Rare earth minerals and clean technologies nexus at the background of Russia's war in Ukraine

by Marju Kõrts

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Abstract:

Rare earth elements (REE) are key enablers for the ongoing energy and environmental transition as they are critical raw materials in many low-carbon technologies. Electric vehicles, batteries, solar photovoltaic systems, wind turbines and hydrogen technologies all require significantly more metals than their conventional alternatives to replace fossil fuel needs. Although the REE are often referred to as single group, in practice each individual element has a specific set of end -uses, and so demand varies between them. The current global rare earth supply chain is highly imbalanced and tightly controlled by just a few countries. Such an imbalance of the critical metals supply poses a significant challenge to the energy transition strategies and national security of many countries. Ukraine has long been referred to as "breadbasket of Europe", this country has great potential to become the "minerals superpower in Europe" and a significant supplier of more than 20 elements from the list of critical raw materials.

1. Introduction

The International Energy Agency's (IEA) latest "World Energy Outlook 2023" indicates a significant shift in the global energy system by the end of this decade[1]. Solar- and wind energy, as well as electric cars, and heat pumps are among the clean energy technologies that are projected to redefine how power is generated and used globally. As energy systems evolve on a global scale, the shift to a clean energy economy will depend on fulfilling critical minerals supply needs. The reliance of low-carbon technologies on the high-risk supply of rare earth elements (REEs) make them a widely listed critical raw material[2]. For example, transformation and growth of the power sector will require considerable inputs of emission-intensive raw materials, in particular neodymium [Nd], dysprosium [Dy], and semi-/precious metals to structural materials such as cement, steel, and fiberglass. The demand for green energy technologies – and corresponding demand for materials and minerals required to build, transport and install these technologies is predicted to increase dramatically in the years and decades to come.

This group of minerals were named "rare earth" elements as they were identified as "earths" (originally defined as materials that could not be changed further by the sources of the heat), and in comparison with other "earths", such as lime or magnesia, they were relatively rare. The name rare earth elements is closely associated with their discovery. Most of them were

[1] International Energy Agency (2023). "The World Energy Outlook 2023". IEA, Paris.

[2] Mineral commodities that have important uses and no viable substitutes, yet face potential disruption in supply, are defined as critical to the Nation's economic and national security.

discovered in the 19th century, with the exception of yttrium (1794), lutetium (1907) and promethium (1943). Yttrium was discovered in 1794 by the Finnish mineralogist and chemist Johan Gadolin[3], in a mineral that was later named in his honor gadolinite[4].

Briefly, rare earth elements comprise 17 chemical elements as seen in Figure 1 – fifteen lanthanides (anthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium), scandium and yttrium. All the REEs, except promethium are more abundant than silver, gold, or platinum in Earth's crust, on average. The occurrence, distribution, and potential for economic extraction of the REEs have become the intense focus of world markets in recent years. This has been due to the extensive use of these elements in modern day technology, their criticality in supporting research through medicine, military-based technologies, communication, and their role in the development of clean energy technologies.

Traditionally, the REEs are divided into the following two groups on the basis of atomic weight; (a) the **light REEs** (LREEs), which include lanthanum through gadolinium (atomic numbers 57 through 64); and b) the **heavy REEs** (HREEs), which include terbium through lutetium (atomic numbers 65 through 71). Yttrium, although light (atomic number 39), is included with the HREE group because of its common chemical and physical affiliations with the other HREEs. Rare earth elements are chemically very similar and have always been difficult to separate, but a gradual decrease in ionic radius from LREE to HREE, called lanthanide contraction, can produce a broad separation between light and heavy REE (Atwood, 2012)[5].

Figure 1. List of the rare-earth elements found in natural deposits – the "lanthanides" plus yttrium

Element[6]	Symbol	Atomic number	Atomic weight	Crustal abundance (part per million)
Light REEs				
Lanthanum	La	57	138.91	39
Cerium	Ce	58	140.12	66.5
Praseodymium	Pr	59	140.91	9.2
Neodymium	Nd	60	144.24	41.5
Samarium	Sm	62	150.36	7.05
Europium	Eu	63	151.96	2.0
Gadolinium	Gd	64	157.25	6.2
Heavy REEs				
Yttrium	Y	39	88.91	33
Terbium	Tb	65	158.92	1.2
Dysprosium	Dy	66	162.50	5.2
Holmium	Ho	67	164.93	1.3
Erbium	Er	68	167.26	3.5
Thulium	Tm	69	168.93	0.52
Ytterbium	Yb	70	173.04	3.2
Lutetium	Lu	71	174.97	0.8

Source: Adapted from the U.S. Geological Survey's study "Critical Mineral Resources of the United States – Rare Earth Elements" (2017).

[3] Born in Åbo [now Turku], Finland, 5 June 1760; died: Wirmo, Finland, 15 August 1852.

[4] Gadolinite (Y) is a black or brown mineral that is a source of rare earths and consists of a silicate, especially of iron, beryllium, yttrium, cerium, and erbium.

[5] D.A.Atwood (2012). "The Rare Earth Elements: Fundamentals and Applications".

[6] Promethium (Pm, atomic number=61) is not included in the list because it is extremely rare in nature.

Rare earth elements do not occur as native elements in nature and they are found in the form of minerals, such as phosphates, silicates, carbonates[7], oxides and halides[8]. For example, the producing mines at Bayan Obo and Maoniuping in China, and Mt Weld in Australia, as well as the recently closed Mountain Pass mine in the USA, are all fresh or weathered carbonatites. Rare earth elements are abundant throughout the Earth's crust, but only sufficiently concentrated to be mined and processed economically in certain locations. The estimated average concentration of the REE in Earth's crust ranges from around 130 to 240 ug/g[9] which is actually significantly higher than other commonly exploited elements, and much higher than their respective chondritic abundances (Zepf, 2013)[10]. Cerium and yttrium (Y), for example, are the 25th and 30th most abundant elements by mass, respectively, far exceeding in concentrations tin (Sn), mercury (Hg), molybdenum (Mo), and all precious metals. However, the crustal abundances of many other REEs including those of great practical value are exceedingly small, especially if recalculated to atomic concentrations. Atoms of terbium (Tb) and thulium (Tm), for instance, are two and five times less abundant in the continental crust than Mo and two orders of magnitude rarer than copper (Cu)[11].

The mining and processing landscape of critical materials is geographically concentrated, with a select group of countries playing a dominant role. In the mining of critical materials, dominant positions are held by Australia (lithium), Chile (copper and lithium), China (graphite, rare earths), the Democratic Republic of Congo (cobalt), and Indonesia (nickel). This concentration becomes even more pronounced in the processing stage, with China accounting for 100% of the refined supply of natural graphite and dysprosium (a rare earth element), 70% cobalt, and almost 60% of lithium and manganese respectively (IRENA, 2023)[12]. For obvious reasons mentioned above, the reality is that geopolitical competition over access to critical minerals is accelerating, both among consumers and producers. The current geographic concentration of production, processing and refinement of critical minerals is a considerable challenge to the security of supply of these commodities.

Mineral supply chains have been used as political and economic leverage during international disputes in the past (Sovacool et al., 2020)[13]. However, if it comes to a weaponization of REEs that could lead to an acceleration in production outside China and in turn undermine China's dominance in the industry. Also, the phenomenal growth in the demand for minerals that the energy transition presupposes, can in any case be hardly met by any single country or producer alone, especially since China is approaching its limits in terms of low-cost supply of labor and

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[7] Carbonates, igneous rocks containing approximately 50% carbonate minerals, represent the main source of global REE.

[8] Halides are the salts of sodium fluoride and hydrochloric acid. A halide ion is a halogen atom bearing a negative charge.

[9] V.Balaram. "Rare earth elements: A review of applications, occurrence, exploration, analysis, recycling, and environmental impact". In *Geoscience Frontiers* 10, 4 (2019), pp. 1285-1303.

[10] V.Zepf (2013). "Rare earth elements: what and where they are".

[11] A.R.Chakhmouradian, F.Wall (2012). "Rare Earth Elements: Minerals, Mines, Magnets (and More)".

[12] International Renewable Energy Agency (2023). "Geopolitics of the Energy Transition: Critical Materials".

[13] B.K.Sovacool, S.H.Ali, M.Bazilian, B.Radley, B.Nemery, J.Okatz, D.Mulvaney. "Sustainable minerals and metals for a low-carbon future". In Science 2020; 367: 30-33.

capital-intensive manufacturing capacity. Strategies to diversify the supply and production chains for these materials are starting to emerge, reflecting multiple economic, political and social priorities and considerations (IRENA, 2023)[14]. The challenge of procuring adequate supplies of critical minerals is thus a key obstacle facing both global decarbonization of the economy and international security.

The competition over access to critical minerals is driven by expectations that demand for REEs will increase as the world transitions away from fossil fuels. Rare earth elements are essential for permanent magnets that are vital for wind turbines and EV engines. Electricity networks need a huge amount of copper and aluminum, with copper being a cornerstone for all electricity-related technologies. This all means that the shift to clean energy system is set to drive in the requirements for these minerals, meaning that the energy sector is emerging as a major force in mineral markets. Until the mid-2010s, this sector represented a small part of total demand for most minerals. However, as energy transition gathers pace, clean energy technologies are becoming the fastest-growing segment of demand (ibid, 2022).

Similarly, demand for minerals like cobalt, lithium and rare earths is also expected to increase at unprecedented rates due to their strategic role in the production of electric vehicles (EVs) and energy storage. Electric vehicles, for example, are growing rapidly as a share of overall automotive market, accounting for 17% of total auto sales in Europe (in 2021) and 35% in China respectively (in 2022)[15]. Markets in the United States, such has California[16], have indicated to only permit EV sales by 2035, while nearly every major auto manufacturer plans to produce only EVs by the end of the next decade. At the same time, the types of mineral resources used vary by technology. Lithium, nickel, cobalt, manganese and graphite are crucial to battery performance, longevity and energy density. The continued rapid growth of energy and automotive industries will put enormous strain on the REE industry. It will need to scale production, find alternate sources of supply, and increase manufacturing efficiency to ensure global supply can meet demand.

The minerals and metals identified as critical to the development and deployment of four key green energy technologies – solar and wind energy, as well as EVs and energy storage are presented in Figure 2. These minerals include, but are not limited to aluminum, cadmium, chromium, cobalt, copper, gallium, germanium, graphite, indium, iron, lead, lithium, manganese, molybdenum, nickel, rare earths, selenium, silicon, silver, tellurium, tin, and zinc.

[14] International Renewable Energy Agency (2023). "Geopolitics of the Energy Transition: Critical Materials". IRENA.

[15] R.Walton (2021). "Global EV Sales rise 80% in 2021 as automakers included Ford, GM commit to zero emissions: BNEF". In *Utility Dive*, 12 November 2021.

[16] California Air Resources Board (2022) "California moves to accelerate to 100% new zero-emission vehicle sales in 2035". Press release, 25 August 2022.

Figure 2. Minerals required for green energy technologies

Green energy technology	Minerals required
Solar	Bauxite & Alumina[17], Cadmium, Copper, Gallium, Germanium, Indium, Iron, Lead, Nickel, Selenium, Silicon, Silver, Tellurium, Tin, Zinc
Wind	Bauxite & Alumina, Chromium, Cobalt, Copper, Iron, Lead, Manganese, Molybdenum, Rare Earths, Zinc
Electric vehicles and energy storage	Bauxite & Alumina, Cobalt, Copper, Graphite, Iron, Lead, Lithium, Manganese, Nickel, Rare Earths, Silicon, Titanium.

Source: Data primarily from the World Bank (2017)[18], Levin Sources (2017)[19], U.S. Geological Survey (2017), Bloomberg New Energy Finance (2018) and the American Exploration & Mining Association (2013).

The wide application of new products and technologies in the global market has made the world's demand for rare earth resources to grow rapidly. To take advantage of their unusual physical and chemical properties, the REEs are used in a variety of industrial and technology applications (Goonan, 2011; Long, 2011)[20]. In general, the lighter REEs and yttrium are cheaper, produced in greater quantities, and therefore, they are more extensively used in comparison with heavier REEs. The least common and most expensive REEs, from holmium to lutetium, are limited to a very few, highly specialized, high-technology applications.

Given their similar chemical nature, many different REEs have related or complementary uses; thus, it is more convenient to describe their uses by applications rather than by individual element. Rare earth oxides such as neodymium and praseodymium are used in magnets, aircraft engines and green technologies. Neodymium-iron boron magnets, which are the strongest known type of magnets, are used whenever there are space and weight restrictions. Nickel-metal hydride batteries use anodes made of a lanthanum-based alloys. Samarium and dysprosium are also used in rare earth magnets. Dysprosium is of particular importance because substituting it for a small proportion of neodymium improves high-temperature performance and resistance to demagnetization. More specifically, a certain number of elements are essential in the military field, whether in optical systems, in terms of missile guidance control or on-board computer systems. Indeed, technologies linked to REEs allow having more qualitative military equipment.

[17] Aluminium oxide or alumina is a chemical compound of aluminum and oxygen with the chemical formula Al_2O_3.

[18] D.L.Arrobas, K.L.Hund, M.S.Mccormick, J.Ningthoujam, J.Drexhage (2017). "The Growing role of minerals and metals for a low carbon future". World Bank Group.

[19] Levin Sources (2017). "Hybrid Electric, plug-in hybrid electric and battery electric vehicles". See also Levin Sources (2017). "Solar photovoltaic and energy storage in the electric grid".

[20] T.G.Goonan (2011). "Rare earth elements – End use and recyclability: U.S. Geological Survey Scientific Investigation Report 2011-5094". Also available at http://pubs.usgs.gov/2011/5094. See also K.R.Long (2011). "The future of rare earth elements – Will these high-tech industry elements continue in short supply?" U.S. Geological Survey Open-File Report 2011-1189.

1.1 Critical raw materials

The classification of raw materials or mineral resources can be different for countries with different levels of economic development and natural resource endowment. Determining which minerals or metals are critical depends on the nature of the country's industry, national interests and security concerns, technology, and market changes. The term "*critical minerals*" is the most common terminology, and is often used interchangeably with the terms "*strategic minerals*" or "*energy transition minerals*". Assessment of the criticality of materials is dynamic and continuously changing owing to economic, geopolitical and technological factors. Presently, there is no universally accepted definition of what "criticality" means. Many countries and regions maintain lists of critical materials, which typically reflect current technologies, the prevailing global dynamics of supply and demand, and the context in which the assessments are conducted. The factors for determining criticality remain subjective and location-specific.

A mineral commodity's importance and the nature of its supply chain can change with time, such that a mineral commodity that may have been considered critical 25 years may not be critical now, and one considered critical now may not be so in future. Therefore, critical materials are today the focus of much international dialogue and diplomacy. These considerations would then determine the mineral strategy of each country and/or region. That is the main reason why the high technological and economic importance of Critical Raw Materials (CRM), combined with concerns on their future availability depending on geopolitical factors, has led to increasing attention for CRM.

There is currently no shortage of these mineral resources, but recent price spikes for cobalt, copper, lithium and nickel highlight how supply could struggle to keep pace with world's climate ambitions. The European Commission has recently moved from concerns to policy with its Action Plan on Critical Raw Materials[21]. Governments including those of the European Union and the USA have compiled lists that identify materials that are critical for their economies. However, criteria used to identify critical minerals often include the political and economic stability of producing countries, "substitutability" of minerals and the production share in the country. Nevertheless, a mineral might be classed as "critical" if there is instability in the producing country, as this might imply a threat to stable supply. In case substitution of one mineral for another is difficult, it makes a particular mineral used for a certain purpose very precious. This in turn, leads to a high dependency on stable supply. On the other hand, it can bring along the tendency that very few countries dominate production, meaning that they are able to control large parts of supply, causing a significant dependency on only a few producing countries.

Nickel, lithium and cobalt are all classified as critical by the U.S. Geological Survey (USGS) and are essential to modern battery performance and continued growth in the electric

[21] See the report accompanying the presentation of the Action Plan (European Commission, 2020) and the September 2020 Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee of the Regions "Critical Raw Materials Resilience: Charting Path towards Greater Security and Sustainability".

vehicle market share. They allow modern batteries to deliver higher energy density, greater storage capacity and the ability to recharge repeatedly without efficiency loss (IEA, 2021)[22]. Below there is a brief analysis of the critical minerals, their main uses and its potential in developing renewable energy sources in the energy mixes.

Nickel is a versatile mineral used in a wide range of clean energy technologies but also in traditional industries like steel. It mainly occurs in nature in combination with iron and sulphur as well as in the form of nickel-laterite ores which are typically formed by geological processes in tropical regions[23]. About 60% to 70% of the current worldwide nickel resources are derived from laterites whereas the rest is extracted from nickel sulfide ores. Even though the nickel content is low, the extraction of laterite ores has increased considerably in recent years due to a high demand as well as improved processing techniques. Global nickel resources are currently estimated at nearly 350 million tons. Similar levels are found at the bottom of the world oceans (Nickel Institute, 2023)[24]. Indonesia is the world's leading producer, with the Philippines and Russia being distant second and third. Battery manufacturing together with the demand for stainless steel is the biggest driver for the global nickel mining industry.

Primary nickel production is generally divided into two main product categories. Type 1 nickel is of a higher quality and suited to specialized applications in which a very high purity is required, while type nickel 2 is lower quality and suitable for more general alloying applications. Battery grade nickel (or Class 1 nickel) contains more than 99.8% nickel content and is used in rechargeable batteries. That is a major beneficiary, especially as the configuration of lithium nickel manganese cobalt (NMC) oxide batteries, used in electric vehicles[25]. Nickel Class 2 comprises nickel pig iron and ferronickel. These nickel products commonly have a lower nickel content and are used especially in stainless steel production, where producers take advantage of the iron content. Roughly 48% of the total nickel mining output is related to class 1 nickel products, with class 2 nickel products accounting for the remaining 52%. The high demand for electric vehicles together with increasing the energy density of the batteries forces manufacturers more and more to increase the nickel content and to decrease the cobalt content in batteries. By 2025, the batteries related demand for nickel is expected to increase by approximately 15% of the world nickel production (DERA, 2021)[26].

Unlike copper and aluminum[27] – both of which face green metals demand driven super cycles

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[22] IEA (2021). "The Role of Critical Minerals in Clean Energy Transition".

[23] Reuters (2022). "Vale sees 44% increase in global nickel demand by 2030". 07 September 2022.

[24] Nickel Institute (2023). "Nickel – an abundant resource of the future". March 2023.

[25] NMC batteries are a type of lithium rechargeable battery that use a complex alloy of nickel, manganese and cobalt in the cathode end. They have a high energy density, which means more driving range and a high voltage platform (more specific energy and power).

[26] DERA (2021). "*Batterienrohstoffe für Die Elektromobilität*". In DERA Themenheft.

[27] Currently copper is the conductive material of choice. Although in comparison to aluminum, copper is heavy and expensive. It is not clear why copper is still used as conductor in modern electric and semi-electric vehicles – when aluminum is lighter and significantly less costly. However, before aluminum can replace copper in power supply systems, a number of technological challenges need to be surmounted.

in coming years – extreme tightness and rapidly rising prices in the nickel market are already here. Uncertainty around the trading relationship with Russia, producer of nearly 20 percent of global class 1-nickel supply, has led to more disruption in the supply chain. While nickel is exempted from sanctions on Russia, there have been fewer takers for Russian nickel in Europe and the USA, which has led to material being rerouted into China. Due to accelerated Russia's supply risk and some positioning extremes, prices increased rapidly early in the year. Some market participants expect nickel's tightness to be solved by using a chemical short-cut and pre-existing supply capacity, converting low-purity class 2 nickel – used in stainless steel – to the high-purity class 1 nickel required for batteries. The main potential game changer is the successful conversion of Class 2 nickel (lower quality, with less than 99.8%) to battery grade nickel (Class 1)[28].

Lithium in its pure form is the lightest solid element. It is highly reactive and therefore does not exist in nature as a pure metal, but exclusively in the form of lithium salts. The salts are found as solids in the form of minerals or dissolved in solutions, for example, in salt lakes. Lithium is currently mined only from land reserves in the form of ores and brines amounting to approximately 22 million tons worldwide. Global resources are estimated to be around 89 million tons (Lithium content). South America holds more than half of these resources, in particular Bolivia (21 million tons), Argentina (respectively 19 million tons) and Chile (10 million tons)[29]. Lithium battery production is the main application for lithium (70%). Other typical applications for lithium are ceramics and glass production (15%), lubricants (4%) and metallurgy processes (2%).

Silver and cobalt are both crucial for the energy transition and characterized by geological scarcity. Silver is essential in the production of both solar panels and EVs. Silver's conductivity and corrosion resistance make it necessary for conductors and electrodes, nearly every electrical connection in an EV uses silver and, in total, the auto sector uses 55 million ounces of it annually. In 2018, the International Energy Agency predicted that there would be 125 million EVs on the road by 2030; by comparison, only 3 million were in operation at the end of 2017[30]. Recent innovations in the solar industry are forecast to cause PV-driven solar demand to wane. Due to efficiency upgrades, some new PV cells will require as much as 50% less silver than current panels. If these new-generation PV panels become widely adopted, then that may put downward price pressure on silver. However, this metal is significantly mobilized in PV crystalline technologies, and its substitution possibilities are limited in the near term perspective. Its supply can hardly be increased while the fast growing activity in PV manufacturing is already the third largest user of silver (Gallagher, 2021)[31].

[28] BMI (2021). "Battery Grade Nickel: Assessing Global Supply Bottlenecks and Opportunities".
[29] M.Schmidt (2023). "Rohstoffrisikobewertung – Lithium". In *DERA Rofstoffinformationen* 54".
[30] International Energy Agency (2018). "Global EV Outlook 2018: Towards cross-modal electrification". IEA & OECD.
[31] T. Gallagher. "Will Green Infrastructure Spur Silver Demand?" In *Forbes*, 13 August 2021.

Cobalt is considered unavoidable for permanent magnets and in mainstream batteries (Beylot et al., 2019)[32]. It should be worth mentioning that cobalt does not occur naturally in its pure form, but only in the form of minerals containing cobalt. Demand for cobalt increased sharply, with batteries accounting for less than 30% of total demand in 2000, as compared to 60% in 2019. Two-thirds of the known resources are in the Copper belt intra-sedimentary copper deposits, in the Democratic Republic of Congo (DRC) and Zambia, where the ore grade is 10 times higher than elsewhere. The output from existing and planned cobalt mines, mainly concentrated in the Democratic Republic of Congo, is expected to keep pace with demand in the near term. However, with a sizable proportion of cobalt being a by-product of copper and nickel mining, the future availability of cobalt will be closely linked to the availability and mining of those products. Some countries have large reserves but have not yet commenced production (e.g. Indonesia).

Graphite is a key mineral for the energy transition, contributing to clean technology solutions. The global demand for graphite could grow by up to 500% by 2050, compared to 2018 levels. Today graphite is used across various industries such as automotive, steel-making, the nuclear industry, powder metallurgy, fuel cells, and flame retardants. This wide use is the result of graphite's many different properties. Graphite is strong yet flexible, good conductor of electricity and heat, but it is also fire and cold resistant[33].

Graphite used as an anode electrode material for lithium-ion batteries is largely classified into natural graphite and synthetic graphite. The term "*natural graphite*" generally refers to multiple types of graphite, including amorphous, flake, and vein graphite. However, practically only flake graphite is typically suitable for lithium-ion battery applications. *Synthetic graphite* is a manufactured product made by high-temperature treatment of amorphous carbon materials. In most instances, the primary feedstock used for making synthetic graphite is calcined petroleum coke and coal tar pitch, both of which are composed of highly graphitizable forms of carbon. Both natural and synthetic forms of graphite can be used as an anode material for lithium-ion batteries. Although both are called graphite, they are essentially very different commodities with unique properties. Natural graphite occurs in a variety of geological settings around the world. Synthetic graphite is purer in terms of carbon content and tends to behave more predictably, which is why it has found a niche in solar energy storage and electric arc furnaces (used to reduce iron from iron ore). Synthetic graphite typically comes in two forms: electrodes and graphite blocks. It can be significantly more expensive to produce than natural graphite, as the process is fairly energy intensive. In fact, the cost can be double or triple the standard price for natural graphite. Restrictively high prices and specific uses for synthetic graphite mean that it does not often compete with natural graphite. It is the form of synthetic graphite that directly determines in which industries it will be used (Pistilli, 2023)[34]. Synthetic graphite is used in many manufacturing industries, such as for conductive fillers and coating to name some examples.

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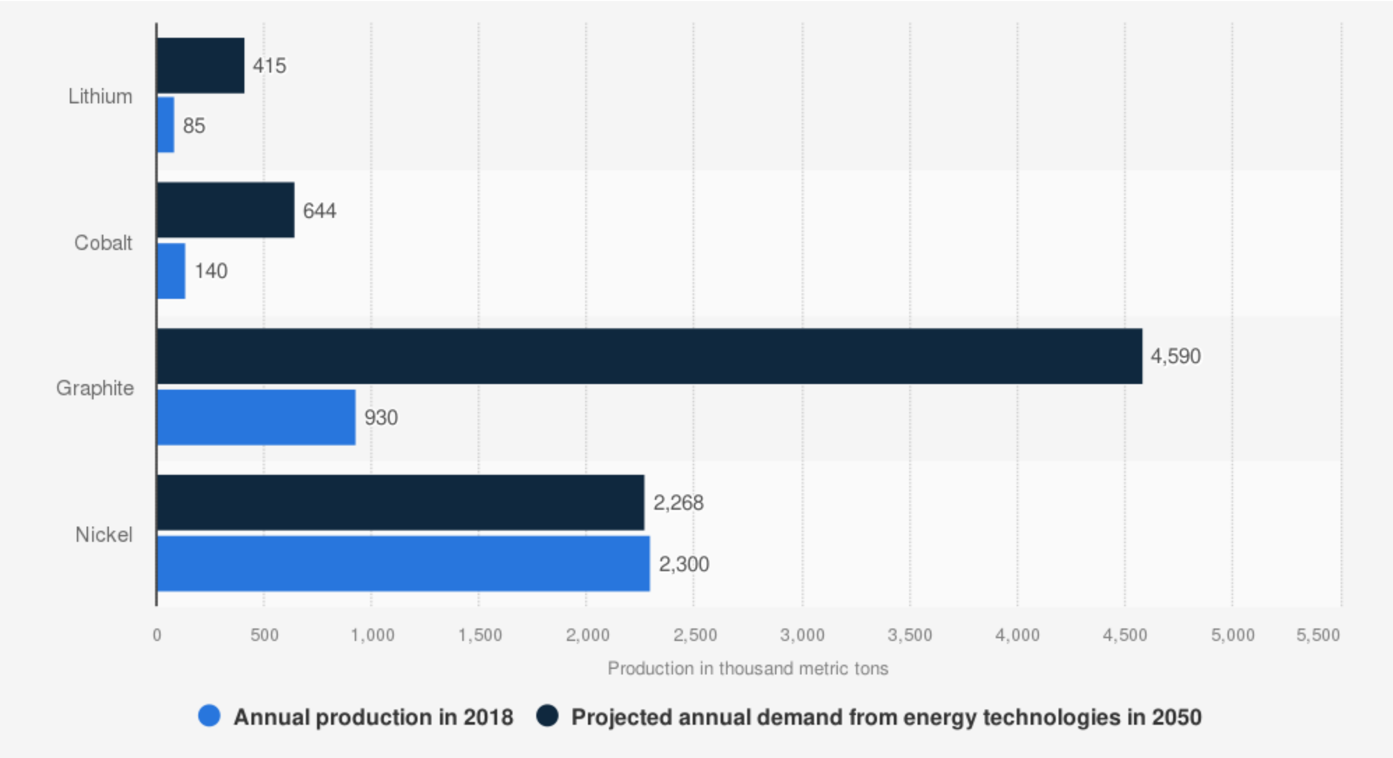
[32] A. Beylot, D.Guyonnet, S.Muller, S.Vaxelaire, J.Villeneuve (2019). "Mineral raw material requirement and associated climate-change impacts of the French energy transition by 2050". *In Journal of Cleaner Production* 208, 1198-1205.

[33] M.Fernley (2020). "Battery Materials Explained". In *Battery Materials Review*, 2020.

[34] M.Pistilli. "Graphite Investing: What is Synthetic Graphite (Updated 2023)? In *Investing News Network*, July 10, 2023.

Figure 3. Production of key battery raw materials worldwide in 2018 with a projected demand from energy technologies in 2050, by mineral (in 1,000 metric tons)



Source: World Bank; US Geological Survey. Statista 2023

The development of renewable energies and the need for means of transport with reduced carbon dioxide emissions has generated new interest in storage, which has become a key component of sustainable development. Energy storage is a dominant factor in renewable energy plants. It can reduce power fluctuations, enhance the system flexibility, and enables the storage and dispatching of the electricity generated by variable renewable energy sources such as wind and solar. Different storage technologies are used in electric power systems. They can be chemical or electrochemical, mechanical, electromagnetic or thermal storage.

Energy storage will be needed for wind and solar electricity generation as well as battery electric vehicles. A range of battery technologies and hydrogen powered options are being explored, which allow substitution of one or more of these metals and minerals; however, these technologies are unlikely to make major inroads to displace current Li-ion battery technologies until 2030 at the earliest (Grey & Hall, 2020)[35]. Although the projected percentage increase in demand of the major metals is relatively small, it is significant in absolute terms, for example, a 9% increase in aluminum by 2030 would mean extra 103 million tons of aluminum to be mined (more than the world's total annual production of 2019)[36].

Lithium-ion batteries (LiBs) are one of the most widely used types of rechargeable battery, and their dominance continues to grow on yearly basis. LiBs have boosted the technological advances for the last three decades, especially in mobile and transport applications as well as potential

[35] C.P.Grey & D.S.Hall. "Prospects for lithium-ion batteries and beyond – a 2030 vision". In *Natural Communications* 11, 6279 (2020).

[36] World Bank Report (2020). "Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition".

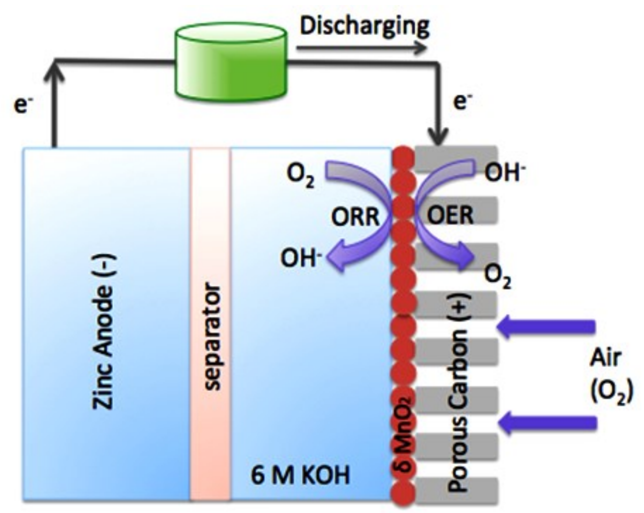
large-scale energy storage systems for electric grid applications. Extensive research and development have been dedicated to explore and improve the key components of LiBs, including negative Li-on host graphic anodes. For example, a mixture of graphite, lithium, cobalt, nickel, and manganese is needed for state-of-the-art battery electric vehicles (BEVs), whereas vanadium is the metal of choice for static power storage for industrial needs, such as solar and wind farms (ibid, 2020).

As noted earlier, graphite together with minerals like lithium and cobalt, plays an essential part in producing batteries. The two most commonly used types of batteries are solid-state and lithium-ion batteries. While both types of batteries store and release energy, they differ significantly in their design, materials, and performance. For example, lithium-ion batteries are composed of two electrodes, an anode, and cathode, separated by liquid electrolyte. The advantages of lithium-ion batteries are well-known, they have high energy density, long cycle life, and relative low self-discharge rates. However, they have also several disadvantages. One of the biggest issues is their tendency to overheat and catch fire. In addition, the use of liquid electrolytes make them less durable and less resistant to impact and vibration.

Solid-state batteries are a new type of batteries that promises to overcome many of the limitations of lithium-ion batteries. Instead of using electrolyte, which is typically a ceramic material, solid-state batteries also typically use a lithium metal anode, offering higher energy density than the graphite anode used in lithium-ion batteries. One of the biggest advantages is their safety, as this type of batteries do not use a liquid electrolyte, the risk of overheating and fire is greatly reduced.

At the moment, almost all anodes are graphite (a market dominated by China), but there is active development of zinc-air batteries that use air as the anode and solid-ion batteries that use hard carbon as anode. Zinc-air batteries (non-rechargeable) and zinc-fuel cells (rechargeable) are metal-air batteries powered by oxidizing zinc with oxygen from the air. These batteries have high energy densities and are relatively inexpensive to produce. The major disadvantage is their limited power output, which is mainly due to the inadequate performance of air electrodes. The other major disadvantage is the dependence of both performance and operating period on ambient conditions such as humidity and temperature (Arai, 2015)[37]. Post-2030, other storage technologies like flow batteries or a wide selection of long-duration storage technologies could become competitive. It is mostly dependent on the evolution of policy and the electricity mix.

Figure 4. Zinc air batteries



Source: Climate.com (2015).

[37] H.Arai (2015). "Metal Storage/Metal Air (Zn, Fe, Al, Mg)". *In Electrochemical Energy Storage for Renewable Sources and Grid Balancing.*

Therefore, graphite is a critical mineral of governments across Europe and the USA, given its importance to strategic sectors and the risks associated with its supply. Technologies that enable the decarbonization of two economic sectors: transportation and steel production will rely heavily on a consistent supply of high quality graphite, leading to an exceptional growth in the demand for graphite over the coming decades. During the next few decades, the strong uptake of electric vehicles (EVs) will result in the availability of terawatt hours of batteries that no longer meet required specifications for usage in an EV. Finding applications for these still-useful batteries can create significant value and ultimately even help bring down the cost of storage to enable further renewable-power integration into the grids. With continued global growth of electric vehicles (EV), a new opportunity for the power sector is emerging: stationary storage powered by used EV batteries, which could exceed 200 gigawatt-hours by 2030[38].

EV batteries have a tough life. Subjected to extreme operating temperatures, hundreds of partial cycles a year, and changing discharge rates, lithium-ion batteries in EV applications degrade strongly during the first five years of operation and are designed for approximately a decade of useful life in most cases. Yet, these batteries can live a second life, even when they no longer meet EV standards, which typically include maintaining 80% of total usable capacity and achieving a resting self-discharge rate of only about 5% over a 24-hour period. After remanufacturing, such batteries are still able to perform sufficiently to serve less-demanding applications, such as stationary energy storage services[39]. Repurposing old batteries from electric vehicles in alternative energy storage applications – like a fast-charging stations or rooftop and microgrid storage systems – is one of the ways to extend EV battery lifespans and electrify the transportation sector in a more sustainable manner (Brin, 2023)[40].This means that these batteries can be used in stationary systems, in combination with renewable energy generation, such as wind and solar, and/or to supply services to the electricity network. The process of reusing EV batteries to be used on the grid is still in its infancy and most of the companies working on it are in the start-up or academic laboratory stage. Therefore, it is worth pointing out that the practice of using second-life EV batteries as a form of grid storage could accelerate, which would limit total demand for new batteries (Roberts, 2022)[41].

[38] K.Balaraman (2023). "EV batteries can be repurposed as grid storage to reduce battery supply chain impacts: report". In Utility Dive, Dive Brief, 11 July 2023.

[39] When an EV battery reaches the end of its useful life, manufacturers have three options: they can dispose of it, recycle the valuable metals or reuse it.

[40] J.Brin (2023). "Building Batteries Better". Report, National Resources Defence Council.

[41] D.Roberts (2022). "Here are the minerals we need for batteries, solar and other clean energy tech". In *Canary Media*, newsletter, 07 February 2022.

Figure 5. Repurposing used EV batteries for grid energy storage

Source: Adapted from the article by Hive Power Tech (2022) "Is Repurposing EV Batteries for Grid Energy Storage a Sustainable Plan?"

Recycling can make sense if the battery electrodes contain highly valued metals such as cobalt and nickel, because there could be a sufficient gap between the procurement and recycling cost, especially given the predicted tight supply of nickel and potentially cobalt in the 2020s. While having an additional source of battery metals through recycling can be compelling to battery makers looking to secure supply. It will be critical to develop a recycling process that is sufficiently cost-competitive with mining for this path to gain scale. It should be highlighted that new processes that recover more material are not yet fully mature (McKinsey & Company, 2019)[42].

Solar is another technology that is expected to increase significantly in the coming decades, but at the same time it is difficult to predict the exact trajectory of minerals demand. The World Bank study on mineral intensity in clean energy transition[43] looks at four common PV technologies: crystalline silicon (crystal Si), copper indium gallium selenide (CIGS), cadmium telluride (CdTe), and amorphous silicon (amorphous Si). All four are made primarily with aluminum, copper, and silver, with different additional minerals contributing to different technologies. In terms of size, aluminum and copper are the biggest. When it comes to **copper**, clean energy technologies – batteries and solar, but also transmission and distribution systems – are the fastest growing source of demand. The near-term availability of copper supply, of which 40% currently comes from Chile and Peru, has been boosted by recent investments (IEA, 2021)[44]. Copper is not included on the USGS's (United States Geological Survey) list of the top fifty most critical minerals (Burton, 2022)[45], but others, including the IEA and the World Bank, regard it as critical.

[42] McKinsey & Company (2019). "Second-life EV batteries: the newest value pool in energy storage".
[43] World Bank Group (2020). "Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition".
[44] IEA (2021). "The Role of Critical Minerals in Clean Energy Transition".
[45] J.Burton (2022). "U.S. Geological Survey releases 2022 list of critical minerals". USGS, 22 February 2022.

1.2 Rare earth elements reserves, supply and demand

According to the latest critical minerals report from the International Energy Agency (IEA), growing quantities of relatively scarce minerals will be needed to feed the world demand for clean energy[46]. The total worldwide reserves of rare earths amount to approximately 130 million metric tons as seen in Figure 6. Most of these reserves are located within China, estimated at some 44 million metric tons. After China, the major rare earth countries based on reserve volumes are Vietnam, Brazil, and Russia. The United States also has significant reserves, estimated to amount to 2.3 million metric tons.

China with one-third of world's REE reserves is still the world leader in REE exploration and production. Before REE mining boom in China, the U.S. dominated the global market, Mountain Pass initiated operations in 1965 and was the leading producer worldwide for decades (Barakos, 2017)[47]. However, mining activities stopped in 1998, mainly due to the competition from China as well as in response to environmental issues in the surrounding area of Mountain Pass (Ali, 2014)[48]. With an estimated 210,000 metric tons produced from mines in 2022, China was also the world's largest producer of rare earths that year. This country produces most of its rare earths in the southeastern part, such as in the provinces Jiangxi and Fujian, however production also occurs in other parts of the country such as Inner Mongolia and Sichuan.

Rare earth minerals remain critical in various applications with future demand expected to remain strong driven by the clean energy economy though electro-mobility and wind power. Global production of rare earth oxide (REO) (210,000 of 300,000 tons in 2022) is dominated by China (70%), followed by the USA (14%), and Australia (4%)[49]. Due to the increasing demand for EVs and energy storage batteries, the demand for and prices of minerals like lithium, cobalt and manganese – all used in lithium-ion batteries – are already increasing (USA News Group, 2017)[50]. Each mineral carries a different demand risk depending on whether it is cross-cutting (needed across a range of low-carbon technologies) or concentrated (needed in one specific technology). Absolute production numbers and relative increases in demand for each mineral may also play a role in their ability to meet supply as well as have climate and environmental implications.

[46] International Energy Agency (2022). "The Role of Critical Minerals in Clean Energy Transitions". World Energy Outlook Special Report. IEA.

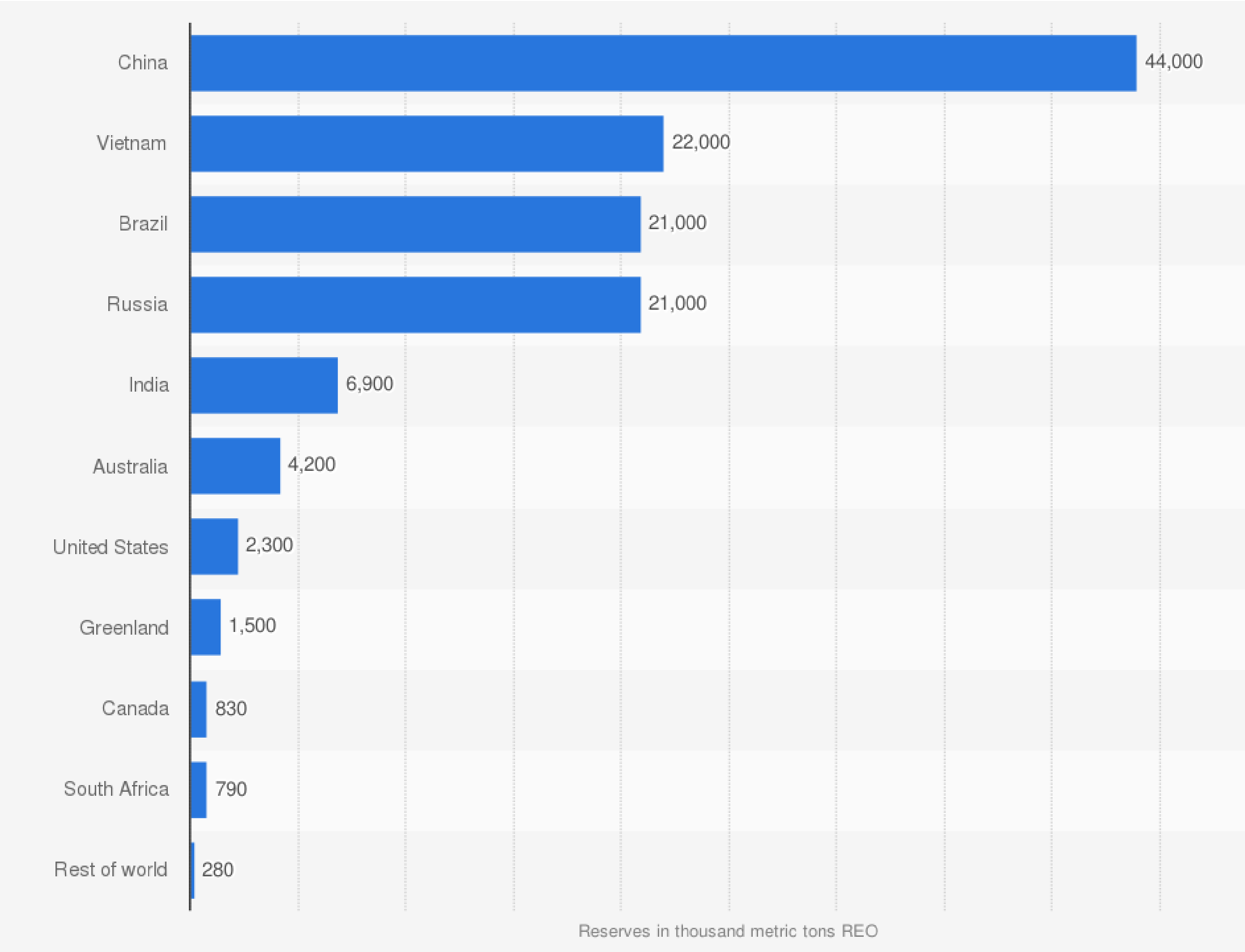
[47] G.Barakos (2017). "Investigating the realistic perspectives of the global rare earth mining industry". 2nd Rare Earth Resources Conference (ERES 2017) at Santorini Greece.

[48] S.Ali (2014). "Social and environmental impact of the rare earth industries". In Resources 3 (1), 123.

[49] S.L.Liu, H.R.Fan, X.Liu, J.Meng, A.R.Butcher, L.Yann, K.F.Yang, X.C.Li (2023). "Global rare earth elements projects: New developments and supply chains". In *Ore Geology Reviews*, Volume 157, June 2023, 105428.

[50] USA News Group (2017). "Demand for high grade manganese growing with EV market". In *Newswire*, 8 November 2017, a press release.

Figure 6. Reserves of rare earths worldwide as of 2022, by country (in 1,000 metric tons REO)



Source: US Geological Survey. Statista 2023

Currently, no rare earths are mined in Europe and this continent mostly imports them from other regions. Although, Europe has a number of areas of suitable geology with REE resources and some new developments can be seen. For example, recently, the Swedish state-owned company LKAB has discovered Europe's largest deposit of rare earth metals. The store, situated in Kiruna in the northern region of Sweden, holds a stockpile of over 1 million metric tons of rare earth oxides[51]. This discovery bolsters Europe's ambition to rely less on imported raw materials needed for the green transition. The other promising sites include alkaline igneous rocks such as those found in the Gardar Province of south-west Greenland (Kvanefjeld and Kringlerne exploration projects) and within the Fennoscandian Shield (including the carbonates of Fen in Norway and Sokli in Finland, and the Norra Kärr syenite in Sweden). Other potential mining sites outside Europe include Thor, Hoidas, and Strange Lake (Canada), Bear Lodge (United States), Nolans Bore (Australia) and Steenkampskraal (South Africa), of which only the last two projects have achieved „permitted status" to date (Ganguli & Cook, 2018)[52].

[51] Drishti IAS (2023). "Rare Earth Elements Discovered in Sweden". 17 January 2023.

[52] R.Ganguli, D.R. "Rare earths: A review of the landscape". In *MRS Energy & Sustainability* 5, 16 (2018).

China's dominant position in the supply chain stems not only its ownership and control of critical minerals mines, but also processing facilities. Not only mining and processing of REOs are concentrated in China but also most of the REEs smelting industry (95%). Some smaller capacities exist in Vietnam and Laos (5%). Smelting capacity in Japan and other western countries is negligible. China' dominance is of particular concern, especially given its current rivalry with the USA, and there are recurring pieces of news that China is considering limiting exports of REEs (e.g. Tabeta, 2023; Yu & Sevastopulo, 2021)[53] of which the U.S and EU are large consumers. China controls nearly 60% of global lithium processing and 40% of copper processing as well as 85-90% of the processing operations that turn REEs into metals and magnets. Simultaneously, this country also processes the most nickel (35%), whilst Indonesia with a 30% share of global production, has a 15% processing share.

The lithium supply chain presents a different picture as it is dominated to a lesser extent by one country. The largest proven reserves are in Chile, Australia, Argentina, China and the U.S. Lithium typically comes from rich underground brine deposits or hard-rock spodumene deposits. Australia is the lead producing nation, contributing about 46% of global mine production, predominantly from its hard-rock lithium deposits in Western Australia. China is in a third place mining about 17% of lithium in 2019, although they are responsible for nearly 60% of global lithium processing. The U.S. has one smaller lithium mine, contributing 5,000 metric tons to the 350,000 metric tons of global supply[54].

More than 60% of the world's cobalt supply comes as a by-product from the mining of copper in the Democratic Republic of Congo (DRC), producing roughly 130,000 metric tons, the peak production volume in indicated period (as seen in Figure 6). Cobalt mined in the Democratic Republic of Congo is then mainly refined in China before it is available to the industry (according to the U.S. Geological Survey on Mineral Commodity Summaries for cobalt)[55]. Supply from the Democratic Republic of Congo has experienced periodic disruption as a result of political instability; in addition, ongoing child labor issues have major implications for ethical supply and new social contract ambitions. Alternatively, cobalt can be recovered from the waste material of existing terrestrial mines. Estimates in 2012 concluded that unrecovered cobalt from existing nickel mines in Europe could supply 50% of the metal needed for European Li-ion battery plants coming on stream (highlighted in the 2018 EU report in cobalt)[56]. Significant opportunities to recycle cobalt may also be anticipated over the coming years. In the EV batteries sector the recycling potential is significant, as these batteries will be easier to collect. However, given the recent introduction of EVs in global and European markets, large-scale re-

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[53] S.Tabeta (2023). "China weighs export ban for rare-earth magnet tech". In *Nikkel Asia*, 6 April 2023. See also S.Yu& D.Sevastopulo (2021). "China targets rare earth export curbs to hobble US defence industry. In *Financial Times*, 16 February 2021.

[54] "Mineral Commodity Summaries 2021". U.S. Geological Survey, pp.98-99.

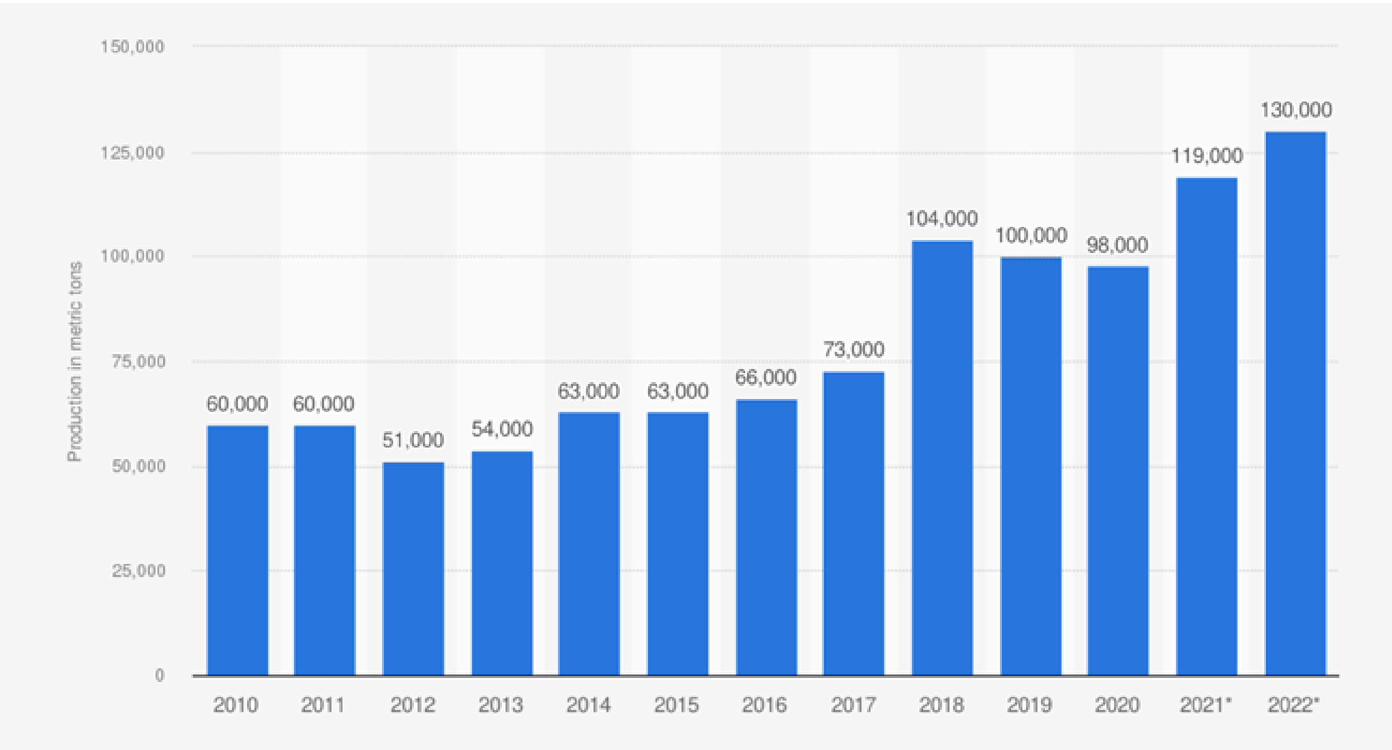
[55] U.S. Geological Survey (2022). "Mineral Commodity Summaries 2022 – Cobalt".

[56] P.Alves-Diaz, D.Blagoeva, C.Pavel, N. Arvantidis (2018). "Cobalt: demand-supply balances in the transition to electric mobility". Joint Research Center Science for Policy Report, European Commission.

cycling can only be more effectively accomplished beyond 2025. For example, in 2030 timeframe, recycling of EV batteries can provide for around 10% of the European cobalt consumption in the EVs sector, if established to the extent of the assumptions used to develop the forecasts.

The Copper Belt in Central Africa contains the world's largest proven cobalt deposits with other significant deposits also located in Australia, Cuba, the Philippines and Canada. In the U.S., cobalt resources are primarily located in Minnesota and Idaho. Michigan is home to on cobalt producing mine, but it only contributes 1 percentage of global cobalt supply. As many entities search for alternative sources of cobalt, some have looked to the ocean floor. The geology of Europe is favorable for a range of new potential sources for the metal. It is estimated that over 120 million tons of cobalt can be found in manganese nodules and crusts on the floor of the Atlantic, Indian, and Pacific Oceans.

Figure 7. Mine production of cobalt in the Democratic Republic of Congo from 2010 to 2022 (in metric tons)



Source: US Geological Survey. Statista 2023

Definitely, most controversially, deep ocean nodules could offer industry all the cobalt and manganese as well as most of the copper and nickel, we may need for the world's battery powered electric vehicles (the Royal Society: future ocean resources)[57]. This project considers two emerging classes of ocean based resources: metals from the deep ocean floor, and the application of the genetics and chemicals produced by marine life. Sustainable use of these novel resources could have significant benefits, but involves interaction with a natural environment that is chal-

[57] The Royal Society (2017). "Future ocean resources: metal-rich minerals and genetics".

lenging to access and less well understood than that on land. These resources will require time and large-scale investments to develop. It is vital to highlight that cobalt demand is growing significantly. While the amount of cobalt per vehicle is indeed reducing as battery chemistries shift, overall demand is multiplying so rapidly with the rise in demand for battery capacity that the DRC remains vitally important. Ocean floor and non-DRC supply provide alternative sources in the longer term, and recycling too, but during this decade the DRC is pivotal (Wood et al., 2021)[58].

Like all material processing, the REE supply chain is also associated with environmental impacts. They are mainly related to the geology of a deposit, mineral type and composition, the methods of extraction, local supply of energy and auxiliary materials, as well as regulatory conditions that mitigate environmental impacts. Green technology requires non-renewable raw materials sourced from primary geological resources (mines) or secondary supply (reuse or recycling). Several options can reduce the risk associated with material availability including technological development, substitution, and recycling. Technological developments can reduce the risk either through reducing the amount of metals used in energy technologies or substituting one element or material by another without reducing their performance. The ambition is a fully circular economy, in which demand can be satisfied by reuse and recycling.

In some ways, recycling rare earths from tossed-out items resembles the challenge of extracting them from ore and separating them from each other. Traditional rare earth recycling methods also require hazardous chemicals such as hydrochloric acid and a lot of heat, and thus a lot of energy. On top of the environmental footprint, the cost of recovery may not be worth the effort given the small yield of rare earths. Chemists and materials scientists, though are trying to develop smarter recycling approaches. Their techniques put microbes to work, ditch the acids of traditional methods or attempt bypass extraction and separation[59]. Another approach already being commercialized skips the acids and uses copper salts to pull rare earth from discarded magnets (Wayman, 2023)[60].

Nevertheless, because of the expected gap between supply and demand, the incentives for REE recycling are expected to increase, and considerable effort has been directed in recent years toward development of new approaches tailored for recovery from secondary sources. The most promising new approaches are specifically designed to take advantage of the special characteristics of recycling feedstock compositions, as compared with primary rare earth ores. One notable advantage is that recycling technologies avoid what is known as the REE “balance problem” where the least valuable lanthanides, cerium and lanthanum, constitute the majority of the REEs in ores such as bastnaesite and monazite (Binnemans & Jones, 2021)[61]. This situation

[58] D.Wood, A.Helfgott, M.D’Amico, E.Romanin (2021). “The Mosaic Approach: A Multidimensional Strategy for Strengthening America’s Critical Mineral Supply Chain”. Wilson Center, Supply Chain Initiative.

[59] One approach leans on microscopic partners, for example *Gluconobacter* bacteria that naturally produce organic acids that can pull rare earths, such as lanthanum and cerium.

[60] E.Wayman (2023). “Recycling rare earth elements is hard. Science is trying to make it easier”. In *Science News*, 20 January 2023.

[61] K.Binnemans, P.T.Jones (2015). In *Journal of Sustainable Metallurgy* 1, 29 (2015).

leads to high costs for recovery of the most valued REEs, because of the need to separate out and stockpile the less desired REEs. The criticality of these materials calls for recycling them and improving technologies that do not rely on CRM, which are the two pillars of broad approach to minerals security.

Move towards Circular Economy has boosted the evolution of recycling industrial waste. In turn, this has increased the potential of recycling industrial minerals from certain waste streams as technical and economic challenges in their sourcing, processing, cost, and distribution are overcome. Although, it is worth mentioning that recycling minerals – sometimes also called as secondary minerals – are not yet in sufficient supply to meet the forecast demand, and therefore the majority of these minerals and metals will continue to be sourced from mining sites (Church & Crawford, 2020)[62]. However, overwhelming challenges in conventional REE explorations and mining make secondary REE resources, such as electric and electronic waste (e-waste) and mine tailings (left-over materials from the processing of mined ore) as promising resources in the future. Due to the supply risk and the monopoly of the REEs market, its recycling is currently considered as an effective method to alleviate market fluctuations. However, economical and sustainable processing techniques are yet to be established to exploit REEs via recycling.

2. Russia, Ukraine, and the Critical Materials – Energy Nexus

Many countries have invested in renewable energy and sustainable infrastructure, becoming dependent on China for raw materials and components used in their manufacturing processes. This kind of dependency poses risks and challenges, leading a new coalition of allies to source minerals for clean energy technologies and reduce reliance on autocratic countries. Before the Russian invasion in Ukraine, Russia was also pursuing its own rare earth ambitions. Despite having the fourth-largest reserves in the world, this country was falling behind in developing deposits, some of which are situated in the harsh eastern Siberian region, as well as its refining technology. In 2020, Russia pledged around 1.5 billion dollars to become the largest producer of rare earths after China by 2030 (Besliu, 2023)[63].

Russian invasion and its continued occupation of Ukraine could disrupt efforts to transition the world to a low-carbon economy due to the significance of both countries in terms of critical minerals. Russian control of Ukraine's reserves would advance this objective while allowing leverage more power over the EU's and other international actors' energy supply chains. Europe, in particular, is stuck in a connection between multiple conflicting goals. Herein also lies the

[62] C.Church, A.Crawford (2020). "Minerals and the Metals for the Energy Transition: Exploring the conflict Implications for Mineral-Rich, Fragile States". International Institute for Sustainable Development (IISD), Switzerland.

[63] R.Besliu (2023). "Ukraine's Resource Curse". In *Green European Journal*, 13 June 2023.

challenge in the climate, energy, and critical materials nexus: countries around the world have to cope with problems of sluggish supply chain, stifled economic growth and have to transform whole industry sectors and the relevant infrastructures.

Russia has the fourth-largest reserves in the world and, prior to its invasion of Ukraine in February 2022, was seeking to become the second-largest rare earth element producer after China. These plans appear to have been frozen though, while the country remains entangled in a war that has lasted longer and been more costly than it expected. Before Russia's invasion, licenses had been issued to explore Ukraine's reserves of lithium, which among other things is essential for the manufacture of electric vehicle batteries. As outlined in Global Data's new critical minerals report[64], among the reserves in Ukraine are the Shevchenkivske field in the Donetsk region and the Kruta Balka block in the Zaporizhzhya region, both located close to areas of conflict with Russia. As such, the current war in Ukraine could have potential implications for the rare earths and critical materials industries, including impeding the transition to green energy.

Russia and Ukraine have long had a close cultural and historical connection that has evolved over the years. This linkage was due to their geographic position but also trade connections. Russia wants to include Ukraine within its territory for a number of geopolitical reasons. Both countries share a common cultural history although have different political systems. Much of the reasons for the annexation is around the natural resources including oil and gas that are found in Ukraine, which supply a large percentage of consumers in the European Union (Johannesson & Clowes, 2022)[65]. This means that it is strategically advantageous for Russia being a non-European member to have control of Ukraine. Another reason is to increase attention on Russia due to world focus now being centered on China and the United States.

The Russian decision to halt natural resource shipments to Europe demonstrates how geopolitical uncertainty might have significant consequencies in the future. Furthermore, trade restrictions further add more volatility to the market. As an outcome, it disrupts the energy trade that boosts its prices and causes inflation in the global market. Similarly, the conflict also affects critical mineral markets. Both countries produce a significant share of basic metals such as nickel, aluminum, and palladium. Delays in their procurement could hit industrial production and the wider supply chain. It drastically changes the market behavior (World Bank Report 2022)[66], e.g. Russia has 11 percent of total global nickel production and its global export share is 15 percent. Russia accounts for a bulk proportion of global commodity exports, mainly energy (i.e., oil, gas and coal), and also industrial metals and agricultural merchandises. Over 35 percent of the global palladium supply is also produced in Russia. Behind the Democratic Republic of Congo, Russia remains the second-largest cobalt producer globally. This country is also an important exporter of palladium[67]; metals of this group are currently used in catalytic converters

[64] Global Data (2023). "Critical minerals -Thematic Intelligence".

[65] J. Johannesson & D.Clowes (2022). "Energy resources and markets – Perspectives on the Russia-Ukraine war". In *European Review*, 30 (1), pp. 4-23.

[66] World Bank (2022). "Mineral-Rich Developing Countries Can Drive a Net-Zero Future". 6 June 2022.

[67] The other major exporters of palladium are South Africa, United Kingdom, USA, Germany, Italy and Belgium.

for emissions abatement for internal engine vehicles. In future, these metals are essential to the catalysts used in electrolyzers and hydrogen fuel cells. Russian palladium illustrates one of the key geopolitical features of critical minerals: alternative supplies are often located in equally challenging markets. For example, the second largest palladium producer is South Africa, where the mining sector has been wracked by strikes for the past decade (Basov, 2022)[68].

Most of Ukraine's territory is a flatland with no meaningful natural obstacles. Furthermore, since it is positioned along a terrestrial gateway that connects the European peninsula with the very core of the Eurasian heartland, for centuries it has operated as a corridor for the imperial pursuits of great powers seeking to move in either direction. Hence, this location can be used as a spearhead of military power projection, a defensive buffer state that provides a strategic advantage conferred by distance or a borderland in which clashing spheres of influence overlap. On the other hand, Ukraine is also a significant from a geo-economic perspective. It hosts infrastructure that connects Russia with Europe, including natural gas pipelines and motorways. Despite prolonged economic hardship, Ukraine retains important industrial capabilities in the fields of steelmaking, aerospace, chemicals and the manufacture of military hardware. In addition, the country also contains deposits of both coal and metallic minerals such as iron, titanium, manganese and uranium. Another relevant aspect is that Ukraine possesses fertile land (known as "black soil") that is suitable for growing cereals, which make it a formidable breadbasket (Alonso-Trabanco, 2022)[69].

Ukraine is also a potential critical mineral superpower, ranking fourth globally in terms of total assessed value of natural resources. The areas in Ukraine where Russia is currently centering its military operations are home to some of Europe's largest supply of recoverable rare earth resources, although much of these are underdeveloped. Minerals and metals currently account for more than 30% of exports from Ukraine. The country produces around 15 billion USD annually in natural resources, and the estimated value of recoverable reserves could be as high as 7.5 trillion (Murray, 2022)[70]. The country also holds 20% of the world's titanium resources and the largest uranium deposit in Europe[71]. Ukraine is believed to have the largest supply of recoverable rare-earth resources in Europe. Over 20 of the 30 most "critical minerals", including rare earths, are located there as seen in Figure 8. Prior to Russia's invasion, Ukraine had become a key candidate to contribute to achieving the Union's ambitious goals. In 2019, the EU and Ukraine launched a Raw Materials Working Group, focusing on sharing information on the critical raw materials supply chain. The country is potential as a supplier of critical minerals has led to the European Union and Ukraine signed a memorandum of understanding on critical raw materials and batteries.

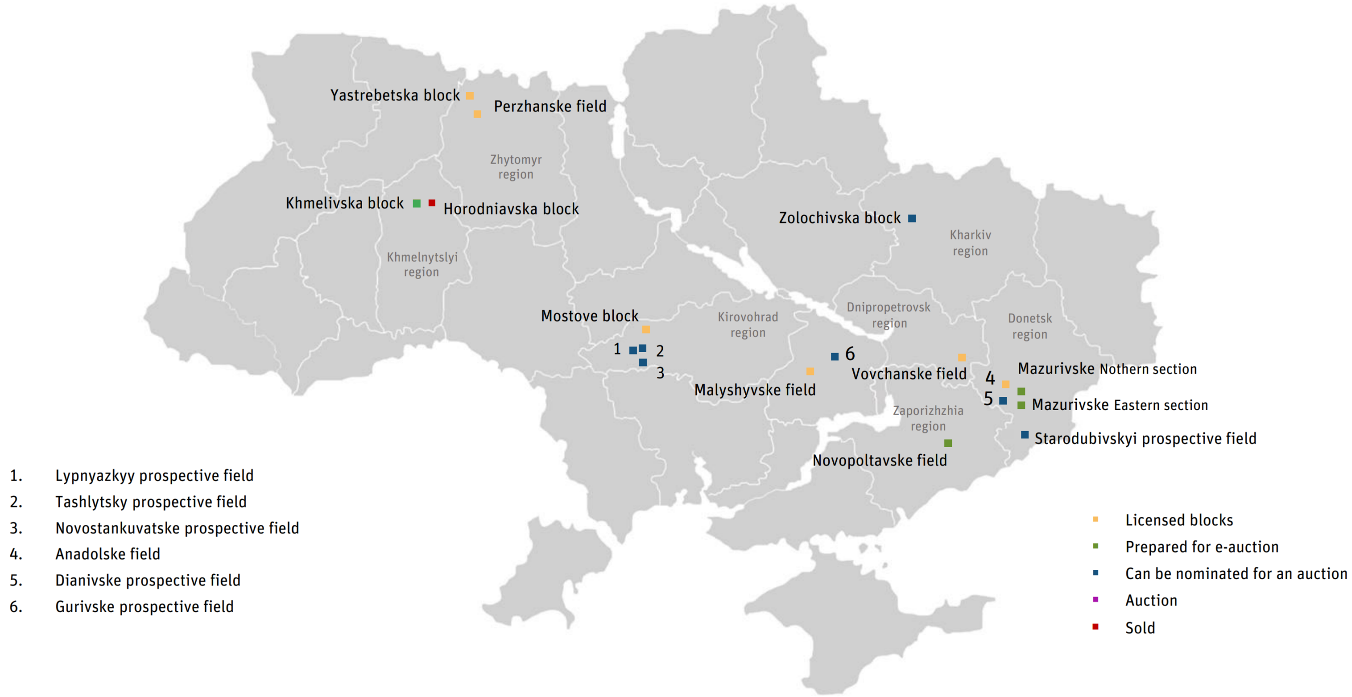
[68] V.Basov. 'Siabanye-Stillwater receives strike notice from two South African unions". Kitco, March 8, 2022.

[69] J.M Alonso-Trabanco. "Ukraine: The Perpetual Battleground". In *Geopolitical Monitor*, Backgrounders, 24 February 2022.

[70] M.Brewster. "Natural Gas, Rare Earth Minerals: What's At Stake for Ukraine in the Territory Russia Is Trying to Conquer?" CBC, 27 May 2022.

[71] "System Shock: Russia's War and Global Food, Energy, and Mineral Supply Chains". Wilson Center, 13 April 2022.

Figure 8. Rare earth minerals spots



Source: Ukrainian Geological Survey

Severe disruptions to global markets caused by Russia's war on Ukraine has exposed vulnerabilities to the security of the supply of raw materials critical for industrial production and for the green transition. These supply chain vulnerabilities are the result of export restrictions, bilateral dependencies, a lack of transparency, including the concentration of production in just a few countries. Ukraine's significant deposits of natural resources, including iron ore, titanium, lithium, and rare earth minerals, make its victory important not only for security but also for gaining access to resources that can be obtained from a democratic country, enabling a shift away from relying on China and Russia for energy resources.

2.1 Rare earth minerals availability, supply and demand in Ukraine

Ukraine is a resource rich country and is endowed with extremely rich and complementary mineral resources in high concentrations and close proximity to each other. The country harbors some of the world's largest reserves of titanium and iron ore, fields of untapped lithium and massive deposits of coal. Collectively, they are worth tens of trillions of dollars. Rare earth metals are an important component of Ukraine's resource base. According to preliminary estimates, the overall lithium resource potential in Ukraine is quite high. The main lithium deposits are associated with Proterozoic complexes (1.7-2.1 billion years old) of alkaline rocks, carbonate and granite pegmatites (Naumenko &Vasylenko, 2022)[72]. Ukraine is also home a myriad of other reserves, including stores of natural gas, oil and rare earth minerals – essential for

[72] S.Vasylenko, T.Naumenko (2022). "Prospects of development of lithium research base in Ukraine". Conference paper.

certain high-tech components, necessary for the western countries in search for alternatives to imports from Russia and China.

Ukraine is currently a candidate for the European Union membership, and Ukrainians perceive themselves as Europeans, adhering to the same principles, values, and strategic goals. Therefore, Ukraine's objectives in the field of rare earth metals align with the goals of the European Union's policy. They tend to remain a reliable and stable trading partner in terms of extraction, processing, and supply of rare earth metals, as well as the components for the battery industry, including the disposal of used equipment with recovery of raw materials. Consequently, a concept of establishing an entire value chain within Ukraine for supplying the EU is being developed (ZPP, 2023)[73].

Ukraine's conventional and unconventional hydrocarbon resources are located in the Dnipro-Donetsk region in the east, the Carpathian region in the west, and the Black Sea-Sea of Azov region in the south. Definitely, Ukraine has the potential to become a significant supplier of **lithium** with reserves estimated at 500 thousand tons, making it one of the worlds' largest. The main locations of lithium ore deposits are indicated in the map as seen in Figure 9.

The Ukrainian Shield is a large and main rare metal province, occupying over 40% of the Ukrainian territory. It starts from the Ukrainian northern border with Belorussia and goes up to the shores of the Azov Sea, in the south of Donbas. According to the studies of the Ukrainian geological service, in the ancient rock of this shield are hidden lithium deposits with great potential. There are four known lithium deposits in Ukraine: "**Shevchenkivske**" in Donetsk region, "**Polokhivske**" and "**Dorba**" in Kirovohrad region, and "**Kruta Balka**" in Zaporizhia region[74]. Most of them have only undergone preliminary geological surveys dating back to the Soviet era, and currently mining is not taking place. The reasons for this vary. The Donetsk region deposit is under occupation, and Zaporizhia region is in a frontline area. Work in these areas will resume only after the de-occupation of Ukrainian territory. The "Dobra" deposit in Kirovhrad Oblast is subject to legal disputes. Only at the "Polokhivske" deposit, despite the ongoing war, preparatory work and the search for a strategic international investor are still ongoing (Aloshyn, 2023)[75]. Three lithium oxide deposits have been identified for future development, one of the deposits is already under the concession of UkrLithiumMining LCC. As demand for lithium is expected to increase significantly with the rise of electric vehicles, Ukraine has good prospects to become a significant player in the lithium market.

[73] Union of Entrepreneurs and Employers (2023). "Memorandum ZPP: "Ukraine's Resource Policy – Strategic Resources and Rare Earth Metals".

[74] For more detailed information see Annex 1 on the critical raw materials in Ukraine (Source Ukraine's Geological Survey).

[75] D.Aloshyn (2023). "From lithium ore to an electric vehicle. Why lithium extraction is Ukraine is just the first step towards TESLA production". In *Interfax Ukraine*, 23 May 2023.

Figure 9. Lithium ore deposits in Ukraine

Source: Adapted from the article by Simone Fant "Ukraine: All lithium reserves and mineral resources in war zones". Deposits on the map are marked with red asterisks.

Ukraine is among the top 10 countries with documented **titanium** deposits worldwide and provides 7% of global production (data from 2021). Currently, titanium is extracted in Ukraine along with ilmenite[76], rutile, and zircon in 6 deposits, yielding 900,000 tons of concentrate containing 350,000 tons of titanium annually. 27 discoveries and more than 30 prospective areas have been explored (S&P Global, 2023)[77]. Titanium and its alloys are used in aviation and missile technology, shipbuilding, machine building, food, medical industry and non-ferrous metallurgy. At present, only placer deposits[78] are being developed, which are about 10% of all proven reserves. The rest is contained in indigenous deposits. However, most of these reserves remain undiscovered, and the country's titanium industry has been affected by the war. Russia's military actions against Ukraine affected the development of the titanium industry in Ukraine, in particular the mining of ores containing titanium and the production of titanium products. The volume of exports of ores containing titanium in 2022 decreased by more than 40%. According to the U.S. Geological Survey and GMK Center[79], as of 2021, Ukrainian ilmenite accounted for about 5% of the world production of ores used for the production of titanium. The main export destinations were the Czech Republic (47.9 % of deliveries in monetary terms), the USA (11.9%) and Romania (9.7%).

[76] The main titanium-containing mineral is ilmenite.

[77] A.Barich (2023). "Metals and the invasion: Ukraine aims for critical minerals after the war". Article, S&P Global, 21 February 2023.

[78] In geology, a placer deposit is an accumulation of valuable minerals formed by gravity separation from a specific source rock during sedimentary processes.

[79] GMK Center (2023). "The U.S. government can invest in the development of the titanium industry in Ukraine – UMCC". Article by M.Malonog.

There are very few producers of **graphite** in Europe, and those that are operational are relatively small. According to Benchmark Mineral Intelligence[80], demand for graphite from battery anode segment is set to experience significant growth as surging electric car sales and the energy storage trend continue. In Europe, battery demand will grow to over 220 GWh by 2025. The total amount of natural and flake graphite required by the global battery market by 2025 is set to be 5.4 times larger than what was needed in 2020. If Europe aims to build its local supply chain for natural graphite, the main challenge it faces is that Asia is currently leading the way (particularly China)[81].

Ukraine possesses some of the world's 5 largest graphite deposits, amounting to 19 million tons of ore with concentrations ranging from 5% to 8%. Currently, 5 thousand tons of graphite concentrate are extracted annually from 6 deposits (ZPP, 2023)[82]. Zavalievsky Graphite has been a producer of natural graphite from the Zavalievsky deposit (Kirovohrad region, Central Ukraine) since 1934. The graphite mine and processing facilities are located adjacent to the town of Zavallia, approximately 280 km south of Kyiv and 230 km north of the main port of Odessa. Production capacity has been reported of up to 30,000 tons per annum graphite (TPA), as compared to 17,000 tons reported in 2021. The company manufactures approximately 25 major grades of graphite with a carbon content of 85% to 99.5% and a size of 10 to 200 microns, as well as colloidal graphite preparations, lubricants and coolants based on graphite (Imformed, 2022)[83]. Unsurprisingly, with the evolution of lithium-ion battery technology and production, there is much interest in developing graphite sources in the region. Graphite reserves are registered within 6 fields, although production is carried out within only one. Zirconium and scandium are concentrated in placer and indigenous deposits[84] in significant volumes; however, their extraction is not carried out. The concession of these deposits is currently held by the Australian company Volt Resources.

3. Renewable energy in Ukraine

Increasing share of renewable energy in the final energy consumption is a way to ensure independence from external supplies of fossil fuels. One such country is Ukraine, which depended on Russian supplies and energy (electricity) from nuclear power plants. The Ukrainian energy sector is mainly based on fossil fuels (natural gas, oil, and coal) as well as nuclear energy. In the structure of primary energy consumption dominated by coal (28.3%), followed by natural gas (28.2%), nuclear energy (23.4%) and oil (13.8%). The share of other energy sources, including hydropower, wind, solar, and other renewables is less than 6% (BP, 2021)[85]. Domestic reliance

[80] "Natural Graphite Price Assessment", but it is also worth looking at the article "Synthetic Graphite Forecasts (2023).

[81] P.Barrera (2021). "Europe's Graphite Supply Chain – Key Facts". In Investing News Network, May 17, 2021.

[82] Union of Entrepreneurs and Employers (2023). "Memorandum ZPP: "Ukraine's Resource Policy – Strategic Resources and Rare Earth Metals".

[83] Imformed (2022). "Industrial Minerals Review 2021-2022".

[84] Placers are type of mineral deposit in which grains of a valuable mineral like gold or the rare earths are mixed with sands deposited by a river or glacier.

[85] BP (2021). "Statistical Review of World Energy". UK, 2021.

on fossil fuels for generating electricity and heat, and on imports, has left the country vulnerable to disruption linked to the current armed conflict.

The Russian invasion has resulted in the occupation and destruction of critical energy infrastructure triggering a sharp decline in total energy supply. About 50% of the country's installed power capacity, thousands of kilometers of electric, gas and heat networks, transformers, compressor stations, heat-only boilers and other infrastructure facilities have been destroyed. In a nutshell, aging infrastructure, a reliance on import, supply shortages, high energy prices and environmental concerns have all highlighted the critical need to rebuild and transition to a more sustainable and resilient energy system. Resorting to renewable energy with cleaner power production gradually becomes the mainstream and attracts attention globally, to replace traditional fossil fuels. Ukraine is not an exception in this regard, as this country has substantial renewable energy (RES) potential, which remains largely untapped.

Ukraine has adopted a series of laws and regulations to promote the penetration of RES. In 2018, the country became a full member of the IRENA. In that direction, an appropriate regulatory framework with the introduction of green auctions was ratified in order to prevent the formulation of monopolies in the market of renewable energy sources in Ukraine. Since 2018, Ukraine has had a feed-in-tariff scheme[86] in place with fixed prices, called the "green" tariff for electricity, which ensures that all generated renewable power is fed into the grid (UNECE, 2023)[87]. The *Energy Strategy of Ukraine until 20*50 sets ambitious targets for increasing renewable and nuclear energy capacity, as well as increasing the use of carbon-free electricity in end-use sectors[88]. By 2050, it is planned to increase electricity production from RES to 525 TWh[89].

Renewables have been valued in the short term for their resilience, with small-distributed systems, like solar panels on the roof or a home enabling backup power during a grid failure. The war, meanwhile, has emphasized the roles renewables can play over the longer term in providing Ukraine with greater security and helping it to be integrated more with the European Union as it works to decarbonize its energy system. About 65% of all renewable generation is located in five southern regions – Odessa, Zaporizhska, Mykolaivska, Khersonska and Dnipropetrovska –, which apart from the Crimea, have the best wind resources and highest insolation. At the beginning of 2022, the total installed renewable energy capacity (all grid-connected) reached 9.5 GW (excluding 0.6 GW of RES capacities located in the territories temporarily occupied by Russia before February 24, 2022 (Energy Charter, 2023)[90]. More than three quarters of this ca-

[86] Feed-in tariff (FIT) is a policy designed to support the development of renewable energy sources by providing a guaranteed above-market price for producers. FITs usually involve long-term contracts, from 15 to 20 years.
[87] United Nations Economic Commission for Europe (2023). "Rebuilding Ukraine with a Resilient Carbon-Neutral Energy System". United Nations, Report, July 2023.
[88] "With support of Ministry of Energy and German Federal Ministry of Education and Research, educational initiative to implement EU Green Deal launched in Ukraine". Ministry of Energy of Ukraine, 05 July 2023.
[89] In order to achieve the above indicators, Ukraine plans to build: (1) 80 GW of new solar and 139 GW wind power plants to expand Ukraine's capacity, (2) 68+ GW of RES facilities for production of renewable hydrogen, (3) 2.4 GW of hydroelectric and pumped hydroelectric plants.
[90] Ibid, 2023.

pacity (78.8%) is produced by industrial solar (around 5,605 MW), 17% by wind (1213 MW), 1.6% by small hydro (116 MW), and the rest (2.6%) by biomass and biogas power plants. Therefore, there is a lot of scope for renewable generation to expand – particularly solar, which generated only 5 per cent of Ukraine's electricity, and wind accounting for about 1 per cent. The use of renewable energy sources today is an important direction for the development of Ukraine's energy sector[91].

One of alternative sources of energy is definitely hydro energy that in Ukraine has not reached its maximum development. With the further development of hydropower, the construction of new hydroelectric power stations and pumped storage power plants, it is possible to extract a significant amount of relatively cheap energy. It is estimated that the theoretical hydropower potential of Ukraine is over 44 billion kWh, out of which 17.5 billion kWh of them refer to economic hydropower potential. At this stage, Ukraine uses 11 billion kWh, which is 62% of the economic hydropower potential (Klimenko, et al., 2013)[92]. This indicates that the Ukrainian hydropower system has great potential for development. The economies of developed countries are usually characterized by a high level of development 84% of the economic potential is used in Italy, 95% in France, and 85% in Switzerland. Therefore, the main development of hydropower in Europe is seen in small hydropower systems and projects to combat the effects of global warming.

Besides, Ukraine, in the field of renewable energy, has strong hydropower resources of small rivers, which is about 63 thousand. Their potential amounts to 28% of Ukraine's overall hydro potential. The development of small hydropower provides an opportunity to solve energy supply problems in remote rural areas, in particular Western Ukraine, where micro and mini hydroelectric power stations could become the basis for their energy supply (Kucher & Prokopchuk, 2018)[93]. Zakarpatya, which has 36% of the total Ukrainian potential, has a very small number of small hydroelectric power stations. This region can make the largest contribution to the implementation of the Energy Strategy of Ukraine on the development of small hydropower, taking into account the greatest potential available.

Climate change also has a great impact on the formation of hydropower potential. Global warming leads to destruction (change) of water resources, and thus limits the possible economic benefits of their use. According to forecasts (Lehner et al., 2005)[94], under the baseline scenario, the EU's hydropower balance will decrease by 25% and Ukraine's – by 35% from the current state. Accordingly, new approaches and methodologies for the assessment and management of water resources are being developed to maintain the hydropower potential at the appropriate

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[91] CMS Law (2022). "Renewable energy law and regulation in Ukraine".

[92] V.N.Klimenko, Y.O.Landau & I.Y.Seagal (2013). Beetroot TO Energy: history, present and future. Electricity and environmental protection. Functioning of energy in modern world". In Science, Phoenix Publishing House, 32, Kyiv.

[93] O. Kucher, L.Prokopchuk (2018). "The Development of the Market of Renewable Energy in Ukraine. Renewable Energy Sources: Engineering, Technology, Innovation". Springer International Publishing.

[94] B.Lehner, G.Czisch & S.Vassolo (2005). "The impact of global change on the hydropower potential of Europe: a model based analysis". In *Energy Policy*, 33, pp. 839-855.

level. Simultaneously, hydropower being an alternative source of energy is not a completely environmentally friendly industry. The construction of new hydroelectric power plants often requires flooding of territories, leading to change in the natural conditions of the river. An excessive number of giant hydropower complexes can lead to irreparable damage to the hydrosphere of Ukraine.

In countries with high agricultural production potential, one of the basic options seems to be popularization of modern methods of obtaining energy from biomass (bioenergy)[95], which so far has played a minor role in the country's energy mix (less than 2% in the case of Ukraine) (Was et al., 2022)[96]. Fortunately, Ukraine has reasonably good generation potential in all renewable technologies, especially in biomass and biogas due to the countries large agricultural sector and available workforce. It is estimated that bioenergy's installed capacity could reach 15 GW. However, under-developed infrastructure and an unstable supply of raw materials means that only a very small number of bioenergy projects have been implemented to date.

Ukraine has the potential to produce 30 percent of Europe's biomethane and the country possesses favorable conditions for the development of solar power plants. The country's first biomethane plant was opened in Chernihiv region, owned by the Gals Agricultural holding. The plant will produce about 3 million cubic meters of gas per year, which will be consumed by about 1,500 customers, including households and industry. Ukraine also boasts one of the highest wind-generation potentials, including offshore resources[97]. It possesses some vast technical potential of offshore wind energy in the Black Sea (estimated at 250 GW). The hydrogen sector also has great potential, according to the EU Hydrogen strategy – Ukraine should play a central role as an energy exporter with 8 GW of green hydrogen capacity until 2030[98]. Data published and compiled by the World Bank Group shows the highest photovoltaic potential in occupied southern regions including Crimea and the Donbas region. With Crimea and much of the southern coast of Ukraine under Russian control, the opportunity for offshore wind development is rather limited.

The growth of renewable energy production from renewable sources is an important area for replacing natural gas, as there is a large reserve for re-orientating biomass exports to the domestic market. Energy security in the face of the Russian military aggression against Ukraine is another perspective that needs to be assessed and considered in the energy and bioenergy development plans. Local generation of energy based on locally available sources allows them to sustain the needs of particular farms or even communities and ensures maintaining of their functions regardless of the external shocks and national or regional grid malfunctions.

[96] A.Was, P.Sulewski, N.Gerasymchuk, L.Stepasyuk, V.Krupin, Z.Titenko and K.Pogodzinska (2022). "The Potential of Ukrainian Agriculture's Biomass to Generate Renewable Energy in the Context of Climate and Political Challenges – The Case of the Kyiv Region". In *Energies* 2022, 15 (18), 6547.

[97] According to the World Bank estimates, Ukraine's offshore wind potential alone amounts to 251 GW.

[98] European Commission (2020). "A Hydrogen Strategy for a climate neutral Europe". 8 July 2020.

Ukraine also intends to increase the share of other renewable sources such as wind, solar, and small hydro in the future. Solar and wind farms can be built in weeks or months, as opposed to the years it takes to build a nuclear power plant. In addition, these installations can provide off-grid electricity to essential infrastructure from hospitals to military installations. For these reasons, bioenergy, hydro, solar and wind generation could constitute the building blocks of Ukraine's future energy system, contributing up to nearly 80% of total energy generation by 2050. Increasing the share of renewable energy in the final energy consumption is a way to ensure independence from external supplies of fossil fuels, which is a fundamental political and economic challenge for many countries at present. To achieve short- and long-term growth in renewable generation, several challenges need to be considered and addressed.

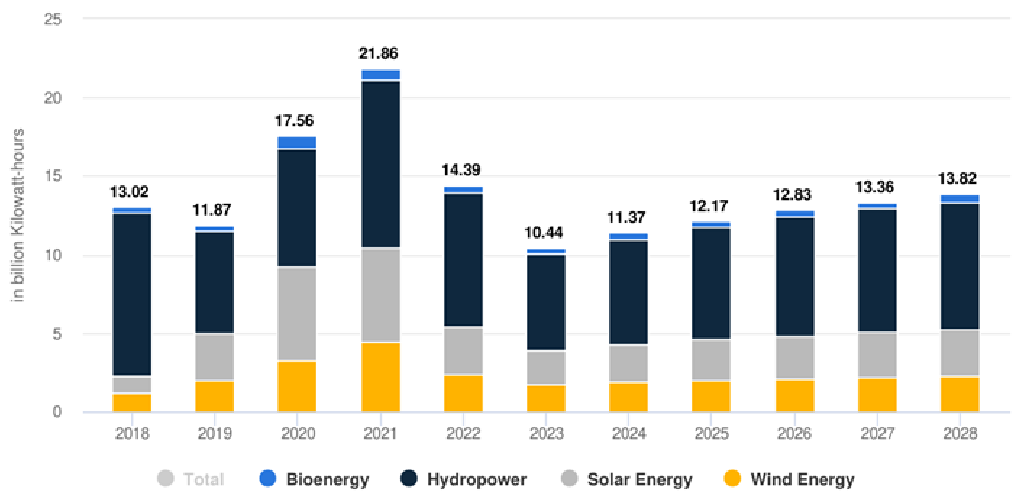
The enhanced resilience of today's renewable energy systems, comprising solar photovoltaic and wind electricity generators, coupled with the storage of electricity in Li-ion batteries and solar hydrogen, is a key attribute of current clean energy technology. Demand load reductions alleviate energy supply and grid constraints, thereby decreasing the risk of power system failures. Resilience has many aspects, but modernization of electricity grid and plans to transition to greater renewable energy are important building blocks. Renewable energy can build a more resilient energy system in two ways:

1) Diversifying energy sources away from fuels, like diesel that must be supplied;

2) Allowing for building distributed energy systems – decentralizing the grid, which enables it to be more resilient to disruptive events, such as extreme weather or attacks.

Increasing the deployment of renewable power generation in Ukraine will be a strategically important step in the reconstruction of the country. Ukraine's electricity grid has been a challenge to maintain even before the war brought targeted attacks against the energy infrastructure. Total wind capacity at the end of 2020 stood at 1.4 GW with 144 MW added during the year. Addressing Ukraine's energy challenge will require comprehensive actions, in particular to ensure environmentally sustainable practices.

Figure 10. Renewable Energy - Energy Production. Ukraine (billion Kilowatt-hour)

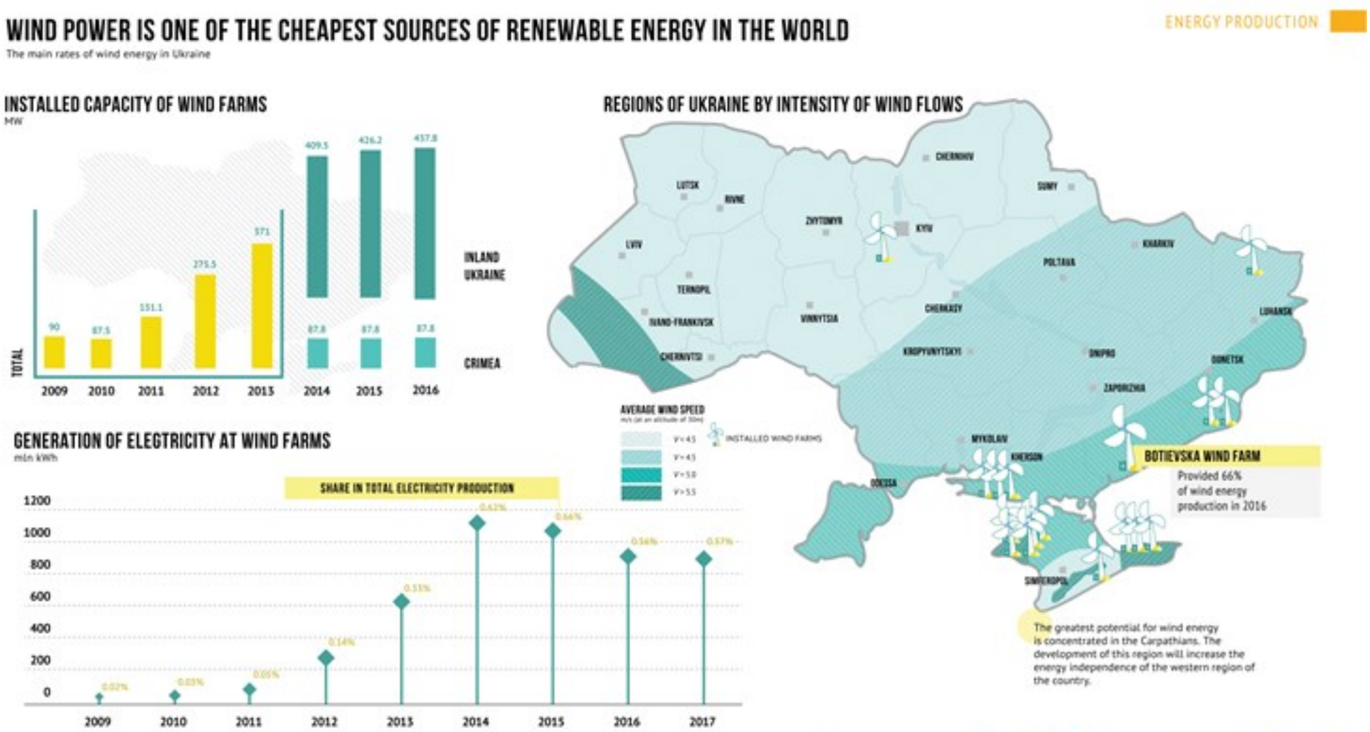


Source: Statista market Insights

Despite the ongoing war, DTEK Renewables, Ukraine's biggest private energy company has launched the first stage of a 500-megawatt (MW) wind power plant in a boost to the country's energy sector following Russian air strikes. Once completed, the Tyligulska wind farm will be the largest in Ukraine. The utility DTEK started building the plant in 2021 but construction stopped after Russia invaded Ukraine on February 24, 2022 (Reuters, 2023)[99]. Significant capacity additions were planned in the southern and coastal regions. DTEK Renewables has indefinitely delayed a planned 700 MW of additional wind capacity in the south of Ukraine. Retaking occupied territories remains Ukraine's priority, but the ongoing war and the scale of destruction in these regions will delay renewable development.

On the other hand, accelerated deployment of solar and wind will help meet Ukraine's renewable power target of at least 30 per cent by 2030. Strategic investment can boost the share of renewables in its energy mix, bringing it into line with the ambition of many European countries with higher targets. Recent research indicates that a reconstruction of the economy after the war prioritizing decarbonization compared with continued reliance on fossil fuels, would require only 5 percent more capital investment, under very conservative assumptions. It would be well worth it, given the innumerable economic, climate[100] and health benefits a green pathway will bring (Romanko & Wiatros-Motyka, 2023)[101].

Figure 11. Wind energy potential in Ukraine



Source: Ukrainian Wind Energy Association, 2017

[99] V.Lakezina. "Ukraine's DTEK launches new wind farm as war rages". Reuters, May 19, 2023.

[100] Ukraine is highly vulnerable to the impacts of climate change. The country is expected to suffer from an increase in intensity and frequency of droughts, high temperature, heat waves, variable precipitation patterns and floods.

[101] S.Romanko, M.Wiatros-Motyka. "Ukraine: renewable energy, war and reconstruction". In *Social Europe*, article, 23 June, 2023.

Solar energy is particularly quick to deploy and can provide decentralized power, much needed amid disruption to the grid from Russian aggression. The government announced in the law on green auctions, adopted in April 2019 that the feed-in tariffs would be replaced by an auction-based quota system coming into force in 2020. All solar PV systems greater than 1 MW, which if applied effectively could facilitate a larger and sustainable development in the country.

As attacks on the Ukrainian critical energy infrastructure continue, a priority in Ukraine is to maintain electricity supply at key facilities – like hospitals and schools and thousands of points that allow residents to warm themselves or charge personal electronic devices when their home's power is out. Most of these key facilities have diesel backup generators that kick in when grid power goes out, which requires a steady stream of diesel fuel to operate. Adding solar power to a diesel-generator-powered microgrid can significantly reduce fuel use and extend its operation without refueling. For example, a 2021 NREL study[102] found that pairing solar generation with a diesel generator could potentially extend operation twofold, from an initial seven days to almost 14 days (NREL, 2023)[103].

Rebuilding Ukraine's energy system will be essential to enabling both broader reconstruction efforts and the return of economic activity. There are two principles that should guide efforts to rebuild Ukraine's energy system: (1) ensuring energy security and independence, and (2) deepening the connection and economic relationship between Ukraine and the European Union. To accomplish both goals, Ukraine should develop its potential renewable energy resources. Renewable energy, including wind, solar, and biomass, are abundant in Ukraine. Developing these resources will support domestic power generation, thereby bolstering Ukraine's energy security and independence. Ukraine has ample potential to become an energy exporter after the war, thereby supporting the European Union's decarbonization and energy security goals (CSIS, 2022)[104]. The war has and will continue to motivate further action in renewable deployment as energy independence from Russia and Ukraine's grid integration with the European Union has become critical to national security.

[102] J.Marquez, W.Becker, S.Ericson. "Resilience and economics of microgrids with PV, battery storage, and networked diesel generators". National Renewable Energy Laboratory. In *Advances in Applied Energy*, 3 (2021).
[103] National Renewable Energy Laboratory. "Ukraine Fights To Build More Resilient Renewable Energy System in Midst of War". NREL, July 27, 2023.
[104] B.Cahill & A.Dawes. "Developing Renewable Energy in Ukraine". Commentary, CSIS, 19 December 2022.

Conclusions

The rare earth mineral resources are irreplaceable in civil, military, and nuclear industries; they have become national strategic resources globally. REEs in general, are considered critical raw materials (CRMs), alongside some other strategic mineral resources, such as cobalt, lithium, tellurium, and nickel. In addition, the above-mentioned strategic minerals, and various rare earth metals[105] – are essential components for manufacturing the "green" technologies – have, thus, become seminal for advanced economies pursuing an energy.

Geopolitical competition and geographic concentration have increased concerns in many countries about critical mineral supply chains. Concentration of mineral production in a few countries make supply more vulnerable to environmental, economic, and geopolitical risks. This vulnerability, along with rising demand and limited production capacity for these critical minerals, has caused recent and significant price spikes. China has imposed restrictions on exports of selected critical minerals to several countries, including the USA, Japan, and Sweden. Other countries have imposed their own restrictions. The fragility of global supply chains revealed by Covid-19 and rising competition from China have only heightened the importance of supply chain security for critical minerals. China is the global leader in rare earths and critical minerals production, as well as industries like batteries, electric vehicles, solar modules and wind turbines. This altogether with the Russia's invasion of Ukraine and that country's willingness to weaponized energy assets has encouraged importing nations to diversify supply sources to reduce supply chain risks.

At the same time, it is too early to conclude that Russian-Chinese cooperation in critical minerals will accelerate due to the Ukraine war and resulting isolation of Russia from western economies. A prolonged disruption of Russian critical minerals supply will stimulate extraction where possible elsewhere, further elevating the strategic profile of, for example, Indonesian nickel, South African palladium, and Chinese aluminum. It should be also noted that switching supplies is easier said than done due to long, multiyear project development and permitting cycles for new supplies and concentrations of many existing alternative supplies in regions challenged by political instability and weak environmental and labor standards.

Many governments are now recognizing that geopolitical risks impose costs of their own, making new investments more desirable. In June 2023, Australia announced its critical minerals strategy to "help Australia become a renewable energy superpower"[106]. In the USA, Inflation Reduction Act provides a 10% tax credit for the cost of production of certain critical minerals as well as subsidies for purchases of certain electric vehicles. The European Union's Critical Raw Materials Act[107] stated it objective (still subject to negotiations) to reduce reliance on third

[105] Some of the more commonly agreed technology metals are cobalt, lithium, tantalum, indium, gallium, selenium and zirconium.

[106] Department of Industry, Science and Resources (2023). "Critical Minerals Strategy 2023-2030". 20 June 2023.

[107] It is a landmark United States federal law, which aims to curb inflation by possibly reducing the federal government budget deficit, lowering prescription drug prices, and investing into domestic energy production while promoting clean energy.

countries and diversify sourcing, increase domestic extraction to 10 percent of EU consumption by 2030 and domestic processing to 40%[108].

At the same time, critical mineral supply chains are complex, and building more diverse and resilient supply will require significant investments of time, expertise and resources. However, in the last decade we have seen significant diversification in the sourcing of critical minerals, and a slight diversification in global processing and manufacturing capacity. Many of the most significant changes to the critical minerals supply chains may not come from new investments to build new mines, processing plants, or manufacturing facilities. The may come from technological innovation that provide new substitutes, new production techniques, new sources, and new extraction methods. For example, sodium-ion batteries are increasingly being used as substitutes for batteries made from lithium, cobalt, graphite. Hydroxide precipitate production is providing a new alternative to cobalt sources from the Democratic Republic of the Congo, where concerns about human rights and instability present significant risks. Simultaneously, critical minerals recycling provides a new source of inputs and reduces dependency and waste (Goldman Sachs, 2023)[109].

Despite the above-mentioned efforts, the challenges are manifold regarding current and future supply of REEs for low-carbon technologies. One strategy to reduce the demand for rare earth elements is for manufacturers and product designers to engineer products that use less or no rare earth elements, or to replace rare earth elements with new or different materials. For example, BMW and Renault have made some of their EVs without rare earth elements (Arena EV, 2023)[110]. While this may make batteries less powerful, cars that are mainly driven in cities may not need as long battery life.

To reduce supply risk in a context of high demand and constrained supply, companies have invested in research and development (R&D), resulting in available substitutes for permanent magnets without REEs and recycling technologies that allow for recovering REEs from secondary sources. Therefore, policymakers should focus on supporting R&D projects through tax incentives Additional measures should be taken to ease the recycling process and reduce its cost, generally, recycling chains must be developed. Although recycling is a long-term solution to meet the demand of REEs of clean technologies, it is unlikely to meet REEs demand in this way in the short term and recycling should be rather seen as a long-term solution.

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[108] European Commission (2023). “Critical Raw Materials: ensuring secure and sustainable supply chains for EU’s green and digital future”. Press release, 16 March 2023.

[109] J.Cohen et al. “Resource realism: The geopolitics of critical mineral supply chains”. Goldman Sachs, 13 September 2023.

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