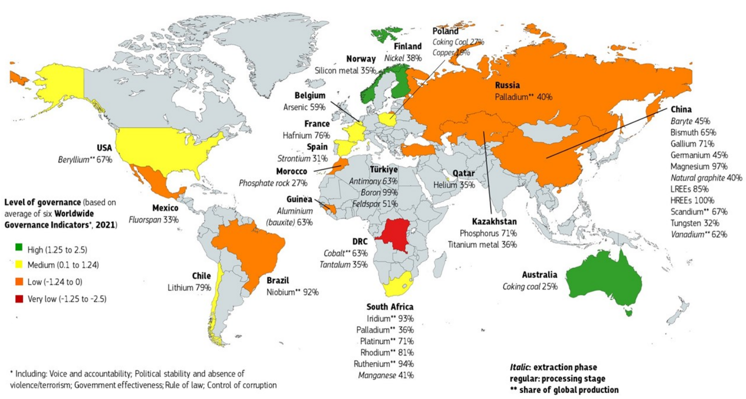

Fig. 3. Major CRMs suppliers for EU (2023) [25].