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Technological innovations in the extraction and processing of critical minerals as a factor of USA resource independence

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Abstract- The article explores modern technological solutions aimed at improving the efficiency of critical mineral extraction and processing in the USA. Particular focus is placed on innovations in geological exploration, secondary resource recovery, production process digitalization, and institutional support. The strategic importance of critical mineral for national security and supply chain resilience is emphasized. Regulatory developments and R&D investment policies are reviewed. The study concludes that a comprehensive approach to innovation implementation is essential for achieving long-term USA resource independence.

***Index Terms*-** critical minerals, processing, digitalization, resource security, innovation.

I. Introduction

Critical metals (CM) are the determinant of the technological, economic, and military capacities of high-tech States. They have a diverse range of applications, from the manufacture of batteries and microchips to renewable energy and the aerospace sector. With the progression of digitalization, the advent of «green» technologies, and the reshaping of global logistical supply chains, the imperative of ensuring secure and self-reliant access to these resources is unfolding geometrically. For the USA, with such a high level of CM consumption, reliance on imports from abroad is translated into a strategic vulnerability, mainly due to the geographical concentration of their production.

Here, there is an increasing need for technological improvement in CM processing and extraction that can not only render the industry economically viable, but can also ensure resource independence for the USA. The relevance of this study is determined by the need for the systematized analysis of the latest engineering solutions in the field of development of nonconventional sources, reduction of production costs, reduction of environmental hazards, and strengthening of the internal production base. The target of the study is to establish the priority directions of technological innovation in CM and assess their prospects as a way of reduction of the USA external resource dependence.

II. Main part. Technological innovations in CM exploration and production

Existing trends in USA CM exploration are going through a spectacular transformation following advances in the field of digitalization and artificial intelligence. Exploration technologies based on the handling of large volumes of data and probabilistic models of mineral occurrence are turning out to be more economically feasible and precise. The use of unmanned aerial vehicles with onboard spectral sensors and machine learning algorithms to analyze satellite images allows not just to reduce exploration time, but also to miss environmental risks. For example, the U.S. Geological Survey (USGS) is establishing digital mapping systems that can combine field observation real-time data, sample chemical analysis, and previous geological data [1].

Specific emphasis is laid on the development of unconventional sources of CM, previously considered to be economically not viable. For example, in the USA, lithium is extracted not only from hard minerals, but also from geothermal brines, as is currently being practiced in California under the Lithium Valley initiative. Such technologies speak of a two-sided benefit: first, as a source, and second –, as complementing the employment of renewable sources of energy. Additionally, the secondary development of man-made accumulations, for example, tailings dumps and metallurgical slag, is an immense promise. In Alaska and Nevada, work is underway to involve previously exploited facilities in the economic turnover, where, thanks to new technologies of separation, it is now economically reasonable to extract rare earth elements (fig. 1).

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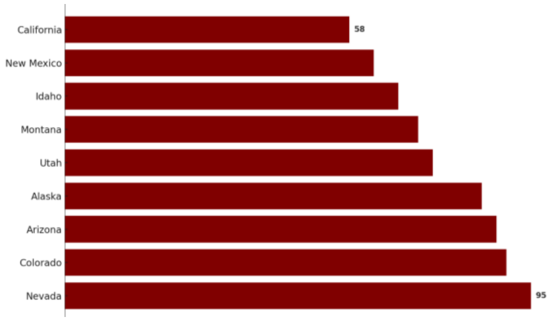

Figure 1. Investment attractiveness index in USA (index value is from 1 to 100) [2]

The most financially sound technologies are those that reduce the need for traditional mining through integrated ore development. Companies in the USA are investing in hybrid methods that combine hydrometallurgical and pyrometallurgical processes with computer monitoring. These methods allow you to recover several types of metals from a single source, increasing the overall profitability of the project. In addition, the application of remote mining facilities and robotization of drilling and handling complexes reduces personnel costs and improves industrial safety.

III. Innovative Methods of Processing and Cleaning CM

Treatment of CM in the USA is emerging as one of the priority areas of resource policy, specifically the need to create closed cycles of production. Innovative efforts on this sector pursue not only increasing purity of the final product, but also reduction of the ecologic burden on treatment plants. One of the most hopeful areas is the use of ionic liquids – organic solvents with good selectivity to transition and rare-earth metals. Ionic liquid application enables a replacement of aggressive acids traditionally used in hydrometallurgy and minimizes toxic wastes' volume [3].

Considerable attention is given to nanostructured and membrane-based sorbent technologies using the selective extraction principles. In particular, within the framework of the federal program Critical Materials Institute, highly selective procedures for the separation of neodymium and praseodymium have been developed, which previously was a technologically difficult issue. In addition, the USA is actively introducing electrolytic recycling technologies adapted to secondary raw materials, for example, electronic scrap and lithium-ion batteries. This direction allows not only for making up for the deficit of strategic metals, but also for reducing the reliance on unstable foreign sources.

Also of interest are biochemical processing methods with the use of microbiological cultures capable of selective leaching of rare metals from slag and ore. These processes have high efficiency in treating low-grade raw materials and man-made deposits unsuitable for traditional methods.

IV. Cost Reduction and Sustainability of Production Chains

Creating low-cost and sustainable CM supply chains requires a systemic solution to primary and secondary processing of resources. One of the main cost drivers is the establishment of a localized complete-cycle infrastructure-mining, refining, and manufacturing of final components. Local technology clusters in the USA are increasingly playing a crucial role, with mining operators, processors, and manufacturers of high-tech products integrated into them. This approach reduces logistics expenses, reduces delivery time, and reduces reliance on vulnerable overseas routes.

Particularly important are recycling technologies for secondary raw materials, for example, waste batteries, electronics, and industrial waste. Investment in this area not only compensates for the shortage of a variety of CM, but also allows for processing material with a higher concentration of metals than in primary sources. For example, recycling lithium-ion batteries can be significantly cheaper than extraction and processing of primary raw materials. The cost of processing is below $9 per kilowatt-hour, while the cost of production is approximately $95 per kilowatt-hour, reflecting the economic feasibility of processing [4].

Supply chain resilience also grows with digital resource management platform integration. With the use of blockchain-enabled systems and predictive analytics, you can trace where metals come from, monitor quality at each stage, and predict supply disruption risk. These are solutions already applied at magnet and cathode-making plants in Texas and New York, where digitalization allows for instant resource re-assignment and low inventory levels.

It should also be mentioned regarding the company working of rapid digitalization of the business. They are modifying their business models to new conditions, for example, shifting from linear to agile, network-based supply management arrangements. Adoption of digital twins, predictive analytics, and real-time monitoring systems enables you to optimize production processes and enhance operational efficiency. There is growing interest in vertical integration policies aimed at controlling all stages of the chain - from mining to the production of final products, which reduces exposure to external shocks [5]. Electronic platforms also make it possible to plan investments with greater accuracy and adjust production capacities according to changes in market demand.

V. Geopolitical and Institutional Aspects of Resource Independence

Resource independence in CM is not only seen by the USA government as an economic mission, but it is also considered a component of national security. Against the backdrop of unstable world markets, increasing dependence on a few suppliers, and possible threats of export restraint by single States, a geostrategic agenda is being formulated with the objective of strengthening the country's production and processing capacity. Since 2021, the USA has put into effect strong regulatory acts, including Defense Production Act provisions, with the aim of stimulating the production and domestic production of CM used in defense production, microprocessors and energy storage systems [6].

The creation of interagency mechanisms and programs, such as the Critical Materials Strategy (CMS) and Minerals Security Partnership (MSP), is vital in the institutional building of resource policy. These structures provide for coordination among the Ministries of Energy, Trade, Defense, and national laboratories. In addition, a program has been launched to support research activities throughout the entire range of the production process-from exploration to industrial end-use. The U.S. Department of Energy (USDE), between 2023 alone, more than $500 million was used for R&D (Research and Development) on recycling and replacement of CM (table 1).

Table 1. Program direction funding (million dollars) [7]

	FY 2023 Enacted	FY 2024 Annualized CR	FY 2025 Request	FY 2025 Request vs FY 2023 Enacted	
				$	%
Program direction					
Salaries and benefits	12,666	13,17	16,39	+3,724	+29 %
Support services	17,048	16,632	17,3	+252	+1%
Other related expenses	6,286	6,198	6,81	+524	+8%
Total, program direction	37	37	42	+5,000	+14 %
Federal ftes	60	60	80	+20	+33 %
Support services					
Technical support	5,967	5,821	6,055	+88	+1%
Management support	11,081	10,811	11,245	+164	+1%
Total, support services	17,048	16,632	17,3	+252	+1%
Other related expenses					
Working capital fund	4,123	4,123	5,061	+938	+23 %
Energy information technology services (eits)	1,588	1,5	1,5	–88	–6%
Other services	575	575	249	–326	–57%
Total, other related expenses	6,286	6,198	6,81	+524	+8%

Bilateral treaties with allied countries on reciprocal development of deposits and processing of raw materials are becoming necessary, but domestic capacity building remains the priority. A network of national competence centers specializing in acceleration of technology implementation and training is being established. Attempts are also being increased at the state level, where tax relief and simplified regulatory regimes are being extended to enterprises engaged in CM.

VI. Prospects and Challenges of Introducing Innovations in the Extraction and Processing of CM

Technological innovations in the CM sector have a great potential to transform existing production and raw materials models of the USA. Large-scale implementation of innovative solutions, however, is tied to a number of limitations caused by both technological and institutional barriers. One of the most severe problems remains the absence of Technology Readiness Level (technological maturity) of a number of innovative developments. A number of promising methods, including bioextraction and electrodialysis, remain at the pilot test or laboratory stage and require significant time and resources to reach industrial use [8].

Another weakness lies in the lack of manufacturing facilities adapted to new processes. Old scheme companies are often unable to be switched to new technology in a short period without full-scale modernization. Additionally, complexity in issuing environmental permits and slow regulatory actions, especially at the state level, severely impede the implementation of even highly effective solutions. All these reinforce the problem of the lag between the technological discovery phase and commercialization.

On the contrary, the prospects are tremendous. In the USA, there is a steady accumulation of interest in partnership modes of interaction between research institutions, the private sector, and government agencies. Consortium programs, for instance, the Rare Earth Cooperative, allow you to pool resources and reduce risks when implementing complex engineering solutions. Increased venture capital focus on startups in the field of green metallurgy and closed manufacturing loops also fosters faster absorption.

VII. Conclusion

The study reveals that technological innovation in the processing and extraction of the key metals is becoming increasingly a key area of strategy for resource independence in the USA. Top-level engineering solutions for non-traditional source development, cost savings, environmental sustainability, and digitalization of production will be likely to guarantee supply provision for the construction of sustainable local supply chains. Government assistance and direct intervention of the scientific and industrial communities also contribute to the rapid shift of the industry.

At the same time, large-scale implementation of innovation is faced with a chain of limitations, including the absence of technology maturity, infrastructure limitations, and regulative barriers. These barriers can be eliminated through systemic policies like funding R&D, institutional reforms, and creating cooperation among the key players. It is achievable only when all hierarchy levels – from the federal bodies to the local factories – act together in a coordinated manner that the strategic goal can be achieved: long-term resource independence of the USA in international competition.

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