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Germanium production from Kazakhstan coals: resource potential, technological solutions and prospects

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Abstract. Germanium (Ge) is a rare trace element belonging to the group of materials that are critical for the development of high-tech industries, including semiconductor manufacturing, optoelectronics, space technologies, infrared optics, and defense systems. This review examines global models of germanium production, including traditional extraction from zinc concentrates and the development of the coal-based route in China; it analyzes the geochemistry of germanium accumulation in promising coal basins of Kazakhstan and assesses the prospects for establishing high-purity germanium production in Kazakhstan based on coal feedstock and technogenic products of its processing in the power and metallurgical industries. The prerequisites are shown for forming a new model of germanium production in Kazakhstan, based on a combination of two sources - zinc metallurgy and germanium-bearing coals – as well as the considerable potential of brown-coal (lignite) basins, including the Turgai and Zhilanshik basins. A technological model is proposed for obtaining germanium concentrates from coal feedstock, producing germanium dioxide (GeO₂), and producing high-purity metallic germanium. This approach is proposed as a basis for developing an export-oriented critical materials industry.

Keywords: *germanium, coal, Kazakhstan, critical materials, zinc metallurgy, hydrometallurgy, fly ash.*

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1. Introduction

Germanium (Ge) is a rare trace element that plays a key role in the production of microchips, optoelectronic devices, space technologies, and defense-related products. Growing demand for germanium is driven by the rapid development of digital infrastructure and critical technologies associated with artificial intelligence, large-scale data centers, and next-generation telecommunications networks.

In recent years, the strategic importance of germanium has increased significantly in the context of national technological and economic security. This is particularly relevant given the high geographical concentration of global germanium production, a substantial share of which is accounted for by China. The European Union, the United States, Japan, South Korea, and several other industrialized economies have therefore included germanium in their lists of critical raw materials or minerals essential to economic and national security.

Against the backdrop of the ongoing transformation of global critical-material supply chains, interest in Kazakhstan as a potential source of germanium is increasing. Unlike most countries, Kazakhstan potentially possesses two independent sources of germanium – zinc metallurgy and germanium-bearing coals. This combination creates favorable conditions for establishing a stable domestic raw-material base and developing an integrated production chain for high-

purity metallic germanium, which is in demand on international markets. The extraction of germanium from zinc concentrates and products generated during their metallurgical processing is consistent with the most widely used industrial practices for germanium recovery worldwide. At the same time, germanium-bearing coals, coal combustion ash from thermal power plants, and industrial waste generated by the energy and metallurgical sectors represent promising alternative sources of this critical element.

The aim of this study is to assess Kazakhstan's resource potential for germanium production from germanium-bearing coals and industrial waste generated during their utilization in the energy and metallurgical sectors; to analyze existing and prospective technological routes for germanium extraction from various types of feedstock; and to develop conceptual approaches to establishing an export-oriented industry for the production of high-purity metallic germanium in Kazakhstan.

The scientific novelty of the study lies in the comprehensive assessment of Kazakhstan's germanium-bearing coals and associated industrial waste as an alternative raw-material base for high-purity germanium production, as well as in substantiating a dual-source model for the development of a national germanium industry based on the integration of the conventional zinc-based feedstock source with the prospective coal-based source.

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2. International experience and the structure of the global germanium market

2.1. Development of the global germanium industry

Historically, centers of germanium production formed in countries with a developed non-ferrous metallurgy sector. The first industrial technologies for extracting germanium were developed in Europe in the first half of the 20th century, primarily in Belgium and Germany, which had a strong base for processing polymetallic and zinc ores. The concentration of germanium in sulfide zinc ores was the reason that zinc metallurgy became the foundation of the global germanium industry.

For many years, the unique germanium-copper-lead-zinc deposits of Tsumeb and Kipushi in Africa provided the basis for germanium production. The technological scheme for extracting germanium from zinc concentrates, adopted at the plant in Balen (Belgium), is still used today in practically every country. The ore is beneficiated on-site by flotation, as a result of which germanium passes into copper-lead and copper concentrates. Special flotation and magnetic separation are then used to obtain the main germanium concentrate, containing up to 1% Ge. During roasting of zinc concentrates and zinc leaching, most of the germanium remains in the solid residue, which is subjected to fuming. Sulfuric-acid leaching of fuming sublimes, precipitation, repeated roasting, leaching, and hydrolysis yield GeO_2 [1]. The main centers of germanium production worldwide and their principal feedstock sources are summarized in Table 1.

Table 1. Main centers of germanium production in the world

Country	Role in global production	Main feedstock sources
China	Largest global producer and processor	Zinc concentrates, germanium-bearing coals, coal ash, technogenic feedstock
Russia	Historical producer	Zinc feedstock, coal feedstock, secondary resources
USA	Producer and consumer of high-purity germanium	Zinc metallurgy, secondary feedstock
Canada	Producer of germanium as a by-product	Zinc concentrates
Belgium	One of the historical refining centers	Metallurgical residues, secondary feedstock
Germany	Historical center of processing technologies	Secondary feedstock, metallurgical products
Finland	Production from non-ferrous metallurgy products	Zinc feedstock

Modern industrial germanium production is characterized by a high degree of concentration and a limited number of producers. Unlike most industrial metals, germanium is not mined as an independent mineral resource but is extracted mainly as a by-product in the processing of other feedstocks – primarily zinc concentrates (60-70%), coal feedstock (20-30%), as well as through secondary processing of scrap and metallurgical waste.

In the United States, germanium production has historically been based on the processing of zinc feedstock and secondary resources. Despite considerable scientific interest in extracting germanium from coal and ash-and-slag waste, these directions have not achieved industrial development comparable to that in China. The American model is more closely associated with the processing of metallurgical waste and secondary metal recovery. Canada, Belgium, Germany, and Finland retain their significance as technological centers for germanium production, using feedstock mainly associat-

ed with non-ferrous metallurgy. Their experience demonstrates a high level of technological maturity in processes for extracting germanium from zinc concentrates and metallurgical by-products [1].

China occupies a special place in the global system. According to data from the U.S. Geological Survey (USGS), China is the leading producer of germanium and holds a dominant position in the global supply chain, including extraction and refining operations. A substantial share of production is provided not only by zinc concentrates but also by the use of germanium-bearing coals, thermal power plant ash, and products of coal and energy industry processing. Through this, China has formed a unique industrial model combining the metallurgical and energy circuits of germanium extraction [2]. China has become the only country in the world able to scale up industrial germanium production from coal to a global level. The associated waste products – coal ash, gas-cleaning system dust, and other technogenic products in which germanium concentrates after the energy use of coal are regarded as a key link in the beneficiation stage of refined-germanium production technology.

Thus, the modern global germanium production system has formed around two main models. The first is the traditional metallurgical model, based on extracting germanium from zinc concentrates, characteristic of Europe, the USA, and Canada. The second is the combined resource model, uniting metallurgical and coal feedstock, which has achieved its fullest development in China. This is an extremely important precedent for Kazakhstan, which possesses significant coal reserves and a large energy sector.

2.2. China's experience in producing germanium from coal feedstock

The prerequisite for the large-scale development of this direction was the presence, in a number of regions of China, of coal deposits with anomalously high germanium content. The best-known germanium-bearing coals are located in the provinces of Inner Mongolia, Yunnan, Guizhou, and a number of other coal-mining regions of the country. In certain seams, the germanium content in coal significantly exceeds average global values, which created the prerequisites for industrial development of this resource. The main germanium-bearing coal deposits of China and their characteristic germanium contents are summarized in Table 2.

Table 2. Main germanium-bearing coal deposits of China [3-4]

Deposit / basin	Region (province)	Coal type	Ge content, g/t	Max. Ge content (g/t) / features
Lincang	Yunnan	Lignite	~850	Up to 2500-3000 in individual seams. Largest deposit in the world.
Xilin Gol (Wulantuga)	Inner Mongolia	Lignite	~137-244	Individual samples contain 820-1530. Second in importance.
Mentou	Yunnan	Lignite	~100-120	Local anomalies up to 400-600 in organic-rich interlayers.
Xuanwei	Yunnan	Bituminous / lignite	~30-55	Local nest-like enrichments. Above the national average (2.8 g/t).
Fushun	Liaoning	Lignite	~15-36	Low in the bulk mass but effectively concentrated in the collected fly ash.

For industrial extraction of the metal in China, a threshold content of 100 g/t is considered the minimum. Germanium in coal is concentrated mainly in the organic matter (80-90%), in the form of humates and germanium-organic complexes. Mineral forms (silicates and sulfides) of germanium compounds in coal do not exceed 20-25%.

During coal combustion, most of the germanium oxidizes and volatilizes – GeO at a temperature of 700°C , GeO_2 at $t > 1000^\circ\text{C}$ – concentrating in fly ash and dust products of gas cleaning, with the germanium concentration increasing 10-15 times compared with the coal. This effect has made it possible to regard ash-and-slag waste not as a by-product of power generation, but as technogenic feedstock for obtaining rare metals.

This allows the use of germanium-bearing coal in the energy sector to be regarded as a necessary technological stage in the beneficiation of feedstock for germanium production.

The technological scheme for producing germanium from coal feedstock in China generally includes several sequential stages: coal mining and preparation, its use for energy generation, collection of ash and dust, hydrometallurgical leaching of germanium, production of a germanium dioxide (GeO_2) concentrate, and then production of high-purity metallic germanium. At the final stages, deep purification and refining of the metal are applied [4].

It should be noted that an analogous technological scheme is also possible in non-ferrous and ferrous metallurgy during converter blowing of copper matte melts or germanium-containing pig iron, the air or oxygen flow entrains volatile vapors of GeO monoxide and GeS sulfide, which condense as aerosol particles, forming converter dust enriched in GeO , GeO_2 , and GeS . This is followed by the collection and processing of converter dust according to the technological scheme described above [5-7].

China is also developing technology for extracting germanium from coal without combustion, using coal-chemistry methods. The high concentration of germanium in the organic matter of coal makes it possible to obtain not only germanium but also humic and fulvic acids - valuable feedstock for fertilizer production and soil reclamation. The alkali extraction-acid precipitation-chlorination and subsequent distillation method is regarded as a promising environmentally friendly approach to producing germanium from coal [8].

The Chinese model is based on the integration of the coal-mining, energy, and metallurgical industries. Within this system, coal is used for its main purpose - generating heat and electricity, as well as producing coke for metallurgical needs. The ash, sludge, and dust generated in the process are regarded as an additional source of valuable components. This achieves a dual economic effect: the main energy and metallurgical production processes are combined with the extraction of strategic metals.

Chinese experience is particularly significant from the standpoint of forming a comprehensive state policy in the field of critical materials. The development of germanium production was carried out not as a separate metallurgical project, but as an element of the national strategy for ensuring the country's technological independence in microelectronics, photonics, and high-tech engineering. As a result, China has formed a complete production cycle from raw material to high-value-added products becoming the largest participant in the global germanium market.

For Kazakhstan, China's experience is of particular interest. First, both countries possess substantial coal reserves and a developed coal-fired power industry. Second, Kazakhstan has accumulated significant volumes of ash-and-slag waste potentially containing germanium and other rare elements. Third, the existing energy infrastructure creates prerequisites for forming a similar resource model combining energy production with the extraction of strategic metals.

Thus, China's experience demonstrates the fundamental possibility of creating an independent model for developing a germanium industry, based on the use of national advantages in coal mining and the energy sector.

2.3. Prospects for germanium production from coal in Kazakhstan

Kazakhstan possesses one of the largest coal bases in Central Asia, represented by deposits of various geological-industrial types and characterized by substantial reserves and significant resource potential. Traditionally, the country's coal resources have been regarded as a source of energy feedstock. At the same time, the modern concept of integrated use of mineral resources assumes a transition from a single-component model of resource development to the extraction of associated valuable components, including rare and trace elements.

As a rule, trace elements are associated with the organic matter of coal (in a sorbed state, in the form of salts of organic acids or complex compounds), and less often with mineral components (their own minerals). Germanium, tungsten, beryllium, vanadium, and lithium are always associated with the organic part of coal, while lead, zinc, and scandium are associated with the mineral part. The organic part, acting as a reducing agent and sorbent (humic and fulvic acids), ensures the accumulation (sorption) of trace elements during coal formation from surrounding hydrothermal and aqueous solutions [9].

From a geochemical standpoint, brown coals (lignites) with a high organic-matter content and the presence of chemically active functional groups are the most promising for germanium accumulation. That is, elevated concentrations of germanium, lithium, and other rare metals are characteristic specifically of brown coals [10].

At the same time, bituminous (hard) coals generally do not exhibit high contents of rare elements. As the degree of coal metamorphism increases, the structure of organic matter changes, its sorption capacity decreases, and, as a rule, the concentration of a number of rare elements decreases as well.

Table 3 summarizes the coal deposits of Kazakhstan that are currently under development or prepared for industrial development. As shown in Table 3, these coals contain a broad range of rare elements and non-ferrous metals, typically at concentrations of up to 0.1-0.2%.

Analysis of the data presented shows that the highest potential for forming a coal-based source of germanium is associated primarily with the brown-coal (lignite) basins of Kazakhstan – the Turgai and Zhilanshik basins. For individual deposits in these basins, elevated concentrations of germanium, lithium, titanium, tungsten, rare-earth elements, and other strategically important components have been established. In terms of germanium content, some of these deposits are comparable to the well-known germanium-coal deposits of China (Table 2) and Russia.

Table 3. Coal deposits of Kazakhstan [11-19]

Basin / deposit	Formation (svita)	Reserves	Coal type	Ge content, g/t	Germanium reserve estimate / geochemical specialization
Developed					
Karaganda	Tentek Fm.	43.1 bn t	Bituminous	n/d	Y, Sc, Ge, Hg
	Dolinskaya Fm.			20-40	REE, Mo, Ge, Hg
	Nadkaragandinskaya Fm.			n/d	REE, Mo, Hg
	Karagandinskaya Fm.			n/d	REE, Mo, Hg
	Ashlyarikskaya Fm.			n/d	Sc, Hg
	Dubovskaya Fm.			n/d	Ga, REE, Sc, Be
	Mikhailovskaya Fm.			n/d	REE, Sc
Ekibastuz	Nadkaragandinskaya, Karagandinskaya, Ashlyarikskaya Fms.	9.7 bn t	Bituminous	Absent	REE, Al, Ti, Zr, Sc, Ba, Hg
Shubarkol deposit	–	2.3 bn t	Bituminous	7	REE, U, Y, Sc, Nd, Gd, Ti, Li, Be, Cu, U, Zn, Ni, Co, Ga, W
Alakol deposit	–	47 mn t	Lignite / Bituminous	10-30	Ge – 80 t, Sc – 180 t, REE
Prepared for industrial development					
Turgai basin. Deposits: Kushmurun, Eginsai, Priozernoye, Chernigovskoye, Orlovskoye, Kyzyltal	Duzbay, Karagan, Kushmurun, Chernigov Fms.	61.9 bn t	Lignite	500-10000	Ti (1.5-1.7%), Ge, REE, Li, Ag
Zhilanshik	Chilikin Fm.	14.5 bn t	Lignite	100-1000	Ge, Re, REE, Au, Mo

At the same time, the degree of study of the Turgai brown-coal basin in terms of germanium distribution, its forms of occurrence, and the possibility of industrial extraction remains insufficient. Industrial development requires additional geochemical studies, including determination of the spatial distribution of germanium, its mineral forms of occurrence, and the technological properties of the coal feedstock [1].

At the current stage, individual bituminous-coal deposits already under development - Dolinskoye, Shubarkol, Alakol – are of interest for germanium extraction as a by-product of energy use. The coal from these deposits is currently used both for power generation and for producing coke for metallurgical needs.

During coal combustion, germanium is redistributed among the combustion products, with the element's concentration in fly ash, dust, and fine fractions increasing 10-15 times compared with the original coal – up to 70-100 g/t. This creates prerequisites for forming a technogenic source of germanium based on coal-fired power facilities.

Technogenic waste from metallurgical enterprises, in which germanium can concentrate during the processing of the corresponding feedstock, is also of interest. During converter blowing of copper matte melts or germanium-containing pig iron, volatile vapors of GeO monoxide and GeS sulfide condense as aerosol particles. The high concentration of GeO, GeO₂, and GeS makes it possible to regard converter dust as valuable feedstock for obtaining germanium.

In this connection, technogenic waste from the Karmet and Kazakhmys enterprises can potentially be considered as sources of germanium, provided that specialized processing technologies are developed. The collection of fly-ash dust is particularly significant when processing germanium-ferruginous ores, such as those at the Western Karazhal and Taldysay deposits in the Atasu ore district. A Ge content in the ore of 8-27 g/t makes it possible to obtain high germanium concentrations in the collected fly ash.

Thus, the prospects for germanium production from Kazakhstan's coal feedstock are associated not only with the development of promising coal deposits, but also with the formation of a comprehensive technological system, including the mining and processing of germanium-bearing coals from operating deposits, the use of dust and ash-and-slag

waste from the energy sector, and the involvement of metallurgical technogenic resources.

Creating such a coal-based germanium production circuit will make it possible to form an additional raw-material base for producing high-purity metallic germanium and to ensure the development of a new direction in the field of critical materials in Kazakhstan.

3. Concept of the technological chain for germanium production from coal feedstock in Kazakhstan

3.1. Key stages of the proposed technological chain

Unlike the traditional production of germanium from zinc concentrates, the coal-based direction is based on the use of technogenic waste generated during the thermal processing of coal. A key element of the model is the transfer of ash-and-slag waste and fly-ash dust from the category of industrial waste to the category of secondary mineral feedstock. A potential technological chain for germanium production from Kazakhstan's coal feedstock can be represented as follows.

The proposed technological chain begins with the identification and development of a germanium-bearing coal deposit, followed by coal mining and preparation. The prepared coal is then used for energy generation or metallurgical purposes, resulting in the formation of ash, fly-ash dust, and other processing products in which germanium can become concentrated. These germanium-enriched materials are subsequently subjected to hydrometallurgical extraction and purification to produce a germanium dioxide (GeO₂) concentrate. At the final stage, the obtained GeO₂ is reduced and refined to produce high-purity metallic germanium.

At the first stage, a geochemical assessment of the coal feedstock is important, along with identification of areas with elevated concentrations of germanium and other rare elements. For Kazakhstan, this stage is particularly important, since a number of promising brown-coal sites – primarily in the Turgai and Zhilanshik basins – require further study in terms of germanium distribution, forms of occurrence, and industrial recoverability.

The next important stage is the organization of separate collection of coal-processing products. Chinese practice shows that the efficiency of germanium extraction increases substantially when separate streams of ash, fly-ash dust, and

other fine-dispersed products where rare elements concentrate are separated. In this connection, modernization of gas-cleaning systems and accounting for ash-and-slag materials is one of the key conditions for creating a coal-based germanium production circuit.

At the metallurgical processing stage, known hydrometallurgical methods of germanium extraction can be used, including leaching, solution purification, obtaining a GeO_2 concentrate, and subsequent reduction to high-purity metallic germanium. The choice of a specific technological scheme should be determined by the composition of the initial feedstock and associated components.

A distinctive feature of Kazakhstan is the possibility of forming an integrated processing model in which germanium can be extracted together with other valuable components of the coal feedstock – lithium, scandium, rhenium, and other rare-earth and rare elements.

Thus, the prospective model for germanium production from Kazakhstan's coal feedstock should be regarded not as a separate metallurgical process, but as an element of a comprehensive system for using coal resources. Its implementation will make it possible to transform coal deposits and accumulated technogenic waste into a source of strategic materials for high-tech industries.

3.2. Main directions of further research and technological challenges

One of the key aspects of further research is a detailed geochemical characterization of Kazakhstan's coal basins in order to identify zones of elevated germanium concentration. Systematic studies are needed to determine the Ge content in coals of various stages of metamorphism, as well as to establish its relationship with the organic and mineral components of the coal matter.

A second important direction is the study of germanium distribution during the thermal processing of coal. Particular attention should be paid to the distribution of the element among fly ash, slag, and gas emissions, as well as to the mechanisms of its concentration in fine-dispersed fractions. This data is key to developing effective industrial extraction schemes.

A third direction is the development and adaptation of hydrometallurgical technologies for extracting germanium from ash, fly-ash dust, and other technogenic products. In particular, optimization is required of leaching processes, solution purification, selective extraction, and production of germanium dioxide (GeO_2), as well as subsequent reduction to high-purity metallic form.

Special attention should be given to creating an experimental and pilot-industrial base for testing germanium extraction technologies under Kazakhstan's conditions. Such facilities will make it possible to assess the technological and economic efficiency of processing specific types of coal and technogenic feedstock, as well as to determine optimal parameters for industrial implementation.

Among the systemic challenges is also the need to form a regulatory and institutional framework for the transition from treating ash-and-slag waste as industrial waste to regarding it as secondary mineral feedstock. This implies changes in approaches to accounting, storage, and processing of technogenic materials.

Finally, an important direction is the development of a comprehensive economic model for germanium production,

considering the multicomponent nature of the feedstock, the high degree of product processing, and dependence on world prices for critical metals. Such a model should serve as a basis for investment decision-making and for shaping state policy in the field of critical materials.

Thus, further development of this direction requires the synergy of geological, technological, economic, and institutional research aimed at forming a new high-tech germanium production industry in Kazakhstan.

4. Conclusions

The review confirms that Kazakhstan has substantial potential to develop a national germanium industry based on two complementary raw-material sources: the traditional zinc-metallurgical route and the emerging coal-based route. The greatest prospects for the latter are associated with the Turgai and Zhilanshik lignite basins, as well as several operating bituminous-coal deposits, including Dolinskoye, Shubarkol, and Alakol. In addition, metallurgical and energy-sector waste generated by major industrial enterprises may represent an important secondary source of germanium. Together, these resources create the basis for establishing an integrated and potentially export-oriented production chain for high-purity metallic germanium.

The practical implementation of this potential requires a coordinated program of geological, technological, and institutional development. Priority should be given to detailed geochemical characterization of germanium-bearing coals, assessment of germanium distribution in ash, fly ash, and metallurgical dust, and adaptation of effective hydrometallurgical recovery technologies to Kazakhstan's feedstock characteristics. Equally important is the development of pilot-scale processing facilities and a regulatory framework that recognizes ash-and-slag materials and other technogenic products as secondary mineral resources. Such measures would enable Kazakhstan to diversify its critical-materials base, increase the added value of domestic mineral resources, and strengthen its position in the global germanium supply chain.

Author contributions

Conceptualization: FSK, DEF; Data curation: FSK, DEF; Formal analysis: FSK; Funding acquisition: DEF; Investigation: FSK; Methodology: FSK, DEF; Project administration: DEF; Resources: FSK, DEF; Software: FSK; Supervision: DEF; Validation: FSK, DEF; Visualization: FSK; Writing – original draft: FSK; Writing – review & editing: FSK, DEF. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Қазақстан көмірінен германий өндіру: ресурстық әлеуеті, технологиялық шешімдер және келешегі

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Аңдатпа. Германий (Ge) – жартылай өткізгіштер өндірісін, оптоэлектрониканы, ғарыштық технологияларды, инфрақызыл оптиканы және қорғаныс жүйелерін қоса алғанда, жоғары технологиялық салаларды дамыту үшін аса маңызды материалдар тобына жататын сирек шашыранды элемент. Осы шолуда германий өндірудің әлемдік модельдері, соның ішінде мырыш концентраттарынан дәстүрлі түрде бөліп алу және Қытайда көмір негізіндегі бағыттың дамуы қарастырылған; Қазақстанның перспективалы көмір бассейндерінде германийдің жинақталу геохимиясы талданып, көмір шикізаты мен оны энергетика және металлургия өнеркәсібінде өңдеу нәтижесінде түзілетін техногендік өнімдер негізінде Қазақстанда жоғары тазалықтағы германий өндірісін құру перспективалары бағаланған. Қазақстанда германий өндірудің екі көзді – мырыш металлургиясы мен германийлі көмірлерді - ұштастыруға негізделген жаңа моделін қалыптастырудың алғышарттары, сондай-ақ Торғай және Жыланшық бассейндерін қоса алғанда, қоңыр көмір (лигнит) бассейндерінің елеулі әлеуеті көрсетілген. Көмір шикізатынан германий концентраттарын алу, германий диоксидін (GeO₂) өндіру және жоғары тазалықтағы металл германий алу жөніндегі технологиялық модель ұсынылған. Бұл тәсіл экспортқа бағдарланған критикалық материалдар индустриясын дамыту үшін негіз ретінде ұсынылады.

Негізгі сөздер: германий, көмір, Қазақстан, критикалық материалдар, мырыш металлургиясы, гидрометаллургия, ұшқын күл.

Производство германия из углей Казахстана: ресурсный потенциал, технологические решения и перспективы

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Аннотация. Германий (Ge) – редкий рассеянный элемент, относящийся к группе материалов, критически важных для развития высокотехнологичных отраслей промышленности, включая производство полупроводников, оптоэлектронику, космические технологии, инфракрасную оптику и оборонные системы. В данном обзоре рассмотрены мировые модели производства германия, включая традиционное извлечение из цинковых концентратов и развитие угольного направления в Китае; проанализирована геохимия накопления германия в перспективных угольных бассейнах Казахстана и оценены перспективы создания в Казахстане производства германия высокой чистоты на основе угольного сырья и техногенных продуктов его переработки в энергетической и металлургической промышленности. Показаны предпосылки для формирования в Казахстане новой модели производства германия, основанной на сочетании двух источников – цинковой металлургии и германиеносных углей, а также значительный потенциал бурогоугольных (лигнитовых) бассейнов, включая Тургайский и Жыланшиковский бассейны. Предложена технологическая модель получения германиевых концентратов из угольного сырья, производства диоксида германия (GeO₂) и высокочистого металлического германия. Данный подход предлагается в качестве основы для развития экспортно-ориентированной отрасли критических материалов.

Ключевые слова: германий, уголь, Казахстан, критические материалы, цинковая металлургия, гидрометаллургия, зола уноса.

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