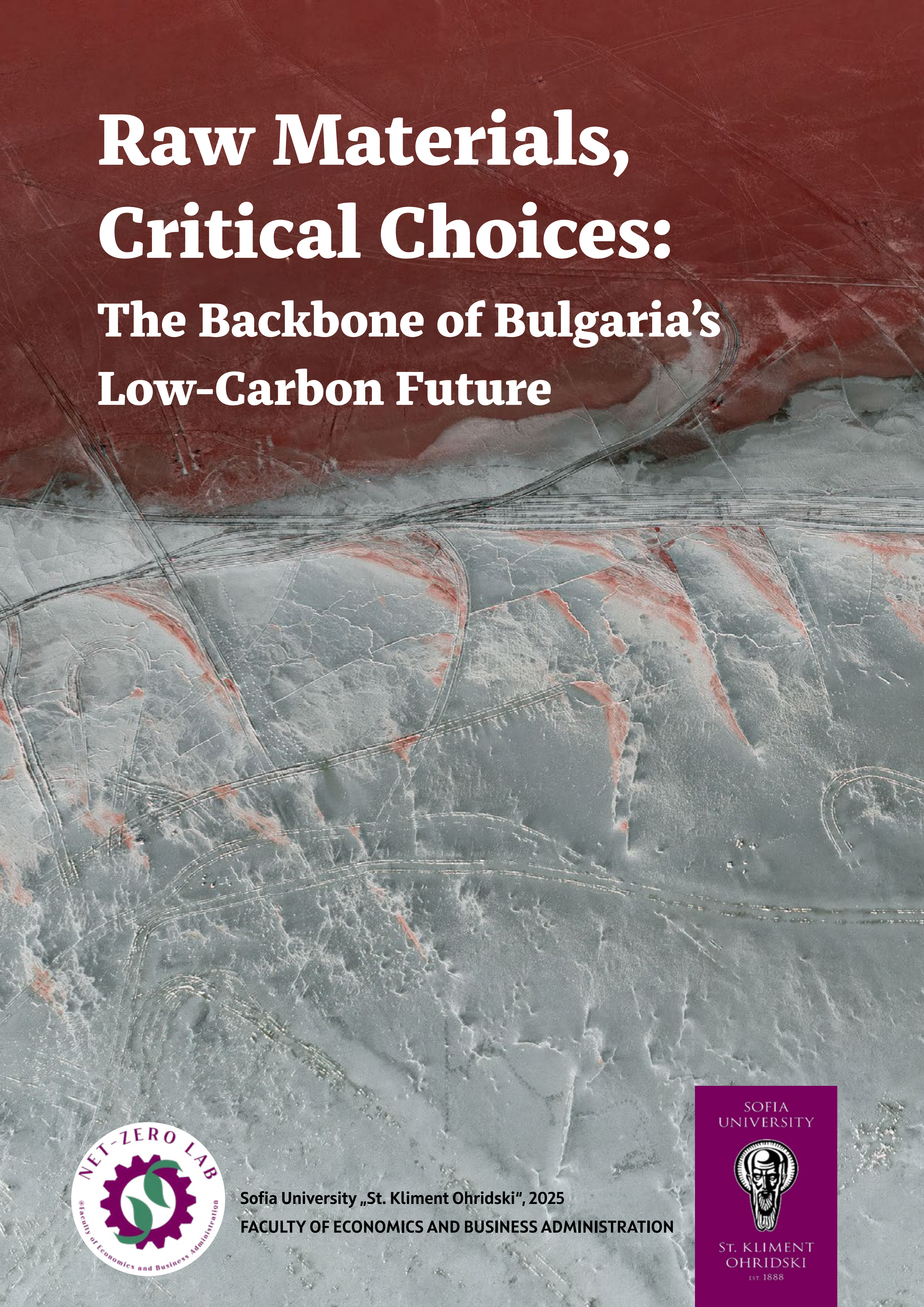

Raw Materials, Critical Choices:

The Backbone of Bulgaria's Low-Carbon Future

NET-ZERO LAB
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SUMMARY

The tangible effects of geopolitical conflicts and socio-economic shifts have necessitated a reassessment of the European Union's economic priorities. Currently, the EU identifies 34 elements as critical raw materials (CRM), essential for the economy and at high risk of supply chain disruptions. These minerals are vital for producing advanced technologies, renewable energy systems, defense applications, and industrial processes.

This report explores the role of critical minerals in Bulgaria's transition to a sustainable economy. It examines the country's potential for mining, processing, and recycling essential raw materials, emphasizing lithium, rare earth elements (REEs), aluminum, barite, graphite, manganese, feldspars, and zinc. While Bulgaria has a strong mining tradition, particularly in copper and gold extraction, its potential for critical minerals remains underexplored. The report highlights the need for targeted research, sustainable extraction methods, and circular economy strategies to enhance Bulgaria's contribution to Europe's raw material supply chain. By integrating responsible resource management, enhancing local production, and supporting EU supply chain diversification, Bulgaria can play a crucial role in ensuring a stable supply of critical minerals, essential for the European Green Deal and net-zero ambitions.

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LIST OF FIGURES

LIST OF ABBREVIATIONS

Al	Aluminum
Ba	Barium
Co	Cobalt
Cu	Copper
CRMs	Critical Raw Materials
Dy	Dysprosium
EVs	Electric vehicles
EC	European Commission
GWh	Gigawatt hour
G	Graphite
IOCG	Iron oxide-copper-gold
La	Lanthanum
Li	Lithium
Lu	Lutetium
Mn	Manganese
MW	Megawatt
MWh	Megawatt hour
Nd	Neodymium
Ni	Nickel
REEs	Rare Earth Elements
RES	Renewable energy technologies
Pm	Rromethium
Sc	Scandium
Si	Silicon
Ti	Titanium
Y	Yttrium
Zn	Zinc

1. INTRODUCTION

The tactile effects of geopolitical conflicts in recent years on global industries, along with the significant socio-economic changes on a global scale, have necessitated a reassessment of the European Union's economic priorities. Currently, thirty-four elements from the periodic table have been determined by the European Union as critical raw materials with strategic importance for the European economy (CRM) and high supply risk.[1]

Critical minerals are naturally occurring substances that are essential to the economy and national security of a country or region and are at risk of supply chain disruptions. These minerals are crucial in the production of a wide range of products, including advanced technologies, renewable energy systems, defense applications, electronics, and various industrial processes. The European Critical Raw Materials Act of 2023[2] defines the following materials as critical: antimony, arsenic, aluminum/bauxite, barite, beryllium, bismuth, boron, copper, feldspar, fluorspar, gallium, germanium, hafnium, helium, lithium, magnesium, manganese, graphite, nickel, niobium, phosphates, scandium, silicon, strontium, tantalum, titanium, tungsten, vanadium, and the platinum group elements, including platinum, palladium, rhodium, ruthenium,

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[1] European Commission. (2020). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Critical Raw Materials Resilience: Charting A Path Towards Greater Security And Sustainability.* COM(2020) 474 final.

[2] European Parliament and Council of the European Union. (2024). *Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2018/17*.

and osmium. The same document defines as strategic the following materials: bismuth, boron, cobalt, copper, gallium, germanium, lithium, magnesium, manganese, graphite, nickel, platinum group elements, rare earth elements including neodymium, praseodymium, terbium, dysprosium, gadolinium, samarium, and cerium, silicon, titanium, and tungsten (Fig. 1).

Fig. 1. Periodic table with critical minerals highlighted in yellow

Source: Virginia Department of Energy.

The "critical" designation is based on two main factors:

- **Economic Importance:** These minerals play a key role in the functioning of the economy, often being indispensable for certain industries or technologies. For example, rare earth elements are critical for the production of high-performance electronics, batteries, and military equipment.
- **Supply Risk:** The supply of these minerals is vulnerable to disruptions due to various factors such as geopolitical instability, trade restrictions, concentration of production in a few countries, and environmental concerns. For instance, many critical minerals are primarily sourced from countries with complex political landscapes, making their availability uncertain.

Countries and regions, such as the European Union and the United States, periodically assess and publish lists of minerals that they consider critical, which helps guide policy, research, and investment decisions to ensure secure and sustainable supply chains for these essential resources.

Infobox

Critical Minerals: A Terminology Note

Fig. 2. The minerals Ilmenite, Rutile and Titanite.

ilmenite ($FeTiO_3$) **rutile** (TiO_2) **titanite** ($CaTiO(SiO_4)$)

Source: mindat.org.

Most of the "critical minerals" are in fact chemical elements that appear on the periodic table (Fig. 1). These elements often combine with others in nature to form minerals, so in the description of available domestic resources of these important materials we often describe occurrences of the predominant mineral ores from which they are extracted. For example, the "critical mineral" titanium (symbol "Ti") does not occur in nature as the free element, but it is found in several common rock-forming minerals including ilmenite ($FeTiO_3$), rutile (TiO_2), and titanite ($CaTiO(SiO_4)$) (Fig. 2).

2. CRITICAL MINERALS IN THE CONTEXT OF THE TRANSITION TO LOW-CARBON ECONOMY

The development of the European economy and the transition to renewable energy sources (RES) and zero-waste technologies rely heavily on mineral resources. Despite progress in recycling, mining and ore extraction remain the primary sources of these essential raw materials. The successful implementation of green technologies depends on securing a stable supply of these minerals while ensuring that new technologies are safe for both people and the environment. Recognizing this, the European Commission (EC) has introduced new legislative initiatives aimed at strengthening domestic mining, processing, and recycling of critical raw materials.[3] Green technologies require significant quantities of non-renewable resources, primarily sourced from geological deposits.

This highlights the urgent need to enhance reuse and recycling efforts. Consequently, scientific research and innovation must focus on optimizing primary raw material utilization, both at the European level and in Bulgaria. Moreover, there is a strong connection between critical raw minerals and the decarbonization process, underscoring the importance of a sustainable and secure supply chain for these essential materials. A significant part of these minerals plays a crucial role in the transition to a low-carbon economy.

Here are some key points to consider:

- **Essential Components for Clean Technologies**: Critical raw minerals, such as *lithium, cobalt, nickel, rare earth elements*, and others, are essential for manufacturing clean energy technologies. Lithium and cobalt are vital for lithium-ion batteries used in electric vehicles and renewable energy storage systems, while rare earth elements (REEs) are essential for the production of wind turbines and solar panels. **The global market for key clean technologies is projected to triple to more than $2 trillion over the coming decade as energy transitions advance.**[4]

The global market for key clean technologies is projected to triple to more than $2 trillion over the coming decade as energy transitions advance.

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[3] European Parliament and Council of the European Union. (2024). *Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2018/17*.

[4] International Energy Agency. (2024). *Energy Technology Perspectives 2024.*

- **Electrification of Transport**: The shift towards electric vehicles is a significant part of global decarbonization efforts. The demand for key minerals used in EV batteries is expected to rise dramatically in the next years, after it reached **more than 750 GWh in 2023**, up 40% relative to 2022. Electric cars account for 95% of this growth.[5]
- **Energy Transition**: Countries and industries seeking to decrease greenhouse gas emissions (GHG) are investing in RES. CRMs are required to build the infrastructure needed for this transition, including grid systems that incorporate renewable sources like solar and wind. For instance, in 2021, it was found that **zinc accounted for 5.500 kg/MW for offshore and onshore wind** infrastructure.[6]
- **Geopolitical Considerations**: The concentration of certain critical minerals in specific regions can lead to geopolitical tensions. Ensuring a stable and sustainable supply of these minerals is vital for decarbonization strategies in various countries. A significant European effort in that direction is the Critical Raw Materials Act, that proposed new procedures on monitoring, stockpiling and demand coordination to anticipate geopolitical risks.
- **Recycling and Circular Economy**: As demand for critical minerals grows, there is an increased focus on recycling and the circular economy. Developing technologies to recycle minerals from used batteries and electronics can help mitigate resource scarcity and reduce environmental impacts. Recycling methods such as direct recycling could decrease recycling costs by 40% and lower the environmental impact of secondary pollution.[7]
- **Sustainable Mining Practices**: With the rising demand, there is a strong emphasis on sustainable mining practices to minimize environmental degradation and ensure that mineral extraction does not exacerbate climate change. Countries like the United States, Germany, China, India, and Indonesia must reduce primary extraction pressures through recycling, increasing secondary raw materials, and adopting circular economy practices to extend product lifespans and enhance material efficiency.[8]

Several critical elements are important to decarbonization efforts as they are essential for the development of clean energy technologies and infrastructure. Here are some of the key elements:

- **Lithium (Li)** Used primarily in lithium-ion batteries for electric vehicles (EVs) and energy storage systems.
- **Cobalt (Co)** Another vital component in lithium-ion batteries, helping to improve battery stability and energy density.

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[5] International Energy Agency. (2024). *Global EV Outlook 2024.*

[6] International Energy Agency. (2021). *The Role of Critical Minerals in Clean Energy Transitions.*

[7] Ma, X., Meng, Z., Bellonia, M. V., Spangenberger, J., Harper, G., Gratz, E., ... & Wang, Y. (2025). The evolution of lithium-ion battery recycling. *Nature Reviews Clean Technology*, *1*(1), 75-94.

[8] Organisation for Economic Co-operation and Development. (2023). *Handbook on Environmental Due Diligence in Mineral Supply Chains.*

- **Nickel (Ni)** Increasingly used in battery production, particularly to enhance energy capacity and longevity.
- **Rare Earth Elements (REEs)** This group includes elements like neodymium (Nd) and **dysprosium (Dy)**, which are essential for producing strong permanent magnets used in wind turbines and electric motors.
- **Copper (Cu)** Widely used in electrical wiring and components in renewable energy systems, including solar panels and wind turbines.
- **Graphite** Used as an anode material in batteries and is crucial for energy storage technologies.
- **Silicon (Si)** Key for photovoltaic cells in solar panels, silicon is essential for converting sunlight into electricity.
- **Zinc (Zn)** Often used in energy storage systems and has applications in renewable energy technologies and batteries.
- **Manganese (Mn)** Used in some types of lithium-ion batteries to improve energy density and charge capacity.
- **Aluminum (Al)** Used in solar panel frames and structures, along with being a lightweight material beneficial for electric vehicles.

These elements are critical for the advancement and efficiency of technologies aimed at reducing greenhouse gas emissions, promoting renewable energy, and facilitating the transition to a more sustainable energy future. The responsible sourcing, recycling, and sustainable practices of CRMs are essential in the context of decarbonization.

3. BULGARIA'S ROLE IN THE FUTURE OF RAW & CRITICAL MINERALS

The economic situation in Europe, and respectively in Bulgaria urgently requires scientific research and innovation towards primary raw minerals. In this context, it is crucial for Bulgaria to reassess its potential for raw materials and minerals. It is well known that Bulgaria is a country with traditions in mining, possessing world-class copper[9] and gold deposits[10], significant deposits of non-precious metals and industrial minerals, as well as dozens of operational mines and quarries. The country's potential for extracting, processing, and recycling critical and strategic raw materials and minerals is significant, but targeted research in this area has been lacking over the past thirty years.

The green transition and sustainable socio-economic development in Bulgaria are closely tied to the utilization of the country's potential for extracting strategic elements.

The green transition and sustainable socio-economic development in Bulgaria are closely tied to the utilization of the country's potential for extracting strategic elements. However, for the next 25 years, the country will still rely on the effective use of its existing energy resources. Advances in technology show that even hydrocarbon energy sources, typically considered environmentally harmful, can be harnessed in new and low-emission ways.[11] The country's strategy should include a reassessment of its energy potential, enabling the realization of the green transition goal: reducing greenhouse gas emissions from fossil fuel combustion and gradually transitioning to energy production from cleaner sources.

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[9] Atanassova, I., Benkova, M., Nenova, L., Simeonova, T., & Harizanova, M. (2024). Sources of metals, metalloids and non-metals in surface horizons of soils near Aurubis-Pirdop copper smelter in Bulgaria. Bulgarian Journal of Agricultural Science, 30(4), 561-567.

[10] SEE News. (2010). *Gold Mining and Processing in Bulgaria.*

[11] Sadeq, Abdellatif M., et al. (2024). Hydrogen energy systems: Technologies, trends, and future prospects. Science of The Total Environment, 173622.

Lithium

Lithium is a critical element in modern technology, and lithium minerals will play a key role in the fight against climate change. However, the demand for lithium-ion batteries is dependent on an expanding supply of primary resources. Lithium occurs in limited amounts on the Earth in a surprising diversity of mineral species, from pyroxenes to amphiboles, phyllosilicates (Fig. 3) to phosphates.

Fig. 3. Lepidolite-$K(Li, Al)_3(Al, Si, Rb)4O10(F,Oh)_2$ and Spodumene-$Li, Al(SiO_3)_2$

Lepidolite

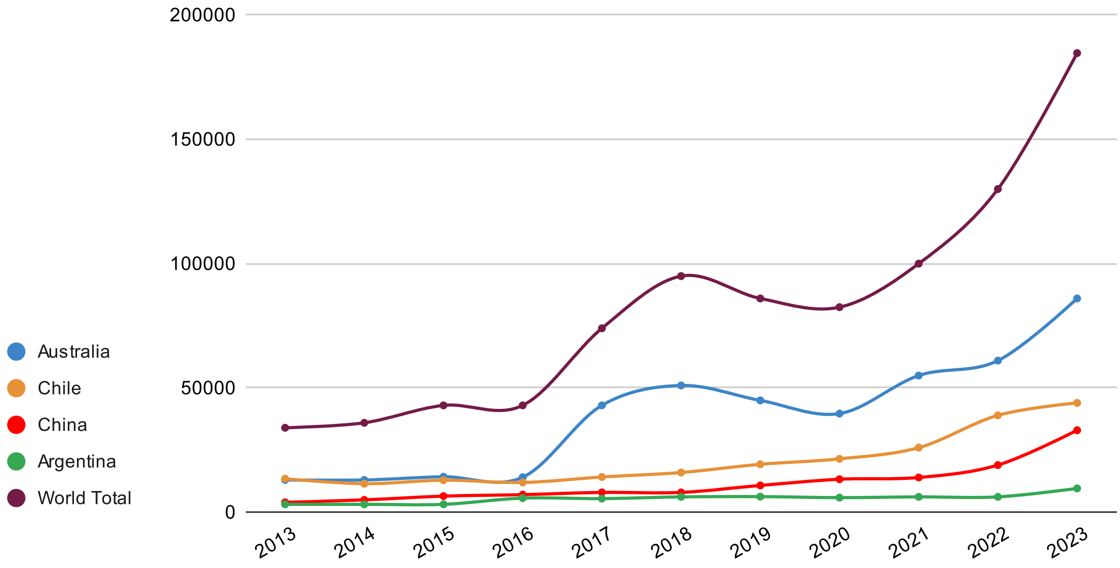
Spodumene

Source: mindat.org.

As a critical raw material, lithium is categorized as such because of:

- **High demand in clean energy technologies:** Lithium is key to energy storage, essential for renewable energy systems and electric vehicles.
- **Supply risks:** The global lithium supply is concentrated in a few countries, primarily Australia, Chile, and Argentina (Fig. 4), creating geopolitical and economic dependencies.
- **Limited recycling:** Currently, lithium recycling is still in its early stages, which adds to supply pressures.

Fig. 4. Global Lithium production for the period 2013-2023.

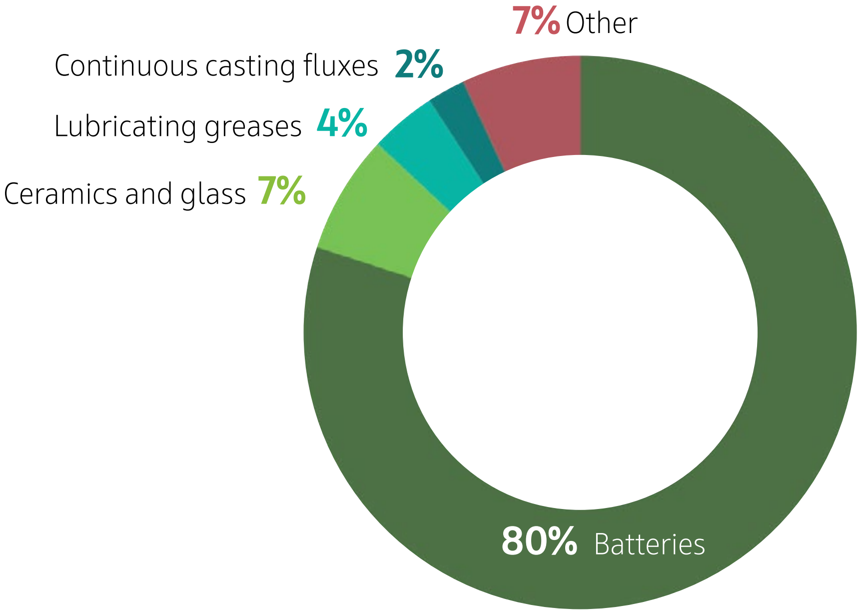


Source: Net-Zero Lab's illustration based on Statista.

Due to these factors, lithium is recognized by the European Union, the U.S., and other countries as a critical element for future energy security and technological development.

Lithium is a highly reactive metal that is used to make energy-dense rechargeable batteries for electronics, such as laptops, cell phones, electric vehicles, and grid storage (Fig. 5). Demand for lithium-ion batteries has grown significantly in recent years, driving global exploration, and enabling new lithium projects to be considered. Batteries accounted for 80% of total demand in 2022.

Fig. 5. Global uses of lithium for 2022.



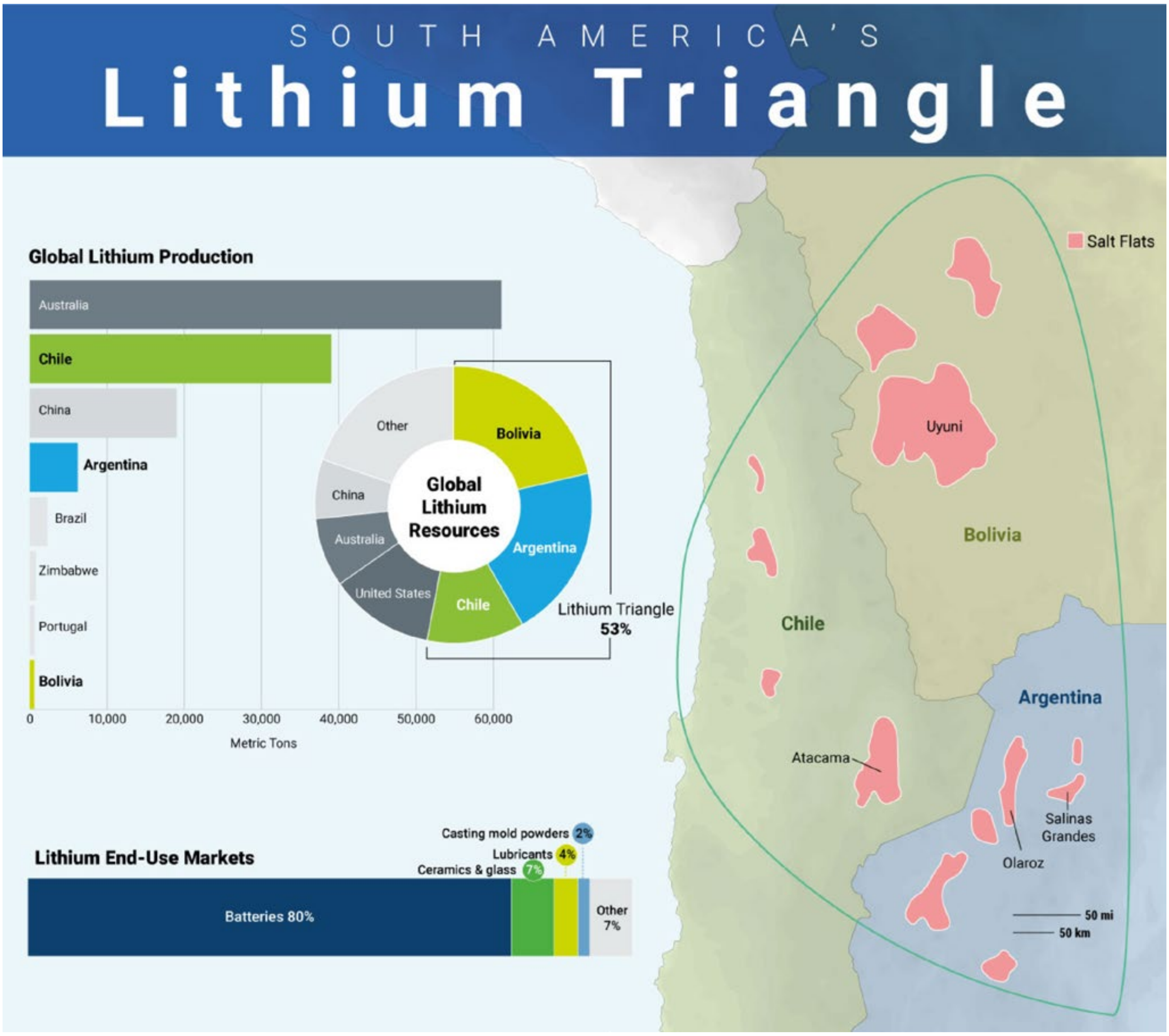
Source: Government of Canada.

Also used in glass products, lithium increases the durability, corrosion resistance, and thermal resistance for use at extreme temperatures. It is used in such items as glass-ceramic stovetops, glass containers, specialty glass, and fibreglass. Because of its natural properties, lithium contributes to improved process productivity and energy savings in glassmaking. Lithium is a critical mineral for the energy transition and net-zero emissions will require greater reliance on both new and recycled sources of lithium for batteries.

Lithium Geology

Despite lithium's abundance on Earth, economically viable concentrated deposits, or "reserves," are relatively scarce. The Lithium Triangle (Fig. 6), spanning regions of Chile, Argentina, and Bolivia, holds the majority of the world's lithium resources. The largest known lithium reserves are found in brine deposits within the Lithium Triangle, accounting for up to 70% of global lithium sources. In contrast, a significantly smaller portion, around 10%, is present in hard rock ores, including spodumene, lepidolite, hectorite, and jadarite (Fig. 3 and Fig. 7).

Fig. 6. Lithium tringle – Chile, Argentina and Bolivia.

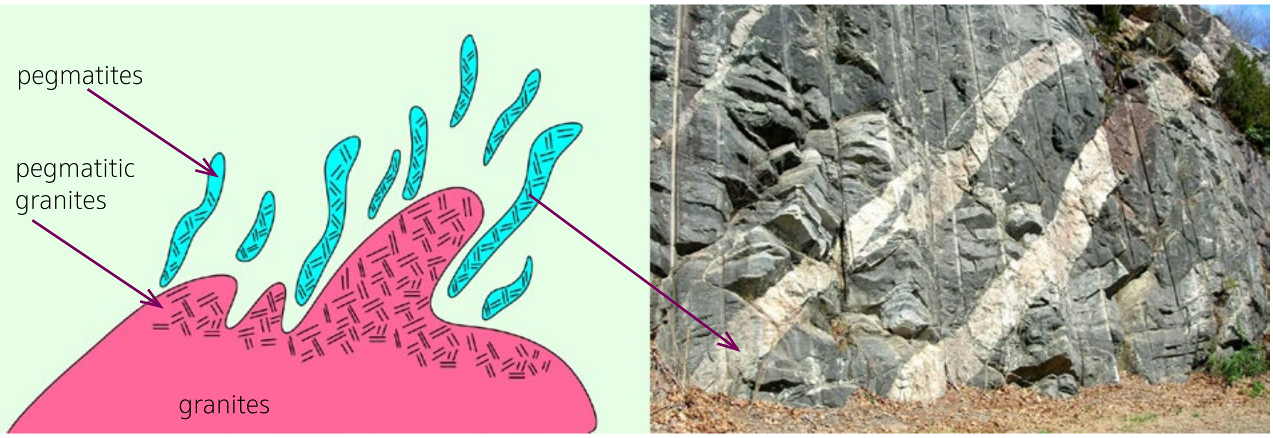


Source: Geopolitical futures.

The easiest and least environmentally damaging method of exploiting lithium is from brines, while exploitation from ore rocks has severe environmental consequences. Therefore, lithium mining is usually conducted in deserts and uninhabited areas of Australia, Chile, China, Argentina, Canada, Zimbabwe, and the United States. Recently, the exploitation of lithium has been considered in two populated areas in Portugal and Serbia.

Lithium mining from pegmatites is another method of extracting lithium, and it involves mining lithium from hard-rock pegmatite deposits. Pegmatites are igneous rock that are formed from magma and are characterized by their large crystal sizes (Fig. 7). These rocks are found all over the world, and some of them contain high concentrations of lithium minerals, such as lepidolite and spodumene (Fig. 3).

Fig. 7. Formation of pegmatites.



Source: Author's archiv.

Given China's dominance over the lithium-ion battery supply chain–accounting for 80% of global raw material refining, 77% of cell production capacity, and 60% of component manufacturing–the European Commission has actively promoted mining projects within Europe to strengthen regional supply chain resilience.[12]

Fig. 8. Mineral jadarite - $LiNaSiB_3O_7(OH)$.

Source: Benchmark Source.

The Jadar Lithium Deposit, located in the Jadar Basin, Serbia, is a significant lithium-boron deposit of global interest. It is characterized by the presence of jadarite [$LiNaSiB_3O_7(OH)$], a unique lithium- and boron-bearing mineral (Fig. 8). Jadarite, which contains approximately 7.2% Li_2O and 47.2% B_2O_3, was officially recognized as a new mineral by the International Mineralogical Association. The deposit itself is associated with Miocene lacustrine volcanic sedimentary rocks, where a tuff layer serves as a key ore-prospecting indicator. The estimated resources include approximately 2.06 million tons of Li_2O and 15 million tons of B_2O_3, making Jadar one of the largest lithium-boron deposits of its kind.

The first reports on high lithium and boron concentrations in the Jadar Valley date back to 1999, when Obradović et al.[13] identified the site's mineral potential. Subsequently, in 2007, Whitfield et al.[14] characterized jadarite as a distinct mineral (Fig. 7). Recent assessments suggest that the Jadar deposit has the potential to supply up to 90% of Europe's current lithium demand, positioning it as a key strategic resource for the continent's transition to battery technologies and electrification.

Despite its significance, the Jadar lithium deposit accounts for only around 1% of the world's total lithium reserves. Rio Tinto, a leading multinational mining company, has been conducting exploration activities in the area for over 15 years. The com-

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[12] Seaman, J. (2024). Critical Raw Materials, Economic Statecraft and Europe's Dependence on China. The International Spectator, 1-18.

[13] Obradović, J., Vasić, N., Kašanin-Grubin, M., & Grubin, N. (2000). Neogene lacustrine sediments and authigenic minerals geochemical characteristics. Geološki anali Balkanskoga poluostrva, 63(1), 135-154.

[14] Whitfield, P. S., et al.(2007). LiNaSiB3O7 (OH)–novel structure of the new borosilicate mineral jadarite determined from laboratory powder diffraction data. Acta Crystallographica Section B: Structural Science, 63(3), 396-401.

pany completed the geological exploratory phase of the Jadar Project in January 2020, following extensive drilling and testing campaigns. In June 2021, the project gained political backing from Serbian authorities, further advancing plans for the development of a lithium mine in the region.

Lithium resources in Bulgaria

Bulgaria has attracted attention for its potential lithium resources, especially as global demand for lithium grows due to its critical role in battery production for electric vehicles and renewable energy storage. While the country is not yet a major lithium producer, its resource potential is significant.

Fig. 9. **Mining salt in Salar de Uyuni, Bolivia.**

Source: Planet Escape.

Some geological estimates suggest that Bulgaria may have significant lithium resources, but detailed data on the size and quality of these deposits remain limited or is missing.[15] Lithium deposits are natural concentrations of lithium in rocks, minerals, and brines. Lithium deposits can be found in several types of geological environments, including salt lakes (known as brine deposits) (Fig. 9), pegmatites (Fig. 7) and volcano-sedimentary rocks.

Lithium brine is a saline water solution rich in lithium. Currently, there is no data confirming the presence of such deposits in Bulgaria. However, pegmatites—a wide-

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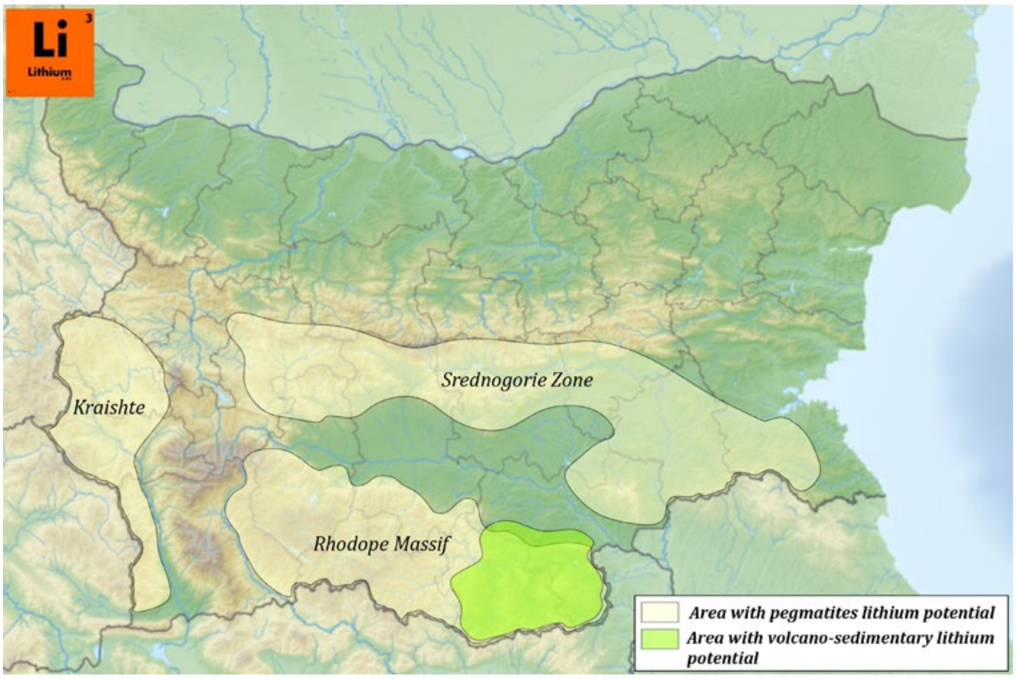
[15] BN – CONSULT INGENERING. *Project "Lithium-Bulgaria".*

ly distributed rock type in the country–have been poorly studied in terms of their lithium resource potential. There are just some sporadic data about spodumene and lepidolite bearing pegmatites. Granite pegmatites are localized south of the Stara Planina Mountain (Balkan Mountains), in Srednogorie zone, Rhodope Massif, and Kraishte region (Fig. 10). The pegmatites are genetically linked to the high-grade metamorphic complex. Granite pegmatites are divided into three groups: rare-earth, rare-metals and chamber pegmatites. In Bulgaria, there are very good possibilities for discovering volcano-sedimentary lithium deposits, similar to Jadar Deposit, Serbia. The ore-prospecting indicator of these deposits is presence of the tuff layer lacustrine volcanic sedimentary rocks. The type of rocks is widespread in Eastern Rhodopes. Bulgaria is believed to have significant but yet-to-be-estimated potential for lithium deposits.

Fig. 10. Areas in Bulgaria with lithium resource potential.



Source: Author's visualization.

Rare Earth Elements (REE)

Rare earth elements (REE) include the 15 lanthanide elements on the periodic table from lanthanum (La) to lutetium (Lu), and also properly include the transition metals scandium (Sc) and yttrium (Y). The REEs are classified as metals and are relatively soft, ductile and malleable. The lanthanide promethium (Pm) is the only radioactive element of the series, is extremely rare in nature, and is mainly produced synthetically as a byproduct of uranium fission.

The REE are commonly subdivided into light REE (LREE), which include La, Ce, Pr, Nd, Pm, Sm, Eu, and Gd, and heavy REEs (HREE), including Tb, Dy, Ho, Er, Tm, Yb, Lu, and Y (Fig. 1). The range of ionic sizes thus allows for substitution into more than 200 rock-forming minerals, especially phosphates and carbonates (Fig. 11). REE-bearing minerals often show selective enrichment in LREE or HREE depending upon the original composition and crystal structure of the mineral compound, the geological conditions in which the mineral formed, and a variety of complex ion exchange mechanisms.

Fig. 11. Economic minerals containing rare earth elements.

Mineral Name	Chemical Formula
Bastnaesite	(Ce,La)(CO$_3$)F
Monazite	(Ce,La,Nd,Th)PO$_4$
Xenotime	YPO$_4$
Parisite	Ca(Ce,La)$_2$(CO$_3$)3F$_2$
Ancylite	CeSr(CO$_3$)$_2$(OH)âªH$_2$O
Florencite	CeAl$_3$(PO$_4$)$_2$(OH)$_6$
Euxenite	(Y,Ca,Ce,U,Th) (Nb,Ta, Ti)$_2$O$_6$
Fergusonite	(Nd, Ce)(Nb,Ti)O$_4$
Apatite	Ca$_5$(PO$_4$)$_3$(OH)(F,Cl)
Allanite	(Ce,Ca, Y)$_2$ (Al,Fe^{3+})$_3$(SiO$_4$)$_3$(OH)

Apatite

Monazite

Source: Author's visualization, based on photos from mindat.org.

These elements have unique chemical and physical properties that make them critical in many high-tech applications. REE are essential for manufacturing various components in electronic devices – smartphones, tablets, laptops etc. (Fig. 12 and 13). Elements like Neodymium and Praseodymium are used in powerful magnets found in smartphone speakers, microphones and vibration motors. Europium and Terbium are critical for the red and green phosphors in LED and LCD screens. Cerium and Lanthanum are used in capacitors and sensors in electronic circuits. The generators in wind turbines use NbFeB magnets, which help produce electricity efficiently from wind power.

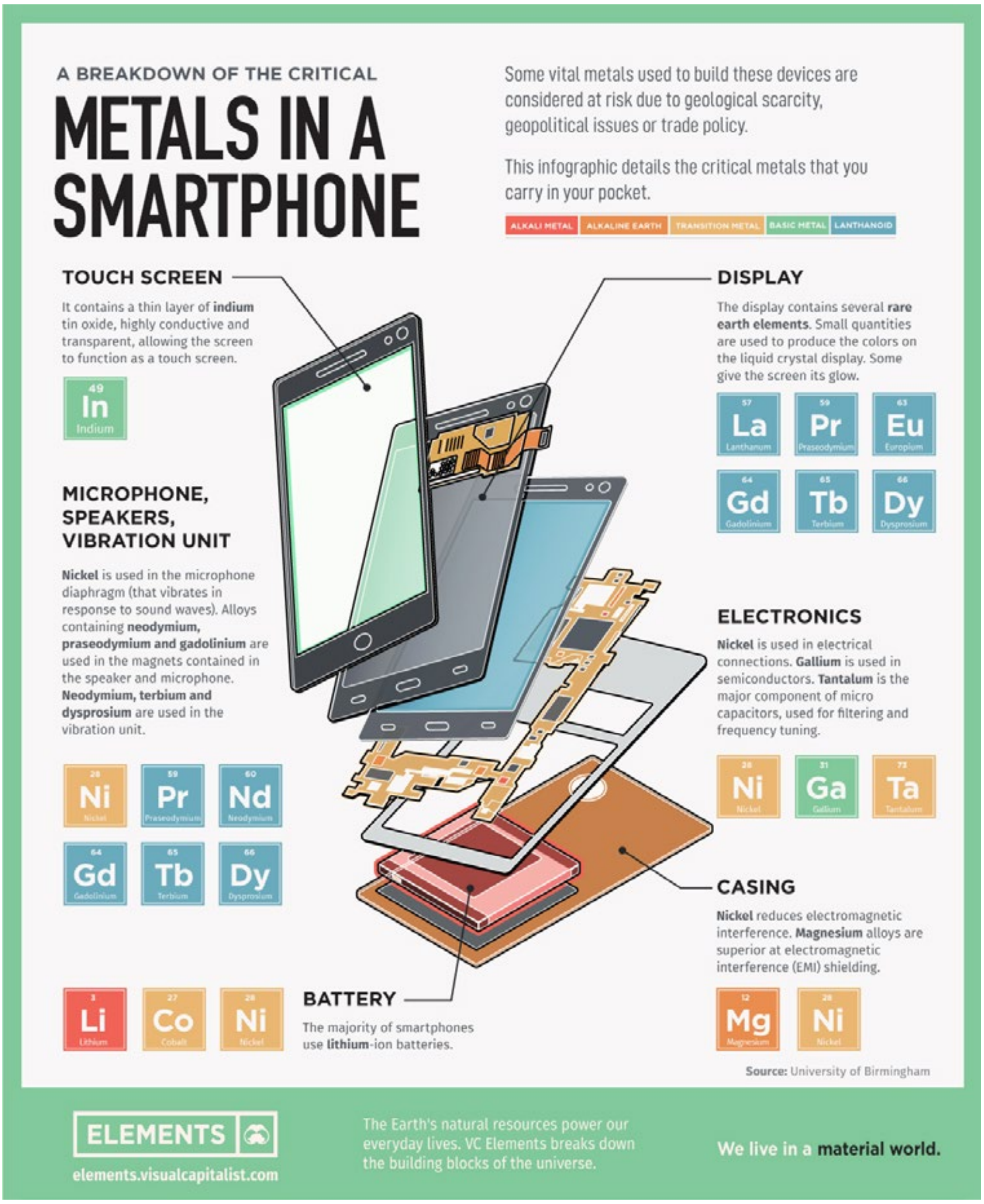
Fig. 12. Some applications of REE.

Source: Author's visualization

Green Energy and Clean Technology

As mentioned, Neodynium-based magnets are vital for the operation of the turbines that convert wind energy into electricity. Lanthanum is widely used in nickel-metal hybride batteries (NiMH). REEs are indispensable for modern technology, particularly in electronics, green energy, defense, and medical applications. Their unique magnetic, catalytic, and phosphorescent properties enable advancements in fields like electric vehicles, renewable energy, and consumer electronics. However, REEs are difficult to mine and process, which makes their supply chain critical to industries worldwide.

Fig. 13. Look inside your smartphone.



Source: Elements.com.

REE Geology

Despite the group name, most of the rare earth elements are relatively abundant in the Earth's crustal rocks, although rarely as native metals. For comparison, the average crustal concentration of lanthanum is 31 parts per million (ppm), slightly greater than the average for copper (Cu), which is 28 ppm. Thulium, the least abundant naturally occurring rare earth element (REE), has an average concentration of approximately 0.30 parts per million (ppm) in the Earth's crust. In contrast, silver's average crustal abundance is about 0.075 ppm. This indicates that thulium is roughly four times more abundant than silver in the Earth's crust.[16]

The relatively large ionic size and charge balance characteristics of REE in magmatic systems generally prevent their incorporation into most common rock-forming

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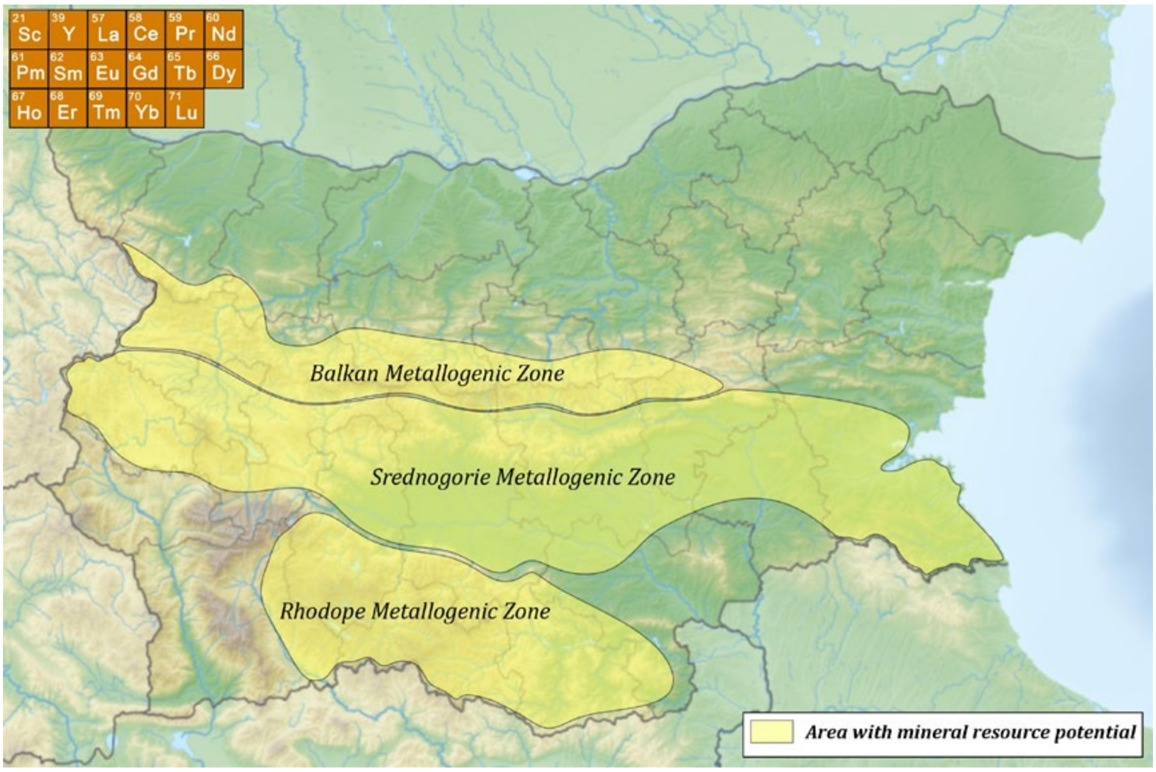
[16] Rare Earths. *The Element Thulium.*

minerals, such as feldspars, quartz, amphiboles, and mica. As a result, REEs tend to concentrate in rocks derived from highly fractionated magmas, including alkaline and silicic igneous complexes, pegmatites, felsic volcanics, and carbonatites. Due to their similar ionic sizes, thorium and uranium are often associated with REEs. Additionally, high-temperature hydrothermal fluids, particularly those enriched in chlorine, fluorine, and lithium, can mobilize REEs. Economically viable REE deposits are found in magmatic systems, iron oxide-copper-gold (IOCG) deposits, heavy mineral placers, and chemical weathering zones, particularly within ion-adsorption clay deposits.[17]

REE Resources in Bulgaria

In Bulgaria, no economical reserves and resources of rare earth elements have been proven, but mineralizations that have not been evaluated have been identified, as well as industrial waste that is a potential source of rare metal raw materials. Additionally, there is data of fundamental importance for the mineralogy and geochemistry of trace elements in various geological formations, as well as results from technologies for the extraction of some of them. There is potential for the discovery of rare earth element (REE) deposits in Bulgaria, particularly within the Balkan, Srednogorie, and Central Rhodopes Metallogenic Zones. (Fig. 16).

Fig. 14. Areas in Bulgaria with REE resource potential.



Source: Author's visualization.

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[17] Smith, M. P., Moore, K., Kavecsánszki, D., Finch, A. A., Kynicky, J., & Wall, F. (2016). From mantle to critical zone: a review of large and giant sized deposits of the rare earth elements. Geosci. Front. 7, 315–334.

Aluminum

Aluminum is a critical mineral essential to metallurgical applications in aerospace, defense, energy, and transportation industries.[18] Its use dates back to ancient Greek civilization in the form of alum, though it was not isolated as an element until 1824. Renowned for its versatility, aluminum is widely used across various sectors of the economy. In everyday life, aluminum is commonly found in household products such as aluminum foil, food and beverage cans, and cooking utensils (Fig. 15).

Fig. 15. Use of aluminum.

Source: ena.org.

It is also extensively used in construction for window frames, doors, roofing, and siding. Due to its low density, aluminum is highly valued in the transportation industry, where it is used in bicycles, automobiles, and aircraft, playing a crucial role in aerospace applications. Additionally, aluminum is integral to the electronics and technology sectors, contributing to the development of advanced materials and components.

Aluminum Geology

Aluminum is primarily extracted from bauxite (Fig. 16), a rock composed of aluminum hydroxide minerals such as gibbsite, boehmite, and diaspore. Bauxite forms in regions where intense weathering affects aluminum-rich igneous or metamor-

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[18] Fortier, S.M., Nassar, N.T., Lederer, G.W., Brainard, Jamie, Gambogi, Joseph, and McCullough, E.A. (2018b). Draft critical mineral list–Summary of methodology and background information. U.S. Geological Survey technical input documenting response to Secretarial Order No. 3359: U.S. GeologicalSurvey Open-File Report 2018–1021, 15 p., https://doi.org/10.3133/ofr20181021.

phic rocks, particularly those containing feldspar. Carbonate rocks can also serve as sources of aluminum.

During weathering, the original minerals in these rocks undergo chemical alteration, breakdown, or erosion, leaving behind a residual clay. Because aluminum is highly insoluble, it remains concentrated in the form of aluminum-bearing minerals. Over time, these minerals may develop into concretionary pisolites within the bauxite rock, contributing to the ore's distinctive composition and structure.

Fig. 16. Boffa Bauxite Mine, Guinea.

Source: mining.com.

Aluminum Resouces in Bulgaria

Small bauxite deposits exist in Bulgaria, but they are too limited for economic development. Historically, several mines were in production. Bauxite ores have been identified in the Paramun, Filipovtsi, and Sekiritsa deposits, where they occur within karst formations in limestones and dolomites. The ore bodies exhibit irregular shapes and variable sizes. The bauxites primarily consist of boehmite and gibbsite.

Barite

Barite (baryte) is a mineral composed of barium sulfate ($BaSO_4$) and is the primary ore for the element barium (Ba). Barium is a silvery, soft, and highly reactive heavy metal that does not occur in its elemental form in nature. Instead, it is commonly found in barite, where it is bound with sulfur and oxygen. Barite typically forms pale yellow or colorless tabular crystals.

The mineral is critical to the oil and gas industry, with nearly 95% of domestic consumption and about 90% of global consumption used in petroleum and natural gas exploration and development. Barite is classified as a critical mineral due to its essential role in metallurgical applications that support energy technologies.[19]

One of its most significant applications is in drilling mud used for oil and gas exploration. Mined barite is ground into a fine powder and mixed with mud to create a heavy slurry. This slurry is then poured down the drill hole to form a plug around and above the drill bit. Due to its softness, barite does not damage the drill bit, but its high specific gravity effectively counteracts upward pressure, reducing the risk of blow-outs caused by high subsurface pressures.

Fig. 17. **Barite-essential oil and gas exploration and development drilling.**

Source: Bleiwas & Miller, 2015.

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[19] Fortier, S.M., Nassar, N.T., Lederer, G.W., Brainard, Jamie, Gambogi, Joseph, and McCullough, E.A. (2018b). Draft critical mineral list–Summary of methodology and background information. U.S. Geological Survey technical input documenting response to Secretarial Order No. 3359: U.S. GeologicalSurvey Open-File Report 2018–1021, 15 p., https://doi.org/10.3133/ofr20181021.

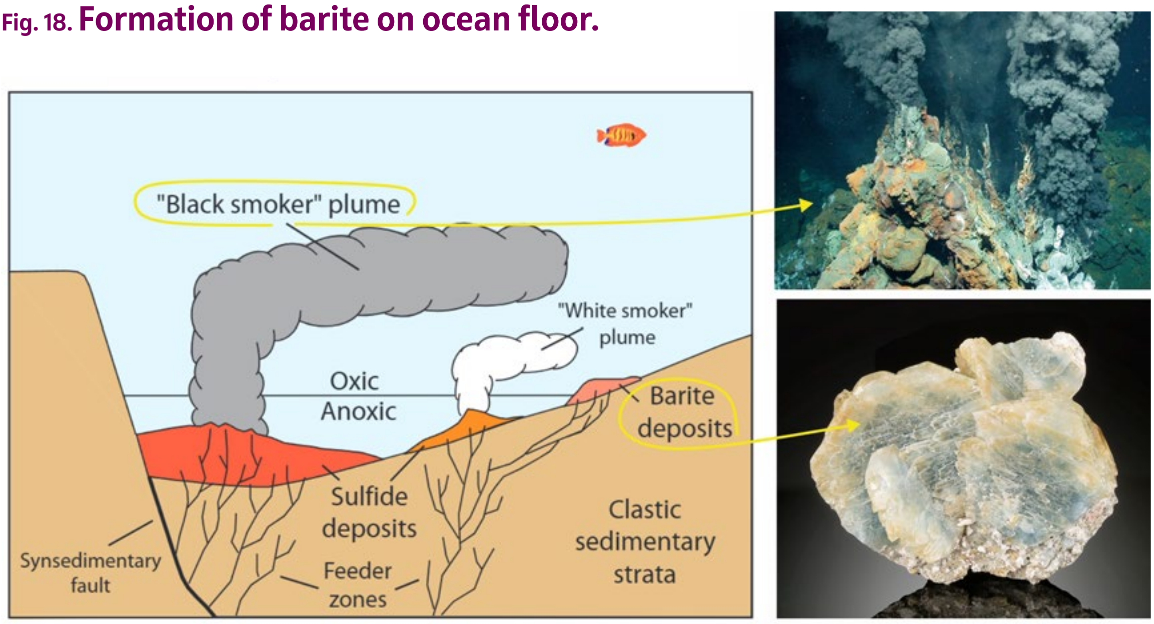
Elemental barium is an additive in optical glass, ceramic glazes, and other products. Barite is used as a weighing agent in a variety of other applications, including paper, brakes, and even playing cards. It is commonly used in the production of paints, rubber, and as a filler or to improve brilliance and clarity. The medical industry uses barite for radiation shielding, or to increase contrast in radiographs.

Barite Geology

Barite deposits can form through various geological processes. As a bedded sedimentary deposit, barite develops from marine sedimentation and biological activity, where barium binds into layered deposits on the ocean floor. Over time, these sediments lithify into shale or mudstone, with barite occurring in nodular, rosette, bedded, or massive forms.

Barite also forms in cavities or veins where high-temperature fluids circulate through permeable rocks, allowing minerals to precipitate. It is commonly found along faults and breccia zones, where extensive mineralization can occur, or within smaller, irregular cavities in rocks. Additionally, barite deposits can result from the weathering of cavity-fill barite mineralization within carbonate host rocks. When these barite-rich rocks undergo weathering, barite can accumulate as residual deposits.

Fig. 18. Formation of barite on ocean floor.

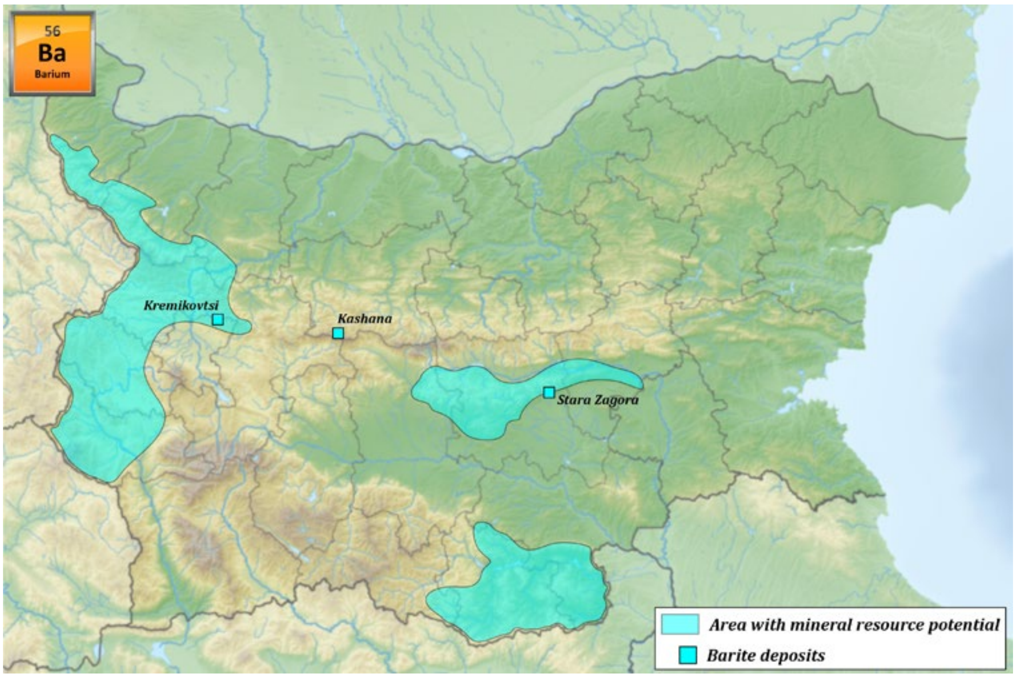


Source: Koski and Hein, 2003.

Barite Resources in Bulgaria

Bulgaria does not maintain a supply of barite, but there is a potential for exploration and eventually of mining of these raw materials. There are several historical barite deposits, three of them of considerable size and reserves, ongoing in the past times – Stara Zagora, Kashana and Kremikovtsi. On the territory of Bulgaria, there are a lot of smaller barite deposits and occurrences which need to be studied and evaluated (Fig. 19).

Fig. 19. **Barite deposits and barite resources area in Bulgaria.**



Source: Author's visualization.

Graphite

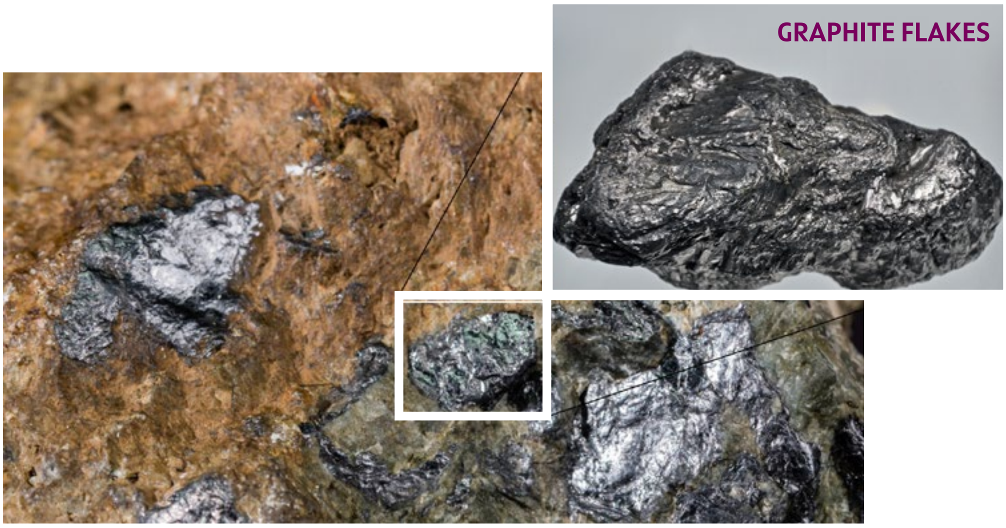
Graphite is a naturally occurring crystalline form of carbon (chemical symbol C) known for its exceptional electrical and thermal conductivity. It is chemically stable, highly lubricative, and extremely soft, making it a unique and nearly irreplaceable material in various industrial applications. Humans have utilized graphite since the Neolithic era, and today, it is classified as a critical mineral due to its essential role in metallurgical processes and advanced technologies across aerospace, defense, energy, electronics, telecommunications, and transportation sectors.[20]

The primary use of graphite is in metallurgy, particularly in steelmaking. It also plays a crucial role in the energy industry, serving as a key material in electrodes, electric motor brushes, batteries, fuel cells, and moderator rods for nuclear reactors. Additionally, graphite is used to manufacture high-temperature lubricants and high-strength, lightweight composites for wind and water turbines. Its superior properties make it an indispensable material in aerospace engineering.

Graphite Geology

Graphite is found in a variety of metamorphic rock formations. Economically viable graphite deposits originate from organic-rich sedimentary rocks that have undergone metamorphism due to intense heat and pressure. It typically occurs in three main forms: amorphous graphite, which results from coal metamorphism; flake graphite (Fig. 20), composed of crystal platelets within crystalline metamorphic rocks that were once carbonaceous sediments; and lump or chip graphite, consisting of coarse crystals formed within fluid-filled veins and fractures in igneous and metamorphic rocks.

Fig. 20. **Metamorphic rocks containing graphite flakes.**



Source: mindat.org.

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[20] Fortier, S.M., Nassar, N.T., Lederer, G.W., Brainard, Jamie, Gambogi, Joseph, and McCullough, E.A. (2018b). Draft critical mineral list–Summary of methodology and background information. U.S. Geological Survey technical input documenting response to Secretarial Order No. 3359: U.S. GeologicalSurvey Open-File Report 2018–1021, 15 p., https://doi.org/10.3133/ofr20181021.

Graphite Resources in Bulgaria

No industrial-scale graphite deposits have been identified in Bulgaria, though several occurrences of graphite-bearing rocks are known. These are primarily associated with high-grade metamorphic complexes and partially graphitized coal shales. Limited graphite extraction has only occurred from graphitized coal shales near the village of Selce in the Kazanlak region.

Flake graphite in metamorphic rocks has been identified in multiple locations within the Central Rhodopes. Notable occurrences include the Vacha River valley (Byalata Stena), the areas around the villages of Mihalkovo and Zabardo, and along the Djurovska and Manastirska river valleys, as well as in the Laki region.

Beyond the Rhodopes, graphite occurrences in metamorphic rocks have been recorded near the village of Shishmanovo (Haskovo region) and south of the village of Lebnitsa (Sandanski region). Additionally, partially graphitized coal shales have been identified in the core of the Mihailovgrad anticline, near the villages of Ignatitsa and Selce.

Manganese

Manganese is classified as a "critical mineral" due to its essential role in metallurgical applications supporting aerospace, defense, energy, and transportation technologies.[21] It is a vital component in steel production, serving as a sulfur-fixing, deoxidizing, and alloying agent. Manganese ferroalloys, including various grades of ferromanganese and silicomanganese, are key ingredients in steelmaking, with major end uses in the construction, machinery, and transportation industries.

Beyond steel production, manganese plays an important role in the manufacturing of aluminum alloys and cast iron. Manganese dioxide is particularly significant for the production of dry-cell batteries, where it is used as a cathode material. Non-metallurgical applications of manganese include its use in plant fertilizers, animal feed, and as a colorant in brick manufacturing.

Manganese Geology

Manganese minerals are relatively common in the Earth's crust, with the highest concentrations found in ferromanganese nodules and crusts along the ocean floor. These deposits form through marine chemical processes and microbial activity, which facilitate the capture and precipitation of dissolved manganese from seawater. While these seafloor deposits represent a vast potential resource, their exploration and recovery are not currently economically viable due to technological and cost-related challenges.

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[21] Fortier, S.M., Nassar, N.T., Lederer, G.W., Brainard, Jamie, Gambogi, Joseph, and McCullough, E.A. (2018b). Draft critical mineral list–Summary of methodology and background information. U.S. Geological Survey technical input documenting response to Secretarial Order No. 3359: U.S. GeologicalSurvey Open-File Report 2018–1021, 15 p., https://doi.org/10.3133/ofr20181021.

Fig. 21. A ferromanganese-coated cobble more than 10 cm diameter, North Atlantic.

Source: Oceanexplorer NOAA

The highest concentrations of economically obtainable manganese are found in ancient marine sedimentary rocks, some dating back 2.5 billion years. Manganese initially accumulates in marine environments, where it can precipitate along continental margins in association with iron. As oxidation and water acidity fluctuate, iron- and manganese-rich layers form, contributing to the formation of banded iron formations. When these sedimentary rocks are later uplifted or transported to terrestrial environments, chemical weathering can lead to supergene enrichment, resulting in the formation of residual and replacement manganese deposits.

Manganese Resources in Bulgaria

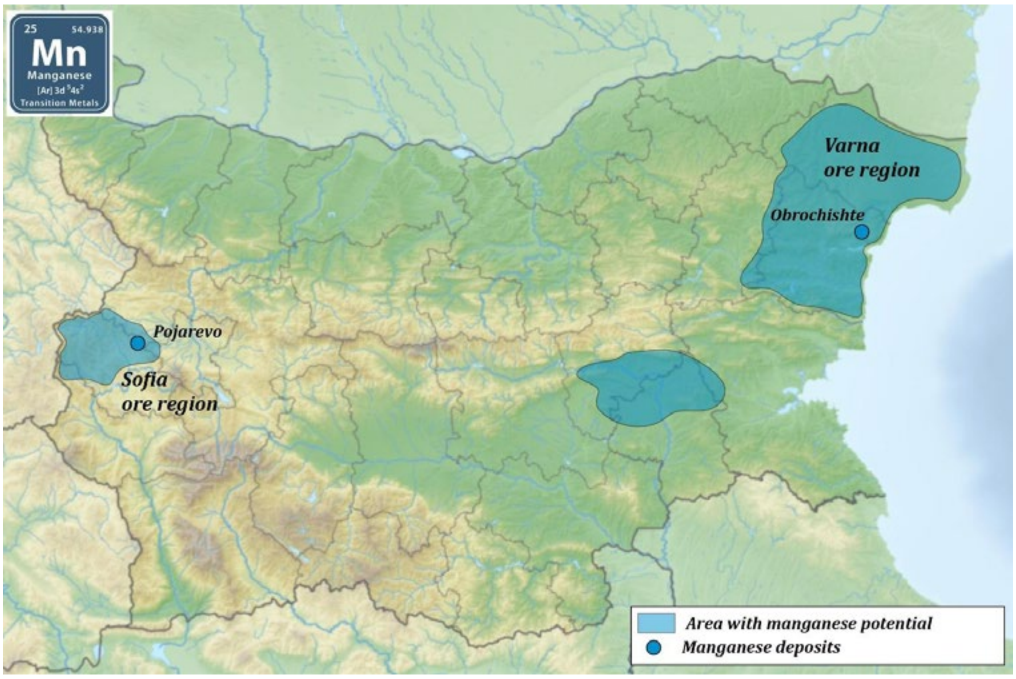
Manganese mining in Bulgaria occurred in two distinct phases: from 1907 to 1947 and from 1953 to 1995. The country's manganese deposits can be classified into three industrial types: volcanogenic-sedimentary, hydrothermal, and weathering. Mining began in 1907, but production remained minimal and was frequently interrupted until 1947. The second phase (1953-1995) saw steady development and expansion of manganese extraction. With the restructuring of the industry and the privatization of mining enterprises, production initially increased. However, manganese ore extraction in Bulgaria has since ceased.

Despite the lack of current production, Bulgaria hosts three relatively large manganese deposits: Pozharevo (Sofia region), Ignatievo and Obrochishte (Varna region), and Enyovche (Kardzhali region) (Fig. 22).

Obrochishte deposit belongs to the Varna Ore Region, part of the Eurasian Manganese Provenance. World class deposits in this area are Chiatura (Georgia) and Nicopol (Ukraine). Manganese deposits and occurrences in Bulgaria spread out from Stara Planina Mountain to the border of Romania. Obrochishte is the largest

Bulgarian manganese deposit, with 58 million tons ore and an average content of 28% manganese. According to the world classification, it refers to large manganese deposits. Recalculated ore reserves rank the deposit first in Europe and fourth in the world in terms of manganese reserves. The explored reserves of Obrochishte make it possible to project a larger output, but no clear decision was made on the production capacity. In addition to the complex mining-technical and hydrogeological conditions and the difficulties of mining the ore, the environmental problems of protecting the Black Sea coast near the deposit are of particular importance.

Fig. 22. **Areas in Bulgaria with manganese deposits.**



Source: Author's visualization.

Feldspars

Feldspars are a group of aluminosilicate minerals containing potassium, sodium, and calcium, with occasional traces of barium, cesium, and other elements in isomorphic substitution.[22] These minerals play a crucial role in various industrial applications, particularly in the production of glass and ceramics, where their alkali and alumina content act as fluxing agents. Additionally, feldspars are used as functional fillers in the polymer, paper, and paint industries. The industrial use of feldspar minerals is primarily limited to the most common varieties with low melting points, such as alkali feldspars (orthoclase and microcline) and Na-rich plagioclase (albite). The glassmaking and ceramic industries are the largest consumers of feldspar. In glass production, feldspar's alkali components lower the melting temperature of quartz and help regulate the viscosity of molten glass. In ceramics, it serves as a fluxing agent in the manufacturing of products such as sanitary ware, tableware, tiles, and enamel frits.

A significant portion of feldspar production is also utilized in functional filler applications, including paints, rubber composites, polymers, adhesives, and coatings. Other specialized applications include its use in welding electrodes.

Fig. 23. **Application of feldspar minerals.**

Source: Author's visualization.

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[22] G.W. Heyes, G.C. Allan, W.J. Bruckard, G.J. Sparrow. 2013. Review of flotation of feldspar Min. Proc. Ext. Met. Rev., 121 (2013), pp. 72-78. Mineral Commodity Summaries 2020. USGS.

Feldspar Resources in Bulgaria

Feldspar deposits in Bulgaria are primarily associated with granite pegmatites, which are widespread and mainly localized in the Srednogorie Zone, the Rhodope Massif, and the Kraishte region. Feldspar extraction from pegmatites is feasible when manual separation is possible, particularly in zonal pegmatites with well-formed quartz and feldspar zones. Notable pegmatite deposits explored for feldspar materials in Bulgaria include Lenishte and Mishevsko (Central Rhodopes), as well as deposits north of Strelcha and in the areas of Koprivshtitsa and Panagyurishte (Srednogorie Zone).

Despite these resources, Bulgaria does not fully meet its domestic feldspar demand through local production. Prospective sources beyond classic pegmatite deposits include certain volcanic or intrusive rocks, such as the weathered zone of dacites near the village of Bobeshino (Kyustendil region), where feldspar crystals up to 3–4 cm in size have been identified, and feldspathized intrusive rocks of the Mezdra type. However, challenges in processing technologies, particularly the removal of iron impurities, and economic feasibility must be addressed for their utilization.

Additionally, Bulgaria has relatively large deposits of quartz-feldspar sands, primarily located in Northeastern and northern Bulgaria (Sredna, Novosel, Iskar, Brashlyanitsa, etc.). These sands may serve as potential substitutes for feldspar raw materials in the future. Overall, Bulgaria holds significant reserves and resources of feldspar, with promising prospects for discovering new deposits.

Zinc

Zinc is the sixth most produced metallic element at the world level.[23] The extraction of this metal is linked to the extraction of many other elements that appear as by-products or during the refining. The main zinc ore-bearing mineral is sphalerite (Fig. 24), which appears in hydrothermal deposits along with lead and often with copper, among other elements. In 2014, China was the main leading producer of this element.[24]

Fig. 24. **Sphalerite (ZnS) – zinc bearing mineral.**

Source: mindat.org.

More than half of zinc production is used for galvanizing (Fig. 25). The second primary use is for alloys and, third, for electrical equipment.[25] For its abundance at the global level and the diversity of its main end uses, zinc is not usually included in criticality studies.

In RES harnessing technologies, zinc is used in solar cells, in solar thermal power (between 650 t/GW and 1400 t/GW), among others. Additionally, each electric vehicle will need around 6 kg of zinc for various components.[26] This demand is not expected to change considerably in the coming decades.

Zinc's Role in Renewable Energy Production

Zinc plays a crucial role in renewable energy production and sustainability due to its superior ability to protect metals from corrosion and its growing application in energy storage systems. As a material essential for the future, zinc supports both decarbonization and infrastructure longevity.

Zinc is a key component in battery technologies designed to reduce carbon emissions. Zinc-ion batteries, in particular, offer a safer alternative to lithium-ion batteries by utilizing a water-based chemistry that eliminates the risk of fires.

In addition, zinc is vital in the production of galvanized steel, a preferred material used by electric vehicle manufacturers. By extending the lifespan of steel products, such as those used in bridges, power transmission systems, and other infrastruc-

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[23] Calvo, G., & Valero, A. (2022). Strategic mineral resources: Availability and future estimations for the renewable energy sector. *Environmental Development*, *41*, 100640.

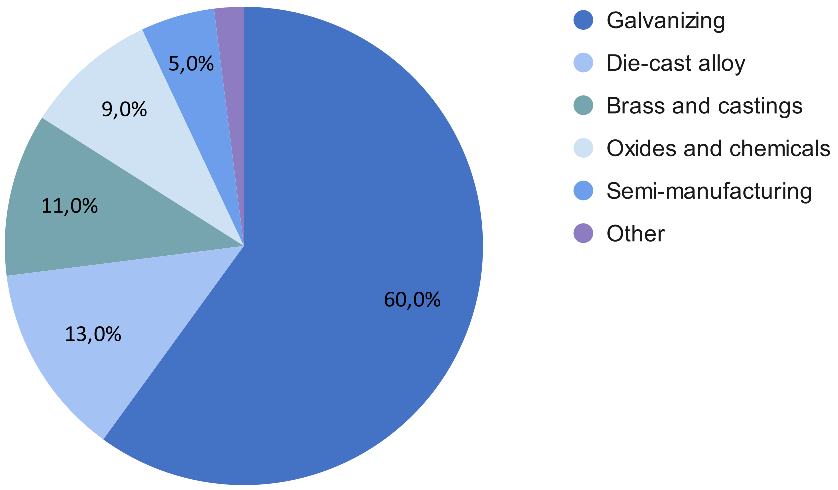
[24] Andy Home. (2024, September). *Zinc concentrates squeeze but there's no shortage of metal.* Reuters.

[25] Calvo, G., & Valero, A. (2022). Strategic mineral resources: Availability and future estimations for the renewable energy sector. *Environmental Development*, *41*, 100640.

[26] Iglesias-Émbil, M., Valero, A., Ortego, A., Villacampa, M., Vilaró, J., & Villalba, G. (2020). Raw material use in a battery electric car–a thermodynamic rarity assessment. *Resources, Conservation and Recycling*, *158*, 104820.

ture, zinc reduces the frequency of replacements and repairs, thereby lowering carbon emissions associated with reconstruction and material production. This dual benefit of durability and sustainability makes zinc an essential material in the renewable energy transition.

Fig. 25. Global uses of Zinc.



Source: Net-Zero Lab's illustration based on data from Natural Resources Canada.

Zinc Geology

Zinc ores are commonly found alongside other minerals in the Earth's crust and are extracted through mining and processing to produce zinc concentrate, which is then refined into zinc metal or other zinc-based products. The primary zinc ore minerals include sphalerite, smithsonite, hemimorphite, and zincite, occurring in various types of deposits such as sulfide, carbonate-hosted, and oxide formations.

The extraction and processing of zinc ores involve a series of steps, including underground or open-pit mining, followed by crushing, grinding, and beneficiation techniques like flotation to separate zinc-bearing minerals from gangue material. The resulting zinc concentrate is then subjected to further refining through smelting or electrolysis to produce high-purity zinc metal or other zinc-containing products.

Zinc Resources in Bulgaria

In Bulgaria, zinc deposits are commonly found with lead, which is why they will be examined together. Bulgaria has a long-standing tradition in the mining of lead and zinc and is very rich in deposits of these elements.

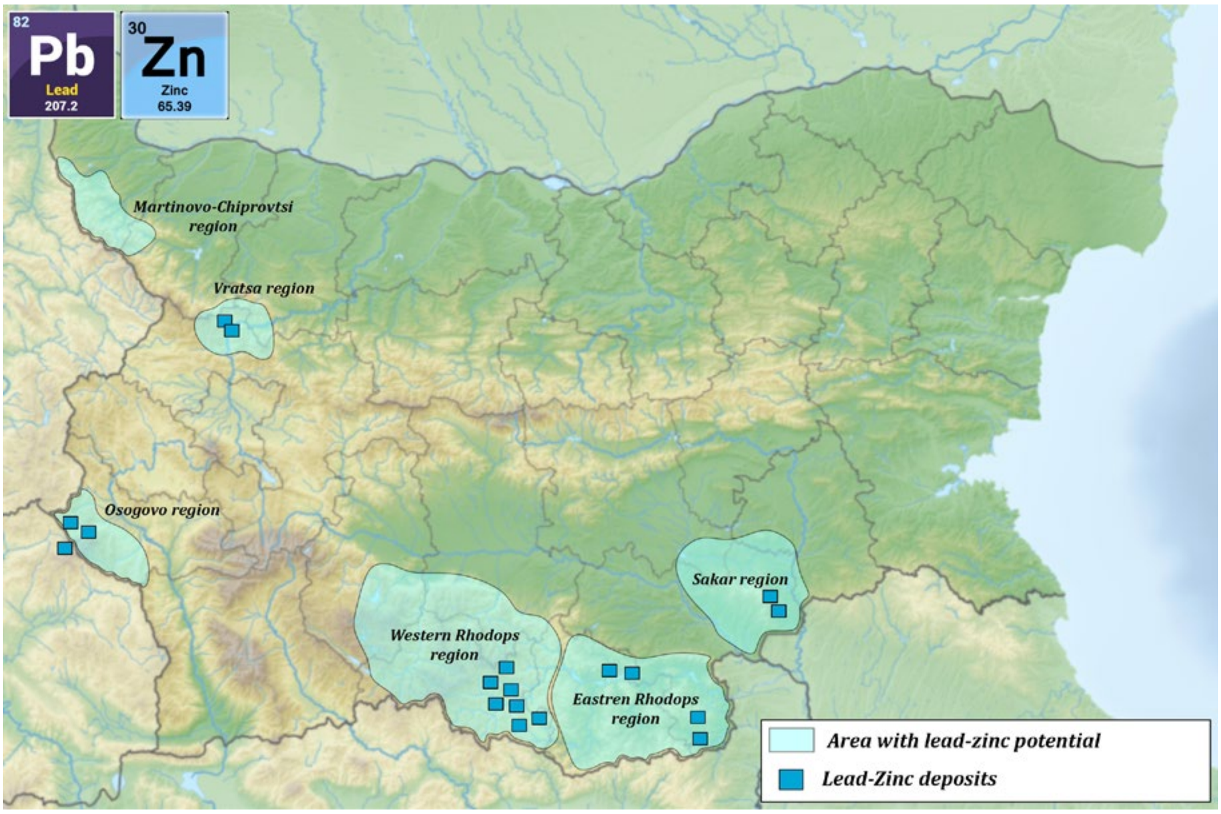
Between 1878 and 1947, limited extraction of lead-zinc ores was carried out by the following joint-stock companies: Pirin, Rodopski Metal, Plakalnitsa, Lykavitsa, Olovnik, Ruda, and Beredzhe-Boruvan. The next period, 1947-1995, is characterized by a rapid rise in the mining of Pb-Zn ores during the 1960s, followed by a sharp decline in the 1990s. Metallurgical plants were built in Kardzhali and Plovdiv, establishing a closed production-technological cycle. By the end of 1995, the extraction and processing of lead-zinc ores were carried out by the following mining companies: GORUBSO EAD, Osogovo EAD, Eliseina EAD, Chiprovetz EAD, Ustrem EAD, and Madzharovo EAD.

Of all the Pb-Zn deposits in Bulgaria, the following currently have extraction concessions:

- Chala: for Pb-Zn ore extraction by GORUBSO-Kardzhali EAD
- Govedarnika and Dzhurkovo: for Pb-Zn ore extraction by Laki Invest Dzhurkovo EAD
- Petrovitsa and Krushev Dol: for Pb-Zn ore extraction by GORUBSO-Madan EAD
- Dimov Dol (near Zlatograd): for Pb-Zn ore extraction by Rudmetal EAD

The lead-zinc deposits in Bulgaria are concentrated primarily in the Rhodope metallogenic zone, and to a much lesser extent in the Western Balkan and Srednogorie metallogenic zones (Fig. 26).

Fig. 26. **Pb-Zn ore deposits and potential areas.**



Source: Author's visualization.

4. CONCLUSION

The future of critical elements, including lead, zinc, and other key minerals like lithium, cobalt, and rare earth elements, is becoming a topic of increasing global importance. These elements are essential for a wide range of modern technologies, from renewable energy systems to electric vehicles, and even in aerospace and defense applications. Bulgaria has the potential to become a key player in Europe's CRM supply chain. Strategic investments in exploration, mining, and processing–coupled with sustainable policies–can help the country maximize its mineral wealth while supporting Europe's transition to a more resilient and greener economy.

In this context, Bulgaria has the opportunity to leverage emerging initiatives such as the National Science Programme "**Critical and Strategic Raw Materials for Green Transition and Sustainable Development**"[27] to establish a foundation for the strategic extraction and utilization of critical raw materials (CRM). Advancing knowledge on the formation and enrichment processes of CRM deposits is essential, alongside an updated assessment of Bulgaria's extraction potential. Additionally, it is crucial to monitor the key mechanisms and pathways through which the extraction, processing, and recycling of CRM, as well as energy production, impact the atmosphere, hydrosphere, and lithosphere.

Expected increase in demand suggest the need to consider demand reduction and efficiency.

As the world transitions to greener and more sustainable energy sources, the demand for certain critical elements is expected to skyrocket. EVs, batteries, solar panels, and wind turbines require significant amounts of metals like lithium, cobalt, nickel, and REEs, along with zinc, which is used in energy storage technologies. Although its use in traditional car batteries might decline, it will still be needed in other applications. The EU should focus not only on managing supply but also on controlling demand. Policies should prioritize demand reduction (sufficiency), which would strengthen the resilience of supply chains by lowering the EU's reliance on importing large quantities of primary (critical) raw materials. Additionally, this approach would help minimize environmental harm and address social injustices in resource-extraction countries.

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[27] Георгиев, С. В. (2024). Критични и стратегически суровини в България: контури на новата Национална научна програма. *Review of the Bulgarian Geological Society*, *85*(3).

Geopolitics of CRM matter.

Critical elements are not evenly distributed around the world, which makes their supply vulnerable to geopolitical tensions. Countries rich in these resources, such as China (which dominates the rare earth market), will have a strategic advantage. At the same time, regions like the EU and the U.S. are increasingly looking to diversify their supply chains and reduce dependence on single-source suppliers by investing in local production and recycling programs. Countries and companies that invest early in the extraction, processing, and recycling of critical elements will be well-positioned to benefit from the demand surge. We can expect significant shifts in global trade patterns, where countries rich in critical elements or those with advanced recycling technologies will have increased leverage in global markets.

The need for sustainable extraction and processing.

One of the biggest challenges in the future will be ensuring that the extraction and processing of critical elements are done sustainably. Traditional mining can be environmentally damaging, so there is growing interest in developing new, less invasive extraction technologies and improving recycling efforts. For instance, recycling batteries to recover elements like lithium and cobalt is a growing industry and is expected to become an essential part of the supply chain.

Technological advancements will likely play a major role in the future of critical elements.

Innovations such as deep-sea mining, urban mining (recycling metals from old electronics), and new methods of extracting elements from ores in a more environmentally friendly manner (e.g., bio-mining using microorganisms) are areas of ongoing research. Moreover, research into alternative materials that can replace critical elements in some technologies might reduce the pressure on some resources.

Addressing the challenge of security of supply.

Supply bottlenecks and shortages could become major issues. For example, as demand for lithium-ion batteries grows with the EV boom, the supply of lithium might become strained unless new sources are developed. This could push companies to explore alternative energy storage technologies, such as sodium-ion batteries, which use more abundant materials. Because of the specificities of CRM markets, the risk of price shocks is high. They are often small compared with other bulk commodities such as steel, and supply is inelastic as investments to increase production have long lead times. In addition, CRM production-related supply-side risk includes 'co-production dependency': some CRMs are obtained as a by-product of one or more host metals from geologic ores. Since, 2008, the EU has launched a number of initiatives, projects and legislative acts in an effort to combat the security of supply challenenge.[28] However, its effectiveness is mixed due to pressing geopolitical events and due to the fact that mitigating the risks associated with CRM supply requires a comprehensive approach. Bulgaria can take the lead in this process on a national scale and implement the following actions:

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[28] European Parliament. (2023, March). Securing Europe's supply of critical raw materials The material nature of the EU's strategic goals.

Boost Research and Innovation.

Bulgaria should invest in research initatives that assess the potential of Bulgaria’s resources, and how to make resource-extraction and refining processes more environmentally-friendly, and to find substitutes for some CRMs.

Implement CRM guiding principles.

To increase awareness, acceptance and trust regarding CRMs sourcing and sustainability, Bulgaria can adapt the European Commission’s voluntary social, economic and environmental EU principles for sustainable raw materials on a national level.

Promote a Circular Economy.

To prepare for a fully circular approach to the CRM supply chain, Bulgaria can invest in research and development initatives to by improve product design, extend product life, and enhance recycling.

The future of critical elements will be shaped by the intersection of technological advancement, geopolitical strategy, and sustainable practices. Those countries and industries that can navigate this complex landscape and secure stable, sustainable supplies of critical elements will have a significant advantage in the coming decades, particularly as the global economy continues to shift towards green energy and advanced technologies.

Sofia University St. Kliment Ohridski, 2025

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