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EUROPEAN POOR AND COMPLEX LITHIUM ORES: PATH TO VIABILITY

Summary. *The article is devoted to the history of the creation and development of a value chain for integrated processing and refining of European domestic poor and complex lithium ores, which found their embodiment in the author's project Li4Life (NOVEL DOMESTIC BATTERY GRADE LITHIUM CARBONATE VALUE CHAIN FOR GREEN LIFE). The author introduces the situation on the lithium raw materials market from 2017 to the recent days. The origins of the brainchild about development domestic lithium ores are given with sufficient justification up to the formation of the conceptual idea in 2021 and the preparation of the Li4Life project proposal, which won the highly competitive competition of the European Commission in the summer of 2023 under Horizon Europe funding program. The technological, legislative and social barriers to the* *development of European lithium deposits are presented, as well as ways to overcome these barriers. The self-sufficiency of the domestic lithium potential for the European Union is demonstrated as a basement for ensuring raw material independence and a green future in full compliance with the goals of the CRMA and Green Deal.*

Introduction. Until a few decades ago, lithium was a relatively unknown metal, with its main applications limited to the glass and ceramic industries. In these industries, lithium compounds such as lithium oxide (Li_2O) and lithium carbonate (Li_2CO_3) were added to glass and ceramics to improve their properties. For example, adding lithium to glass increases its strength, chemical resistance, and thermal stability, making it suitable for use in high-temperature environments or in the production of special optical glasses with a low coefficient of thermal expansion. In ceramics, lithium helps to reduce sintering temperatures and increase the strength of finished products. This relatively modest demand stands in stark contrast to the current situation. Today, lithium is the de facto "white gold" of the 21st century, a key element in the rapidly developing electric vehicle and renewable energy industries. The advent and rapid development of lithium-ion batteries has fundamentally changed the position of lithium in the global market. This silvery-white alkali metal has become an integral part of modern technology, providing energy storage in electric vehicles, portable electronics, energy storage systems (ESS) for solar and wind power plants, and a host of other applications.

We are in the midst of the fourth energy transition, characterized by a sharp increase in the share of renewable energy sources (RES), such as solar and wind power, and increased energy efficiency across all sectors. Critical to the success of this transition is the availability of efficient and reliable energy storage systems, and therefore sufficient amounts of lithium. The demand for lithium is growing exponentially, exceeding current mining and processing capacities. This is driving up the price of lithium significantly and creating geopolitical risks, as countries with large reserves of lithium ore gain significant economic and political influence. The largest lithium producers are Australia, Chile and Argentina, but exploration and development of new deposits is underway in many countries around the world, including China, the United States, Russia, also States of EU. In addition, research is actively underway to find alternative technologies for the production of lithium-ion batteries, including the development of new cathode and anode materials, as well as the study of solid-state batteries, which have the potential to significantly increase the energy capacity and safety of batteries, reducing dependence on lithium. However, despite this research, today lithium will remain a critical element in ensuring energy security and the transition to sustainable development in the coming decades. The issue of ensuring sustainable and ethical lithium production, with minimal impact on the environment, is becoming increasingly important.

Fig. 1. Critical Raw Material Act

Source: European Commission

The European Commission's Joint Research Centre (JRC) forecasts paint a stark picture: a dramatic upswing in the EU's demand for raw materials, particularly those vital to the electric mobility sector. In a high-demand scenario, the JRC projects a twelvefold increase in EU lithium demand for batteries by 2030 compared to 2020, escalating to a twenty-onefold increase by 2050. This necessitates a significant shift towards securing a resilient and sustainable domestic lithium supply chain, minimizing reliance on volatile global markets and geopolitical complexities. Dependence on traditional suppliers such as China and Russia are exacerbated by a complex geopolitical situation, pushing the EU to find alternative solutions and reduce the risks associated with supply disruptions. This situation has become a catalyst for rethinking the role of its own mining resources and resuming geological exploration in Member States. It has led to the enactment of the European Union's Critical Raw Materials Act (CRMA) in 2024 (Fig. 1). This ambitious piece of legislation represents a crucial step towards securing Europe's supply of critical raw materials, including lithium. This necessitates a significant shift towards securing a resilient and sustainable domestic lithium supply chain, minimizing reliance on volatile global markets and geopolitical complexities. The CRM Act goes beyond simply identifying critical materials; it aims to establish a comprehensive framework encompassing exploration, extraction, processing, and recycling within the EU. It includes promoting responsible sourcing, minimizing environmental impact, and encouraging diversification of supply chains to mitigate risks associated with dependence on single countries or regions [1]. The document represents a comprehensive approach to ensuring EU resource security, includes two key lists: 34 critical raw materials and 17 strategic raw materials. These lists include lithium (needed for the production of lithium-ion batteries, which are the basis of electric vehicles and energy storage systems), copper (for electrical wiring and electronics), cobalt (also for batteries), bauxite (raw material for the production of aluminum, widely used in energy and transport), platinum group metals (used

[1] https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/critical-raw-materials-act_en

in catalytic converters, fuel cells), rare metals (necessary for the production of high-tech electronics), rare earth elements (widely used in wind energy, electronics and the military industry), manganese and graphite (a critical component for the production of batteries and other high-tech materials). The CRMA does not stop at listing the necessary resources. It provides for a set of measures aimed at stimulating domestic production of critical raw materials in the EU.

A key aspect is the allocation of "strategic projects" that will receive preferential treatment in the form of accelerated procedures for obtaining permits for exploration and extraction of minerals, as well as the provision of preferential financing. This implies a significant reduction in bureaucratic barriers and attraction of investment in the mining sector. In addition, the law is aimed at diversifying supply sources, developing sustainable mining taking into account environmental and social factors, and stimulating innovation in the field of secondary raw materials processing aimed at extracting valuable components from waste and used materials. However, the implementation of the CRMA faces a number of challenges. Among them is the need to overcome public resistance to the development of mining enterprises due to concerns about the impact on the environment. The successful implementation of the law will require the development of strict environmental standards and monitoring mechanisms to ensure minimal negative impact on nature. It is also important to take into account social aspects, ensuring a fair distribution of benefits from mining development among local communities and minimizing potential negative social impacts. In addition, it is necessary to take into account the geological features of different regions of the EU and optimize the exploration and production strategy taking into account the availability and economic viability of different deposits. Ultimately, the success of the European Critical Raw Materials Act depends on the ability of the EU to harmoniously reconcile energy and climate objectives with resource security and sustainable development.

One of the priority actions of the CRMA is at least 10% of the EU’s annual consumption for extraction. This applies to diversification of the EU supplies. Therefore, the need to develop domestic European lithium deposits is obvious. But the major feature of the latter is the poor and complex mineralization accompanying the lithium potential. In Europe, lithium deposits and ore occurrences are located, for instance, in the Czech Republic, Portugal, Serbia, and also in Ukraine.

Currently, lithium is not mined in Ukraine, although its reserves make up 1% of the world's total and a third of all European reserves. The exact volumes of reserves remain classified. There are four explored lithium deposits in the country: two of them are located in the Kirovograd region, and the other two are in the temporarily occupied territories of the Zaporizhzhia and Donetsk regions. This indicates that Ukraine has some of the largest lithium reserves in Europe.

However, on February 24, 2022 Russia invaded Ukraine. There is a several worldwide assumptions[2] that Russia has a plan to take the minerals that the West needs to decarbonize. Ukraine has abundant resources for a "green" economy. For instance, as part of a planned action, Russian troops expelled Ukrainians from the village of Shevchenko on New Year 2025. The 13.8 million tons of lithium ore that are located nearby Shevchenko are well-known[3]. This bedrock origin lithium deposit is among the richest in Europe and the biggest in Ukraine. It is currently governed by Russia.

Another example, following some open-source data, which, however, are not commercial reports, the resources of the Polokhivske deposit alone exceed 760 LCE kt[4]. At the same time, the official owner's website reports 300 thousand tons of petalite concentrate[5]. However, its production requires environmentally

[2] https://en.topwar.ru/245888-direktor-nemeckogo-instituta-litija-zajavil-chto-ukraina-ne-dolzhna-ustupat-donbass-iz-za-poleznyh-iskopaemyh.html

[3] https://x.com/DD_Geopolitics/status/1878260070368375288

[4] https://open4business.com.ua/zapasy-litiyu-v-ukrayini-ponad-760-tys-tonn-na-polohivskomu-rodovyshhi/

[5] https://ukrlithium.com

friendly technologies that allow extracting lithium from poor and complex ores. The main lithium deposits in Ukraine are located: - Polokhivske deposit in the Kirovograd region; - Shevchenkivske deposit in the Donetsk region; - Kruta Balka in the Zaporizhzhia region. The difficulties associated with the development of Ukrainian lithium deposits are that some of them are located in territories temporarily occupied by Russia. **The development of the remaining deposits requires new technologies for extracting lithium from poor and complex ores**.

Fig. 2. EU-UA strategic partnership

Source: ERMA

In accordance with the European strategic goals, in July 2021, the EU and Ukraine concluded the Strategic Partnership (Fig. 2). According to the goals of the EU's Critical Raw Materials Action Plan, the strategic partnership with Ukraine involves activities along the whole value chain of primary and secondary critical raw materials and batteries. It will also help secure, diversify, and strengthen both sides' supply of critical raw materials, including lithium, which are necessary to achieve the digital and green transitions. Additionally, the collaboration can be essential to maintaining the EU and Ukrainian industries' resilience and worldwide competitiveness. In addition, Argentina, Australia, Canada, Chile, the Democratic Republic of the Congo, Greenland, Kazakhstan, Namibia, Norway, Rwanda, Serbia, Ukraine, and Zambia are among the countries with which the EU has partnered thus far.

ROOTS

Fig. 3. Special Medal for the notable contribution and development of the national raw material sector issued by the Prime Minister of Ukraine

Returning to the article roots, in 2017, Vladimir Sokolov prepared documentation for exploration licensing prolongation for the Polokhivske lithium deposit, located within the Ukrainian crystalline basement, also called the Ukrainian Shield. Vladimir Sokolov is an expert with a strict background in the field of subsoil use and support of official procedures for obtaining geological exploration and mining licenses (or spatial permits as is accepted in local terminology) in Ukraine. Ultimately awarded the Special Medal for the notable contribution and development of the national raw material sector issued by the Prime Minister of Ukraine (Fig. 3). It seemed strange why the exploration license needs renewal, and not the exploitation (mining) license requested? Logic dictated that the field was already ready to start mining since a long time had passed since the start of geological exploration, more than 10 years at that time. It should be mentioned that now owner eventually received a mining license and was enriched in 2021 with by the JORC report. Thus, the degree of maturity had reached international reporting on resources and reserves in accordance with one of the CRIRSCO codes family. **PhD. candidate Irina Sokolova, Prof. Alex Bobrov, Prof. Jose Cabello, Dr. Gregory Abramov, Dr. Sergey Kakaranza, Dr. Sergey Kadurin, PhD. candidate Sergey Klochkov** became interested in understanding the depth of the question. It turned out that the key lithium mineral of the Polokhivske

Fig. 4. Polokhivske lithium deposit in Ukraine

Source: GMK center

deposit is petalite (Fig. 4). While the main hard rock`s lithium commercial mineral at that time, and indeed to this day, was spodumene. Available technologies at that time made it possible to process petalite into a commercial lithium product only by calcination and bringing it to the spodumene formula, and only then repeat the classic processing and refining route for this mineral. But this technology did not look viable, in comparison with spodumene processing, since it added additional processes to the value chain, which increased processing time and costs, energy expenditure, and the release of harmful emissions. Commercial and environmental issues for the petalite processing ipso facto had dubious prospects for viability and as a consequence obtaining a sustainable SLO has not been guaranteed.

The European Union, along with developed nations like Canada and Australia, increasingly mandates a "social license to operate" (SLO) for large-scale mineral extraction projects. This isn't a formal legal document, but rather a crucial demonstration of community acceptance, going beyond simple regulatory approvals from governmental bodies at the national, regional, or local levels, including rigorous monitoring of public opinion and adapting project plans accordingly. This necessitates a proactive approach throughout the entire project lifecycle, from initial exploration to post-operational phases. Obtaining and maintaining a strong SLO demands a nuanced understanding of local perspectives, values, and potential concerns. This requires extensive stakeholder engagement, public forums, and community surveys in a transparent and inclusive way. Failure to adequately address concerns can lead to significant delays, increased costs, reputational damage, and even project failure. The inherent complexities are amplified in regions where local livelihoods are heavily reliant on ecosystem services potentially impacted by mining activities, as seen in countries like Serbia and Portugal, where historical grievances and perceptions of environmental damage can significantly shape community attitudes. This continuous feedback loop allows for early identification and mitigation of potential conflicts. For instance, in 2024 September, hundreds of people protested against the building of lithium mines in Belgrade, the capital of Serbia. The Serbian Movement for the Protection of the Environment coordinated the event. The demonstrators assembled in front of Radio Television of Serbia's (RTS) headquarters. The British-Australian mining and metallurgical corporation Rio Tinto is implementing a lithium mining project near the Serbian city of Loznica, which is the subject of the protests. Or in light of an inquiry into potential irregularities in the granting of concessions for the development of lithium reserves and "green" hydrogen projects, Portuguese Prime Minister António Costa has tendered his resignation to the president of the nation[6]. Therefore, comprehensive communication strategies are paramount, addressing misinformation and fostering trust. This may involve community-led monitoring programs where residents actively participate in environmental impact assessments and contribute to the ongoing evaluation of project sustainability. Ultimately, securing and sustaining a social license is essential for ensuring the ethical, sustainable, and socially responsible development of mineral resources.

Therefore, the time required fundamentally new green approaches not only for the processing and refining of petalite, but also for other poor and complex ores typical for the European regions due to the current European urgency stems from the burgeoning demand for lithium-ion batteries (LIBs), the cornerstone of electric vehicles (EVs) and various other crucial technologies. At the same time, legislative harmonization

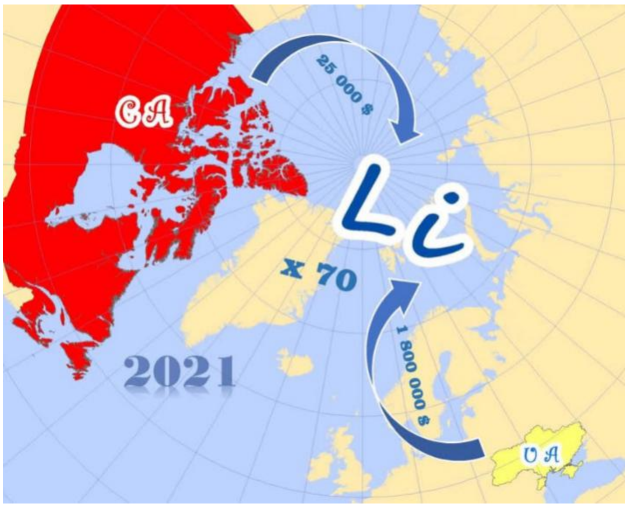

Fig. 5. Comparison of Lithium Property Acquisitions in Canada and Ukraine, 2021

[6] https://www.politico.eu/article/portugal-prime-minister-antonio-costa-resigns/

of the EU with third countries in Europe is also necessary for the successful start and development of domestic lithium projects. Best practices in subsoil use require integration into primary and secondary acts to attract foreign investment. Ukraine is again a classic example in this regard. Returning again to the roots – two events that are key indicators of the investment maturity of the regions occurred in early 2021 (Fig. 5): 1️⃣ Lithium, Shatford Lake deposit, Canada, estimated reserves - 7.3 million tons of lithium oxide ➡️ CBLT (TSXV: CBLT) acquired the rights to the property for $ 25,000[7]; 2️⃣ Lithium, Shevchenkivske deposit, Ukraine, estimated reserves - 5.6 million tons of lithium oxide ➡️ The state regulator announced ambitious intentions to put it up for auction with a starting price of UAH 50,000,000. <-> $1,800,000. Even if we do not take into account that the auction procedure assumes an increase in cost, a simple arithmetic calculation shows a price difference of more than 70 times. The above facts indicate a significant difference in the approach to forming the cost of acquiring rights to potential mining activity objects, which has a significant impact on attracting investment cases and raises the question of the need to pay special attention to this aspect. According to the analytical report of the US Geological Survey from 2016, North America, including the United States and Canada, is the leading region in the world for the exploitation of lithium deposits of the pegmatite type, the geological and industrial type of which includes Shatford Lake and Shevchenkovskoye. It should be noted that, according to expert estimates, the resource potential of Canada and Ukraine regarding this type of raw material is identical, which is due to the geological and structural positions of the Canadian and Ukrainian Precambrian shields. With a 70-fold difference in cost, the choice for business is obvious. This reason, among a number of other factors, explains the lack of lithium deposits being developed in Ukraine and dozens of similar facilities in operation in Canada and the United States, which

[7] https://www.mining.com/cblt-hopeful-with-acquisition-of-shatford-lake-lithium-property-in-manitoba/

form the industrial potential of the region and provide strategic industries and technologies with vital raw materials.

One more progress in achieving sustainable SLO is demonstrated by countries with the best subsoil use practices. It is known that a number of lithium deposits around the world are developed by transnational holdings, which causes social tensions, as is happening today in Serbia. And only individual projects are implemented by national companies. A classic example of a successful solution, when the state and local communities finally take the reins into their own hands, is la Empresa Nacional del Litio (ENL), the creation of which was announced by the President of the Republic of Chile - Gabriel Boric in the spring of 2023[8]. The start of ENL's operational activities guarantees the leading role of local communities in the formation of added value. National control over the management of lithium salt marshes also promotes synergy between local industry and academia, communities, initiating research and innovation with the leading role of the state and local communities in its progress and results.

Another factor determining success today is the speed and favorable conditions for decision-making. Here, the choice of business is a key factor in the investment attractiveness of the country. The leading role in a quick start is played by the best practices of subsoil use, which create a favorable investment climate in each individual country + innovative approaches to smart mining. "The clock is ticking" and a quick start is especially relevant today for lithium mining facilities, the cost of which has jumped over the past

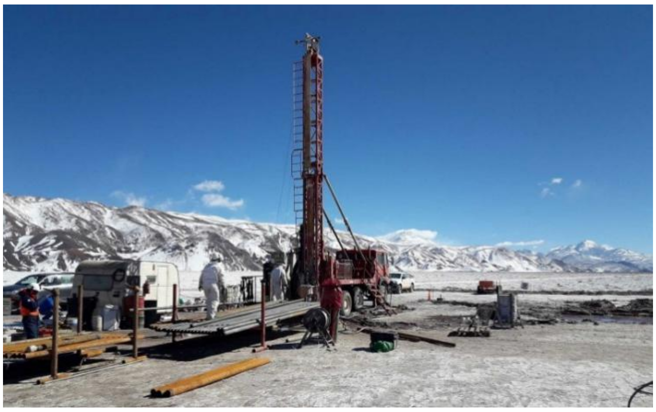

Fig. 6. Tres Quebradas lithium project is located in the "Lithium Triangle" of South America

Source: mining-technology.com/NeoLithium

[8] https://www.gob.cl/noticias/presidente-boric-da-conocer-creacion-de-empresa-nacional-del-litio/

year due to expectations of a boom in demand for batteries needed for the transition to electric vehicles. It is important to seize the moment today, given analysts' forecasts regarding the development of the technological and qualitative situation in the battery market. Another confirmation of this fact was a landmark event announced by the Ministry of Production and Labor of Argentina in early 2022. Chinese mining company Zijin Mining Group Co Ltd is investing $ 380 million in the construction of a battery-grade lithium carbonate plant in Argentina through its local subsidiary Liex[9]. The estimated capacity is 20,000 tons of lithium carbonate per year with the prospect of positive scaling by at least two times in the medium term. It took the investor less than a year to make a decision and another year and a half to reach the design production capacity due to raw materials from the local Tres Quebradas project (Fig. 6).

The long-term sustainability and security of the EU's energy transition hinges on the successful implementation of the CRM Act and its effective management of the lithium supply chain can be supported by the EU's main research and innovation funding initiative is called Horizon Europe. That's one possibility, of course. It gives a possibility to combat climate change, advances the EU's growth and competitiveness, and aid in the National Sustainable Development Goals, contributing with investments in innovative technologies for instance lithium extraction, enhanced recovery from hard-rock deposits, which are more environmentally friendly than traditional methods.

Development. In November 2021, Irina Sokolova, CEO of MinPoL Agency for International Minerals Policy (a private limited company under Austrian law), presented the Li4Life concept at a Smart Specialization Platform (S3P) event in Portugal. This presentation focused on innovative lithium extraction solutions from low-grade and complex ores, directly addressing the challenges outlined by Horizon Europe and the European Battery Alliance

[9] https://www.mining-technology.com/news/zijin-lithium-argentina/

(EBA). The EBA aims to establish a complete, sustainable value chain for advanced battery cell and battery manufacturing within the EU, a goal critically reliant on secure and responsible lithium sourcing. The Li4Life concept emerged from extensive research conducted between 2017 and 2023, highlighting a significant knowledge gap within the European lithium landscape. A comprehensive, classified database detailing the extent and quality of lithium deposits within the EU and associated countries was, and to a large extent still is, lacking. This absence of crucial data severely hampered efforts to accurately assess the EU's potential for domestic lithium production, ultimately hindering the ability to determine the degree to which the burgeoning electric vehicle (EV) industry could rely on homegrown supplies. The lack of readily available, standardized information prevented effective resource management and strategic planning to meet the growing demands of the EU economy. Consequently, the creation of a robust, publicly accessible database of lithium ore deposits, categorized by grade, location, and estimated reserves, is paramount. At the same time, analyzing open data, we can say with confidence that the European resource potential of lithium is even excessive to meet the internal needs of strategic technologies and industries of the EU. For example, it is stated that the Jadar project, after its launch, «would produce 58,000 tons a year of battery-grade lithium carbonate, about 17% of European demand and enough for one million electric vehicles»[10]. The next source states that «If implemented, Rio Tinto's Jadar project could meet 90% of Europe's current lithium needs, positioning the company as one of the world's leading lithium producers»[11].

Conventional lithium extraction methods, such as surface and underground mining, present several significant drawbacks. Their economic viability is often compromised when applied to smaller, lower-grade deposits, effectively limiting the exploitable resource base. Furthermore, these methods frequently result in

[10] https://www.mining.com/left-and-right-unite-against-rio-tinto-lithium-project-in-serbia/
[11] https://www.mining.com/web/serbian-protestors-rally-to-oppose-rio-tintos-lithium-mine-project/

substantial environmental damage, including habitat destruction, biodiversity loss, water contamination, and soil erosion. Such environmental impacts often trigger significant opposition from local communities, leading to delays, increased costs, and even project cancellations. These factors underscore the urgent need for more sustainable and environmentally benign extraction techniques.

The Li4Life concept championed Borehole Mining (BHM) technology as a promising alternative to the conventional mining. BHM is based on (1) remotely operated in-situ water-jet cutting of ores, (2) producing slurry, (3) its simultaneous pumping to the surface, (4) separation of cuttings from the slurry and (5) pumping down (recycling) of the clarified water. Providing an immediate access to the ore, this technology excludes necessity of earth moving and construction of open pit or underground mine. In fact, this technology does not require personnel presence below the earth surface, at all. It all makes this technology the most rapid and cost-effective. BHM, particularly when adapted for pegmatite mica-containing rocks (a common host for lithium ores), offers several key advantages provided by specifically designed BHM Tool (Fig. 7). This method involves drilling boreholes to access the ore body, minimizing surface disturbance and reducing the overall environmental footprint compared to traditional open-pit or underground mining. The precise nature of BHM allows for a selective extraction, reducing waste rock generation and the associated environmental burdens. Moreover, BHM's lower land usage and reduced infrastructure requirements can significantly lessen the impact on surrounding ecosystems and communities. The comprehensive advantages of applying BHM to lithium

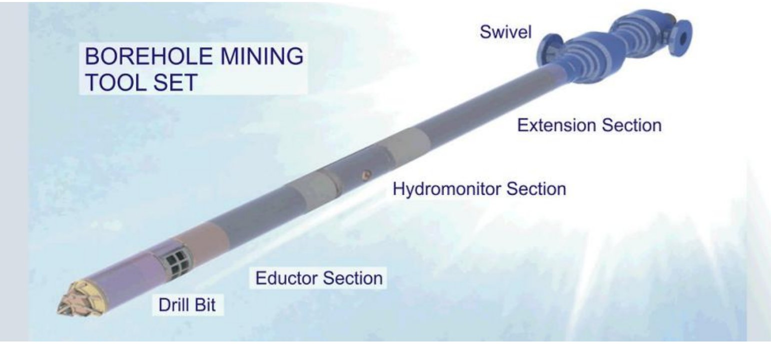

Fig. 7. Borehole Mining Tool Set.
Source: Borehole Mining International, Inc.

extraction include enhanced selectivity, reduced water consumption, and decreased greenhouse gas emissions. BHM has proven records in mining of metals, coal, phosphate, diamonds, rare earths, and other mineral commodities from the depths up to 1km. It works year-round in remote areas at sub-zero temperatures onshore and below the seafloor. This technology is presented as a key tool for incorporating previously uneconomical or environmentally problematic lithium deposits into the EU's overall lithium balance, thereby increasing resource security and fostering sustainable development. The Li4Life concept also emphasize the importance of incorporating robust environmental impact assessments, community engagement strategies, and responsible waste management practices into all phases of the lithium extraction process to ensure long-term sustainability and public acceptance. The successful implementation of BHM, along with the development of a comprehensive characterization database, represents a crucial step toward achieving the EBA's ambitious goals and securing the EU's position as a leader in the clean energy transition. Further research into optimizing BHM techniques for various lithium ore types, including poor or complex and geological settings is essential to unlock the full potential of this innovative approach and address the critical need for sustainable lithium sourcing within the EU.

Traditional lithium extraction from concentrates relies on energy-intensive, environmentally harmful, multi-stage metallurgical processes. These methods typically involve high temperatures and concentrated acids, resulting in significant costs and waste generation. Furthermore, these conventional processes are ill-suited for recovering lithium from end-of-life batteries, a crucial aspect given the burgeoning electric vehicle market and the growing need for sustainable battery recycling. The inherent complexities and environmental burdens associated with these traditional methods necessitate the exploration of more efficient and eco-friendly alternatives. A promising approach involves the development of hydrometallurgical processes that circumvent the need for extreme temperatures and harsh chemicals. The Li4Life concept, for example, proposes a novel refining strategy that integrates Deep Eutectic Solvents (DES)[12] with Electro Dialysis ED[13)] for efficient lithium purification. DES, a class of sustainable solvents composed of readily available, relatively inexpensive components, offer several advantages over traditional solvents, including reduced toxicity and improved selectivity for lithium ions. Coupling DES + ED extraction, a membrane-based separation technique, allows for efficient separation and purification of lithium, minimizing energy consumption and waste production. Microwave (MW) assisted leaching can further enhance the efficiency of the initial extraction step, leading to faster processing times and improved metal recovery rates.

Conlusion. This integrated approach improving the viability of extraction, processing and refining of poor and complex ores from European lithium deposits, developed by the authors since 2021, aims to produce battery-grade lithium carbonate, regardless of the mineral source, at a competitive price. The Li4Life concept, having absorbed all the diversity of integrated solutions, also incorporates innovative mining techniques to reduce the environmental impact of lithium extraction. Specifically, it advocates for the use of borehole mining (BHM), a method particularly well-suited for smaller, hard-to-reach deposits often overlooked by conventional open-pit mining. This approach offers several significant advantages: it drastically minimizes land disturbance, reduces the need for extensive surface infrastructure, lowers overall mining costs (particularly labor costs and infrastructure development), and significantly mitigates risks to miner health and safety. The reduced environmental footprint associated with BHM directly addresses the growing public concerns regarding the environmental and social impacts of mineral extraction. Furthermore, BHM's suitability for smaller deposits and its lower CAPEX and OPEX opens up new

[12] https://pubs.acs.org/doi/10.1021/cr300162p

[13] https://doi.org/10.1016/j.hydromet.2019.105124

opportunities for lithium extraction in regions previously deemed uneconomical or environmentally sensitive, promoting sustainable development and contributing to a more circular economy. The practical application of BHM worldwide (including polar and offshore zones) further validates its viability and potential as a sustainable mining practice. Ongoing research into optimizing DES+ED parameters and further refining the BHM process, coupled with improved battery processing technologies, offers a promising pathway towards a truly sustainable lithium industry capable of meeting the ever-increasing global demand while significantly minimizing its environmental and social footprint. The improved characterization database will ensure a fast and purposeful process of mining of lithium ores with guaranteed production of high-quality lithium salts of battery quality, reducing the time for making a decision on the development of a deposit or deposits. The whole range of measures also will give the opportunity to establish the EU domestic production of battery grade lithium concentrate in line with CRMA targets in quantities exceeding 10% of domestic needs and to form European innovative clusters uniting representatives of the entire value chain from mine to battery.

Acknowledgement. I owe a particularly profound debt of gratitude to my father and long-time mentor, Vladimir Sokolov. His unwavering guidance and support have shaped my career trajectory from its inception. His encyclopedic knowledge of mining sciences, encompassing geological exploration, resource estimation, and mine planning, provided an essential foundation for my work. Beyond the technical expertise, he instilled in me a deep-seated appreciation for the intricacies and challenges involved in responsible resource extraction. His insightful advice for research and development, particularly in overcoming significant challenges in lithium extraction from poor and complex ores, including refining Li4Life approach to sustainable lithium solutions. I am eternally thankful for his mentorship and the profound influence he has had on both my professional and personal life.

Beyond this, I extend my deepest gratitude to the geological scientists and engineers whose collaborations **Prof. Alex Bobrov, Prof. Jose Cabello, Dr. Gregory Abramov, Dr. Sergey Kakaranza, PhD. candidate Sergey Klochkov** was instrumental in the joint development of innovative, smart, and environmentally conscious solutions for lithium extraction and processing. Their expertise in specific fields, ranging from geological science and engineering to environmental remediation and sustainable energy technologies, proved invaluable, including breakthroughs in selective leaching techniques, the development and demonstration of novel smart and green mining technologies for lithium extraction, and the optimization of energy-efficient processing methods, wouldn't have been possible without their contributions. Especial thanks **Prof. Sergey Kadurin** for scientific supervising of Master Degree achievement in the rare metal's expertise. These Li4Life advancements significantly increase social acceptance through the reduction of the environmental footprint associated with lithium production, mitigating concerns about water usage, greenhouse gas emissions, and habitat disruption