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A new concept for complex mining of mineral raw material resources from DTEK coal mines based on sustainable development and ESG strategy

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Abstract

Purpose. The research purpose is to develop a concept for complex mining of mineral resources from coal mines using the example of PJSC DTEK Pavlohradvuhillia mines with a transition to multi-product production of clean drinking water, utilization of methane, secondary coal from rock dumps and sludge reservoirs, low-potential thermal energy of mine groundwaters and associated raw materials from desalination waste.

Methods. The research uses an integrated approach, which includes an analysis of existing experience and available complex coal mining technologies, laboratory studies of mine water desalination technology by the reverse osmosis method with thermal distillation of concentrated brine, and chemical analysis using ElvaX laboratory equipment.

Findings. This paper presents the research results of a comprehensive analysis of mineral raw material resources related to coal mining. The technically achievable energy potential that can be produced from the secondary coal of rock dumps and sludge reservoirs has been determined, which in total is 183.3 TJ. The annual heat potential of methane gas utilization has been estimated, which in total of PJSC DTEK Pavlohradvuhillia's mines reaches 7.1 PJ. The possibility of extracting up to 1.12 TJ/year of associated thermal energy from the water-drainage installation of mine complexes has been determined. For the conditions of the Zakhidno-Donbaska mine, the authors of the paper have developed a technological scheme for the water preparation process by the reverse osmosis with the desalination brine treatment by the method of multistage evaporation on adiabatic evaporators.

Originality. For the first time, the energy flows related to coal mining technology have been comprehensively analyzed for the possibility of their joint use to cover the needs of the mine complex. The prospects for complex mining of mineral resources have been assessed based on the adaptation of the mine complex production facilities to the multi-product production of clean drinking water, utilization of methane gas, low-potential thermal energy from mine groundwaters and secondary raw materials of desalination waste.

Practical implications. The proposed set of technological solutions will ensure the sustainable development and diversification of the production of PJSC DTEK Pavlohradvuhillia coal-mining enterprises, as well as the effective transformation of coal-mining cities during the period of transition from mono-product production to the creation of multi-business production complexes that comply with ESG principles. The creation of multi-product mine complexes capable of producing not only coal, but also heat and associated mineral raw material resources, should become a guarantee of stable social-economic development of coal-mining regions.

Keywords: *mine, mineral resources, water, desalination, coalmine gas, thermal energy, rock dumps*

1. Introduction

The level of the country's economy development largely depends not only on the availability of rich natural resources, but also on the level of their mining and completeness of utilization. Scientific and technological progress never stops. We are witnessing radical changes in technologies, the development of high-tech production, the creation of innovative products with new consumer properties and characteristics [1], [2]. In this regard, in order to ensure the innovative and technological development of the Ukrainian economy, it is necessary to comprehensively expand the range of mineral resources involved in the use.

Ukraine has all the prerequisites for minimizing energy dependence on neighboring countries and imported energy resources. Over the past years, Ukraine has been conscientiously fulfilling its obligations in terms of alternative energy development [3]. However, for truly sustainable development, a comprehensive modernization of production capaci-

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ties and a transformation of approaches to the production of traditional types of resources are required [4], [5].

"Green" energy, which is actively developing within the framework of decarbonization strategy, is not yet able to work independently in conditions of unstable external environment, lack of large energy storage facilities, changing weather conditions, etc. [6]. Therefore, to cover the gaps in the generation of solar and wind capacities, stable sources are needed, among which there are traditional fuel and energy resources. Despite the loud statements of experts about the reduction in coal consumption, the dynamics of its demand on global markets in recent years shows the opposite. For example, the global volume of coal consumption increased by 5.7% [7], and the market price of thermal coal increased from 58 to 430 USD/t over the past two years [8]. At the same time, the share of coal in global energy consumption still remains significant and amounts to 27% [7], [9].

The role of modern advanced coal mining technologies is increasing, which contribute to the improvement of its quality and the accumulation of coal mining waste in the underground space of mines, resource saving in the exploitation of underground mine workings, especially in difficult mining-geological conditions [10]-[15]. Therefore, the maintenance of our own coal production [16], [17] in parallel with a "soft" transition to alternative energy sources is a priority task that determines the transformation of coal-mining cities and the sustainable development of our country. Since, on the one hand, a significant amount of the country's labor resources are involved in the coal-mining industry, and on the other hand, the stable operation of coal enterprises provides the operation of other areas of our economy with heat and electricity.

However, the mono-structural nature of the activity of coal-mining enterprises with the depletion of the main resource – coal is one of the main causes of social tension arising in coal-mining cities due to the possibility of closing mines [18]-[20]. An analysis of previous practical experience in closing unpromising mines in Ukraine indicates an unpredictable deterioration in the environmental situation that arises from this [21]. Wastes accumulated over many years of mining activity in the form of mineralized mine waters, rock dumps and beneficiation products have a negative impact, polluting the air, water bodies and fertile lands [22].

The DTEK Company strategy is in line with the ESG (Environmental, Social, Governance) principles, which are based on a model for modern innovative business development aimed at environmental and social responsibility. That is why the DTEK Company always focuses on projects aimed at maintaining existing and creating new high-tech jobs, which will further promote the economic activity development of local resources, territorial communities and help reduce tension in coal-mining cities.

Now society lives in the period of the fourth technological order, which requires deep technological changes from business, the use of renewable energy sources, the creation of a circular production that returns waste to production cycles with the introduction of innovative technologies [23], [24]. In traditional coal mining, from the productive flows of mines, in addition to the coal itself, a significant amount of associated rocks rises to the surface, coalmine gas is released, groundwater is pumped out, along with which a huge amount of low-potential thermal energy is dissipated into the environment. All these coal-mining by-products are resources for economically profitable processing [25], [26].

Therefore, in this regard, integrated approaches are needed to modernize existing coal-mining enterprises based on the creation of powerful multi-vector industrial complexes on their basis with the maximum involvement of own mineral raw material resources. The implementation of projects for complex mining of mineral resources from coal mines requires certain research, scientific-technical developments and investments. The lack of understanding of a clear prospect for the development of coal-mining areas without assessing the mineral resource potential and developing a comprehensive model for functioning of production facilities significantly hinders the development of this direction.

Thus, the purpose of this paper is to analyze and assess the prospects for complex mining of mineral resources from coal mines using the example of PJSC DTEK Pavlohradvuhillia mines with a transition to multi-product production of clean drinking water, utilization of methane, secondary coal from rock dumps and sludge reservoirs, low-potential thermal energy of mine groundwaters and associated raw materials from desalination waste.

2. Literature review

2.1. Goals of sustainable development, rational resource management and environmental protection

The global challenges of the 21st century are initiating significant changes in the business environment, since business performance now acts not only as an increase in its economic efficiency, but also as a way to ensure the conditions for the survival of mankind as a whole. According to Larry Fink, founder and general manager of BlackRock, the world's largest investment company with over $10 trillion in assets, "to prosper over time, every company must not only deliver financial performance, but also show how it makes a positive contribution to society" [27].

And if earlier the nature of such challenges was dictated mainly by problems in international relations (problems of war and peace, terrorism, overcoming the economic obsolescence of developing countries, etc.) and relations between society and the individual (demographic problems, drug addiction, cultural and religious differences, etc.), then the current wave of globalization is mainly related to the problems of human-nature relations (ecological problems, energy and raw material problems, climate change, etc.), which are intensified by pandemic processes [28], [29].

As a general social issues, the problems of ecology and resource management were identified among the main ones in the first report of the Club of Rome, which summed up the research results by scientists from the Massachusetts Institute of Technology (USA) in the edition of the Professor Jay W. Forrester works ("World Dynamics", 1971, [30]) and a young scientist-mathematician of the same institute Donella H. Meadows ("The Limits to Growth", 1972 [31]). In addition to the indicators of population growth, production and consumption that were usual for economic predictions of those times, Forrester and Meadows also have taken into account such new factors as the limiting values of natural resources, including the limited ability of natural ecosystems to absorb and neutralize the harmful human activity wastes. Calculations have shown that after the first third of the 21st century, the limit of ecological factors will be clearly marked and this will lead to crisis phenomena in the relationship between mankind and nature, which will affect environmental pollution, a decline in industrial development, famine and epidemics. The current situation largely confirms these predictions. Thus, according to the UN data [32], in 2019 the global material consumption reached 95.9 billion tons, compared to 57.1 billion in 2000 (Fig 1) and with a 300% increase from 27 billion in 1970.

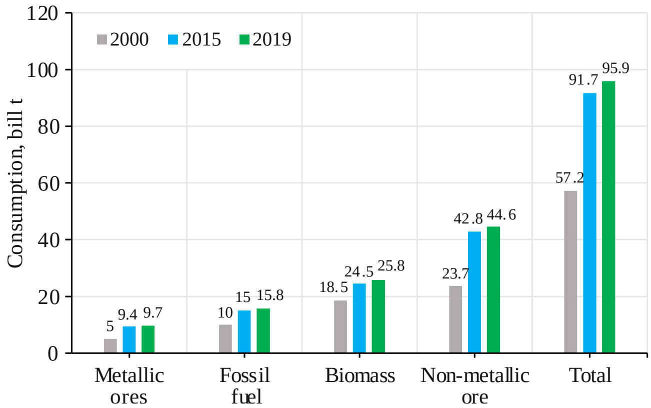

Figure 1. Material trace by type of material, billion tons

Although the material trace growth rate has slowed somewhat in recent years (in the period 2015-2019 it was 1.1% per year compared to 2.8% in 2000-2014), global resource extraction may increase to 190 billion tons by 2060 [33]. The total volume of resource extraction from the bowels of the earth over the past 100 years has increased by about 8 times, in particular, oil production has increased by 12 times, ores and minerals – by 27 times, building materials – by 34 times, biomass – by 3.6 times [34], [35]. The depletion of the reserves of many resources is accompanied by a deterioration in mining conditions and, consequently, a significant increase in the production cost. Mining and processing of materials, fuels, and foodstuffs account for about half of total global greenhouse gas emissions (not including land-use-related climate impacts) and more than 90% of biodiversity loss [36].

The D. Medows report [31] identified possible ways to avoid such a crisis:

– population decline;

– production growth stagnation;

– coordination of one's further activity with the biosphere possibilities;

– creation of new technologies to compensate for environmental pollution.

The results of research by J. Forrester and D. Meadows actually formed the basis for the formation of the sustainable development concept, which is currently considered by many scientists around the world to be the most effective ideology of the 21st century. The first-ever Global Plan for Sustainable Development was adopted at the United Nations Conference on Environment and Development (UNCED), held with the participation of the world leaders from 179 countries of the world in Rio de Janeiro in 1992.

The author of the theoretical concept of sustainable development is considered to be Herman Daly, the leading researcher of the economic aspects of environmental pollution, former World Bank economist, who covered his innovative developments in a monograph "Beyond Growth. The Economics of Sustainable Development" [37]). Based on the definition of the UN Commission and scientific analysis, H. Daly logically interprets the term "sustainable development" as meaning the harmonious, balanced, conflict-free development of the entire earthly civilization, groups of countries (regions, subregions), as well as individual countries of our planet according to scientifically based plans (system approach methods). That is, when in the process of steady innovative intensive (rather than extensive) economic development of countries, a complex of issues of environmental preservation, the elimination of exploitation, poverty and discrimination is simultaneously positively resolved, both for each individual person and for entire nations or population groups, including those for ethnic, racial or gender characteristics.

In September 2015, United Nations Sustainable Development Summit adopted another global document "Transforming Our World: The 2030 Agenda for Sustainable Development by 2030, included a declaration, 17 sustainable development goals and 169 targets on global development" based on the principles of common but differentiated responsibility. And by the end of 2020, about 15000 large companies have joined the UN Global Compact, confirming their commitment to sustainable development goals. Section 28 of the Agenda for the 21st Century states that the Local Agenda 21 (LA21)46 is the primary means of achieving global development goals, since the causes of many development problems and approaches to solving them are precisely in the nature and peculiarities of local conditions. Regions and local governments should achieve a new level of cooperation and coordination in order to improve the exchange of information and experience between local authorities. Local governments should develop programs, strategies, regulations and rules for the implementation of sustainable development goals and, based on consultations with the general public, develop a consensus on LA21 for a particular community. That is, according to the concept of this document, it is considered that each country should adopt a national sustainable development strategy.

Ukraine embarked on the path of sustainable development at the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro (1992) by signing an Agenda for the 21st Century and the Declaration on Environment and Development. Work with the Sustainable Development Goals (SDGs) determined by the UN began in 2015, and the first step was the adaptation of the SDGs for Ukraine, given the specifics of national development, the results of which were reflected in the basic National Report "Sustainable Development Goals: Ukraine". The report became the basis for the national system of SDGs in Ukraine – it identified 86 objectives and 172 national development indicators, set target values until 2030 (and intermediate values for 2020 and 2025). Already in 2021, Ukraine ranked 36th (rising to nine positions) among 165 countries in the annual sustainable development ranking published by the UN and the Bertelsmann Foundation, ahead of such countries as Israel (38th place), Greece (37th), Luxembourg (42th).

In the framework of this activity, the Ministry of Economy of Ukraine in 2020 prepared a Voluntary National Review of Ukraine's progress in achieving the Sustainable Development Goals. It recognized the need to further develop the Strategy for the industrial complex development (modernization) in the framework of achieving Goal 9 (Industry, innovation and infrastructure), which should take into account the national and global challenges of our time. In particular, it was noted that out of 14 indicators measuring progress in achieving the ambitious National Goal 9, data for the period 2015-2019 on 3 indicators were absent. Of the

11 indicators, only 4 showed a positive dynamics, including the 1st indicator that the target had been achieved on the horizon by 2020, the achievement of the targets for 2 indicators is quite realistic, and the 1st one is weak, which with a high probability indicates the unattainability of targets on the horizon of the coming years.

In particular, there was insufficient work of industrial enterprises in the direction of "innovative ecosystem development", which in turn is determined by negative dynamics in the implementation of target 12.4 "Reduce the volume of waste generation and increase the volume of its processing and reuse based on innovative technologies and productions" (Goal 12 "Responsible consumption and production") and target 13.1 "Limit greenhouse gas emissions in the economy" (Goal 13 "Mitigate climate change impacts on Earth").

Consequently, the enterprises of the industrial complex of Ukraine today face the urgent and difficult task of improving their work in order to achieve the specified Sustainable Development Goals, in particular in the areas of rational resource management and environmental conservation.

2.2. ESG strategy principles and business readiness for the transition to a circular economy

The theoretical basis for such work can be the developments of scientists within the framework of such resource-saving and environmental concepts as "circular economy", "decoupling", "green economy", etc.

The closed-loop model or circular economy originated from the discipline of industrial ecology, which used the functioning of ecosystems as a model for industrial processes and systems [38], [39]. In particular, according to M.B. Nagara, its basis was proposed in 1966 by the American economist Kenneth Boulding and had a strong environmental character: "... a person must find his place in a cyclic ecological system..." [40]. The application of this idea at the social-economic level gained popularity after the World Economic Forum (WEF) 2012, at which Ellen MacArthur presented a report "Towards a Circular Economy, 2012".

The "3R" model, which consists of the following components is considered to be the circular economy basic framework:

1) reduce – contributes to the minimum use of raw materials and minerals, which implies a reduction in waste;

2) reuse – reduces resource flows to the production system;

3) recycle – involves the full use of resources, leading to a decrease in environmental pollution.

Later, in 2018, the World Economic Forum expanded the circular economy basic principles to 10R:

1) refuse (refusal to produce a product according to a certain technology and materials, offering an alternative product);

2) rethink (rethinking of directions for using the product, sharing or joint use of the product);

3) reduce (reducing the use of natural resources with increased efficiency in production or consumption);

4) reuse (reuse by another consumer of a product that was in use, for its intended purpose;

5) repair (repair and service maintenance of a defective product with its subsequent use for its primary purpose);

6) refurbish (restoration of an old product for further consumption);

7) remanufacture (reprocessing and use of a part of an old product in a new product according to its primary purpose);

8) repurpose (reorientation of a part of an old product in a new product to another functional purpose);

9) recycle (processing of materials to obtain products of the same or lower quality);

10) recover (combustion of materials with the recovery of energy spent on their production).

The circular economy system used at the enterprise level implies "integrating environmental aspects in the development of production processes and products (ecodesign), organizing clean production with low emissions, implementing waste prevention systems, as well as increasing consumer responsibility through the use of eco-label systems and green public procurement" [39].

The concept of decoupling was first proposed by the Organization for Economic Co-operation and Development (OECD) in the report "Indicators to Measure. Decoupling of Environmental Pressure from Economic Growth" (2002) [34]. In this report, the decoupling (literally "demarcation", "disconnection", "rupture", "separation", "disconnection") between anthropogenic pressure on the environment and economic growth is defined as one of the main goals of the OECD environmental strategy, developed in 2001 for the first decade of the 21st century. Later, in 2005, the European Union (EU) adopted the Lisbon Strategy for economic growth, which gave priority to the rational use of natural resources by reducing the negative impact on the environment while ensuring economic growth, and also called on EU countries to take the initiative of a more sustainable consumption and production in the global economy.

The implementation of decoupling in practice provides for a positive difference in economic growth rates in relation to the environmental pressure growth rates in a particular country, etc. The main way to achieve this is to reduce the norms of materials, energy, water and land resources used per unit of economic activity. In contrast to the idea of minimizing the consumption of primary resources in the decoupling concept, the theoretical "green economy" model focuses on the environmental factor, that is, satisfying human needs, while taking into account interaction with the environment in the long term [41], [42].

In 2012, the UN Conference on Sustainable Development, held in Rio de Janeiro, Brazil, for the first time combined the concept of green economy and decoupling (green growth). These concepts emphasized the need to integrate the environment and economic growth by directing 2% of global GDP capital into green investments. This direction of investment was later referred to as green or climate finance, best known under the acronym ESG, which stands for E (environmental), S (social) and G (governance).

In general, ESG can be defined as:

– «E» (Environmental), which means how investors can help protect our planet, provided that their solutions are designed to reduce carbon dioxide emissions, maintain energy efficiency, combat water scarcity, fight illegal deforestation, protect biodiversity or promote a circular economy;

– «S» (Social) concerns investors who could create a socially responsible economy by advocating for the protection of human rights, such as the prohibition of child labor, bonded or forced labor, the absence of human trafficking and much more;

– «G» (Governance) indicates how investors can help to establish fair governance in public and private institutions. They can help increase transparency in information disclosure and supply chain monitoring, etc.

Currently, ESG is increasingly used in financial sectors around the world, and national governments are seeking to integrate ESG into their national classification system by creating a legal and regulatory framework for their sustainable financing policies. In particular, from March 1, 2021, the EU obliges asset managers and other financial market participants to report on ESG.

In 2020, the World Economic Forum called for the creation of a common ESG reporting standard based on 55 universal indicators and recommendations, as investors currently use about 2000 separate ESG reporting indicators and approximately 600 ratings. The 85 stock exchanges have ESG criteria, and 17 of them are mandatory for listing. Meanwhile, the process of redistributing investments is already taking place. According to the Morningstar Analytical Company, the assets of funds invested in socially responsible companies have reached a record $1.7 trillion. By 2025, the company's ESG will account for almost a third of the world's assets in management – $53 trillion from $140.5 trillion [27], [28].

Unfortunately, for Ukrainian enterprises, the ESG practice has not yet gained the necessary perception. As Managing Director of Korn Ferry in Ukraine, R. Bondar notes, "while the world is actively transforming, the situation in Ukraine is reminiscent of life behind a fence. We pretend as hard as we can that it doesn't concern us... Conversations on this topic with chief executive officers show that few can decipher this acronym at once. Few people know about the sustainable development goals. And only a few people understand what this means in practice". Among those who have taken responsibility for the possibilities of using ESG potential, were representatives of those industries "that are already experiencing the pressure of inevitability: raw materials, metallurgy, oil and gas, power generation. This is especially true for export business, socially-owned enterprises, or participants in the capital borrowing market" [43]. A positive example for others is demonstrated by DTEK Group of companies, which is a member of the United Nations Global Compact, a member of the Global Compact Network Ukraine, a member of the World Economic Forum, and participates in the Energy Futures Initiative.

Doing business in accordance with the global sustainable development policy has become a new rule for DTEK. "Climate change is no longer just a trend, it is a reality. We understand that if an energy company does not change and does not follow the path of decarbonization, then it loses its competitiveness, – notes Dmytro Sakharuk, the Executive Director of DTEK [44] – Changing ourselves is a big challenge for DTEK. Therefore, as part of the New 2030 Strategy, we have committed ourselves to transforming the company into a greener, more efficient and technologically advanced business. Implementation of the strategy will be a significant contribution of DTEK to the decarbonization of the economy of Ukraine and Europe as a whole".

The company's management believes that the key components of this process are the increase in energy production capacity from renewable sources, the development of energy storage systems, the implementation of hydrogen projects and the modernization of electricity grids.

2.3. The practice of integrated use of mineral and raw material resources of coal mines

The search for alternative and affordable water sources has become a real challenge all over the world. The lack of water for the needs of the population and industry is forcing global companies and states to invest significant financial resources in new environmentally friendly water sources. The presence of a large amount of highly mineralized water and the lack of high-quality drinking water encourages the solution of this problem [45]-[47].

The conducted analysis shows that in Ukraine and abroad there is a unique experience in desalination of highly mineralized mine water. For example, in the Western Donbass at the Ternivska mine, a mine water demineralization plant using thermal method has been tested, the productivity of which is 30 m^3/day. At the Petrovska mine of the VP Donetskvuhillia, after testing a pilot-industrial desalination plant using electrodialysis technology, the productivity has increased to 50 m^3/day. On an industrial scale, SE Krasnolymanska Mine uses mine water purification technology for the technical needs of the enterprise (dust suppression in the mine, household water supply, etc.) instead of water supplied from the local network. The volume of water consumption for the mine's technical and household needs is up to 1200 m^3/day. To purify mine waters, high-speed pressure sand filters are used, followed by bacteria disinfection using an Atlantic Ultraviolet Company installation [48].

In 2005-2008, the specialists from the Luhanskhiproshakht Institute developed and implemented a project for the Aqua-Service enterprise on mine water purification. The only drinking water production plant in Ukraine with a capacity of 500 m^3/h was built, which used water from the Isakivs'ke Vodoskhovyshche, to which mine water was supplied. The initial water underwent 8 stages of purification according to the technology developed by GE Osmonics Company, including through reverse osmosis systems. The plant also provided the PJSC Alchevsk Metallurgical Plant with technical and drinking water. In 2009-2011, the specialists of the Luhanskhiproshakht Institute prepared a project for the purification of mine waters from the Voikova mine for the organization of household and drinking water supply in the city of Sverdlovsk (Luhansk region). In 2013, under the Kyoto Protocol, financing of this project began and equipment was delivered to Ukraine, but the project was not implemented due to the outbreak of hostilities. In the same years (2005-2010), the specialists of the Donhiproshacht Institute and the CJSC "Donetsksteel-metallurgical plant" in the city of Antratsyt executed a project to purify mine waters from the Tsentralna mine on the terms of a public-private partnership with the city authorities, but the project was not implemented.

The Donhiproshacht Institute carried out works on the construction project of a mine water purification and desalination complex for drinking water supply in the city of Antratsyt. It was planned to use the former Tsentralna mine waters in the amount of 800 m^3/hour and to obtain an additional 250 m^3/hour from the flooded mine workings of the former No. 7/7 bis mine. It was planned to equip the mine water treatment plant with a complex of automatic UFP Selective Culligan filtration systems.

At present, the use of rock as a building material is very limited both in our country and abroad. In small volumes, it is possible to utilize part of mine rocks for road construction and land reclamation. In Ukraine, the Coal Energy S.A. Company carried out industrial development of mine rock dumps in the city of Snizhne, Donetsk region. The waste rock dump processing capacity has reached 1.2 million tons/year. For the period of 2005-2012, four mine waste heaps with a volume of about 8.5 million tons of rock and an area of 18 hectares have been processed. Mine rocks were used for backfilling of mined-out open-pit and partially in the construction of roads [49].

The experience of using mine rocks has been accumulated by the Heroiiv Kosmosu mine, PJSC DTEK Pavlohradvuhillia. On the mine working level, a crushing complex has been built to crush ordinary mine rock supplied from preparatory faces. Mine rock is used as a material for manufacturing a shotcrete-concrete mixture to ensure the stable state of fastening of the main mine workings [50]. On the basis of the Pokrovska mine, there is a cogeneration modular plant for utilization of coalmine methane and a drilling module for drilling degassing wells from the surface. The system of degassing wells is used to ensure a safe coalmine methane concentration in stoping faces [51], [52].

Hydrogen production on the basis of coal mine technological complexes is a promising way of transforming mining regions through the diversification of production and creation of new points of economic development. An example of such a project is the innovative center for the development of hydrogen technologies, established in Germany based on the closed Ewald Coal Mine [53]. The center conducts a variety of research and testing of new technologies, including hydrogen production and storage. An experimental power plant with a full power-gas-power cycle and a hydrogen fuelling station are operating on the territory of the mine.

Thus, the analysis of domestic and foreign experience in the complex use of mineral resources of coal mines shows that there are promising technologies that can be adapted to the conditions of mining enterprises to provide technical and drinking water to cities, to become an alternative source of natural gas, thermal energy, and to provide industry with building materials. In addition, it is possible to simultaneously reduce the environmental impact by preventing pollution of nature with waste, as well as to solve social problems related to a lack of jobs in mining cities.

3. Methods

To achieve the purpose set, an integrated approach is used, which includes an assessment of mineral and raw material resources related to coal mining (mine water, its low-potential thermal energy, coalmine gas, secondary coal from coal beneficiation waste) suitable for industrial use by determining the technically achievable energy potential for the effective integration of production units into a unified multi-product mine complex with a closed production cycle. Using the example of mine water as the most promising and accessible mineral resource of coal-mining enterprises, a research has been conducted to determine the technical-economic indicators of a waste-free mine water desalination complex with the possibility of scaling it to other PJSC DTEK Pavlohradvuhillia coal enterprises.

Technological schemes for mine water desalination are based on the use of the reverse osmosis method [46], which ensures high purification and desalination of water to drinking quality standards. However, another important issue arises related to the utilization of mine water desalination waste, which is represented by concentrated mineral salt brines. The dumping of desalination waste into ponds or on adjacent land areas causes serious environmental problems. Thus, desalination waste should be converted into a product that will be in demand on the market due to its elemental composition. The solution to this problem is based on the search for effective ways and methods of concentrated brine treatment into dry salt-containing chemical substances that can be used in various areas of production [45]. Therefore, in order to select the optimal method for desalination waste treatment and directions for the subsequent use of dry salts obtained during mine water desalination, it is necessary to conduct appropriate laboratory studies.

For this purpose, laboratory studies on the technology of mineralized mine water desalination by the reverse osmosis method have been conducted with thermal distillation of the concentrated desalination waste brine and a detailed chemical analysis of the dry residue of salt-containing reverse osmosis chemical products using ElvaX laboratory equipment. Based on the results of laboratory studies, the production volumes of clean drinking water and mine water desalination products have been determined. To determine technical-economic indicators, the authors used the multistage distillation method [54]-[56] for calculating the production costs of water desalination and thermal distillation, as well as the methodology of the state construction standard (DSTU B.1.1-7:2013) for calculating the capital costs of a waste-free mine water desalination complex.

Laboratory studies of the mine water chemical composition and thermal distillation products have been conducted by the Department of Mining Engineering and Education of the Dnipro University of Technology. The research methodology provided for the filtration and desalination of mine water in a reverse osmosis system, followed by the release of a dry residue of reverse osmosis mineral salts on the evaporator. The general view and scheme of the laboratory setup are presented in Figure 2. For research, 50 liters of water were taken from the Zakhidno-Donbaska mine. Water sampling was made directly from the mine water intake of the 585 m horizon, which is the central water collector and water reservoir from the underground mine workings.

4. Results

4.1. Assessment of mineral and raw material resources related to coal mining at PJSC DTEK Pavlohradvuhillia mines

At present, the PJSC DTEK Pavlohradvuhillia mines are the flagship of the Ukrainian coal industry, the production facilities of which are located in the Western Donbass. In 2021, the coal mining enterprises of this region provided the production of 16.3 million tons of run-of-mine coal, which is 55.4% of the total output in Ukraine.

For the entire period of production activity of the Western Donbass mines, about 110 million tons of waste rock have been accumulated in rock dumps, and over 8 million tons of coal beneficiation waste is in the sludge reservoirs of the DTEK Pavlohradska CPP LLC. At the same time, the average annual volume of rock waste accumulation from coal enterprises reaches 4.2 million tons. As the practice of European countries and the availability of sufficiently advanced technological and technical solutions in the world show, the rocks of mine dumps, after appropriate preparation and bringing them to the standard physical-mechanical characteristics, can have a multi-purpose use in construction and production of materials. Thus, the accumulated rock dumps and sludge reservoirs are large storage facilities of industrial materials that can be obtained by simple processing and beneficiation methods, creating a production line that meets the requirements of consumers.

Figure 2. Laboratory setup for mine water desalination with a release of a reverse osmosis dry residue: 1 – a mine water tank; 2 – a stopcock system; 3 – a water pressure gauge; 4 – a coarse water filter; 5 – a water supply pump for reverse osmosis system; 6 – a system water pressure controller; 7 – a transparent bulb; 8 – a water quantity meter; 9 – a water pressure gauge; 10 – a rotameter; 11 – a quartz sand filter; 12 – a granular activated carbon filter; 13 – an expanded polypropylene filter; 14 – a reverse osmosis filter; 15 – a post-filter; 16 – a pure water storage tank; 17 – a desalination waste storage tank; 18 – the heating element; 19 – laboratory evaporator; 20 – the evaporator coil; 21 – a distilled water storage container; 22 – a tap for desalinated water selection; 23 – a fuse box

In addition to a combination of various types of rocks, mine rock dumps contain up to 20% of coal, while the amount of coal in sludge reservoirs of the coal beneficiation plant of the DTEK Pavlohradska CPP LLC can reach 40-50%. Thus, taking into account the available averaged statistical information on the combustible mass elemental composition, indexes of ash content, moisture content and other parameters, the energy potential of mine dumps is about 145.3 TJ, and that of sludge reservoirs is up to 38 TJ. It follows from this that the total amount of thermal energy that can be extracted from coal beneficiation products only in the Western Donbass region reaches 183.3 TJ. This is quite enough to ensure the Zaporizhzhia thermal power station operation with a capacity of 3650 MW during the year, or to use the thermal energy of the surface mine complex by its own consumers almost indefinitely.

Coalmine gas-methane is one of the promising alternative sources of fuel and energy resources. Every day, the PJSC DTEK Pavlohradvuhillia mines produce from 10 to 50 m^3 of gas for each ton of mined coal. The most gas-bearing mines are: the Zakhidno-Donbaska mine, the average absolute multigas content of which is 125 m^3/min at a depth of 510 m, followed by the Stepova mine – 100 m^3/min and the Heroiiv Kosmosu mine – 65 m^3/min. The average absolute multigas content of the remaining Western Donbass mines ranges from 10 m^3/min (Samarska mine) to 18 m^3/min (Ternivska mine) (Fig. 3).

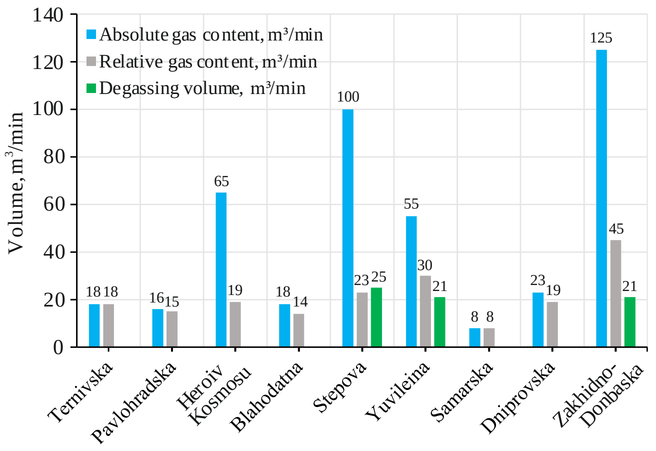

Figure 3. Histogram of the distribution of PJSC DTEK Pavlohradvuhillia mines by multigas content and degassing volumes

Thus, about 800 million m^3 of coalmine gas is produced annually by the presented mines in the process of coal mining process. Provided that the pure methane concentration in the coalmine gas is about 25%, the annual thermal potential of such an amount of methane reaches 7.1 PJ, or 1.97 TW·h, which is equivalent to annual electricity consumption in the Chernihiv region.

At present, coal mining enterprises of the DTEK Energy company are actively implementing projects for the coalmine gas utilization. At the Stepova mine of PJSC DTEK Pavlohradvuhillia, a project on the coalmine gas utilization by the method of high-temperature oxidation using a Caterpillar cogeneration plant with a capacity of 1.6 MW has been implemented. The cogeneration plant generates thermal and electrical energy from the utilized coalmine gas to cover the mine complex capacities. For the period 2019-2022, the cogeneration plant generated 158.1 GW·h of electricity from a methane-air degassing system mixture. The potential for generating electricity from coalmine gas at the enterprises of PJSC DTEK Pavlohradvuhillia is presented graphically in Figure 4.

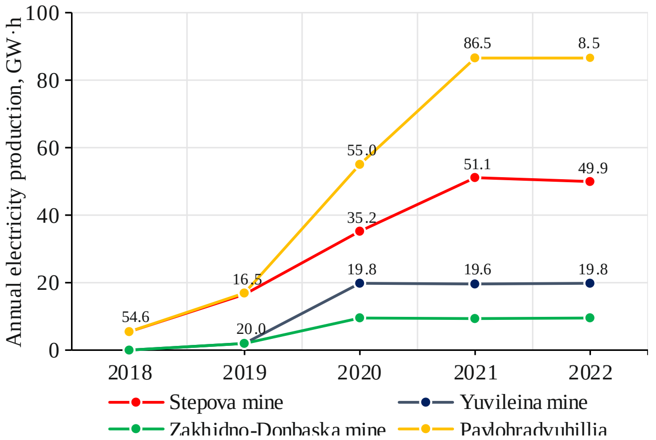

Figure 4. Annual volumes of electricity generation from gas-methane at the PJSC DTEK Pavlohradvuhillia mines

In addition, mines are a source of large water reserves. Only in the Western Donbass, about 30 million m^3 of groundwater is pumped out of the mines annually. These waters, due to existing purification and demineralization technologies, can be used not only to provide technical and drinking water to the mine complex, adjacent mining cities when organizing the appropriate infrastructure and production, but also in the future can be used for the operation of electrolyzers to produce "green" hydrogen. In this case, a complex of plants for producing electricity from sludge dumps, coalmine gas, utilization of low-potential energy of mine groundwaters, organized on the mine surface areas and combined with the generation of renewable energy sources (RES), will ensure the operation of electrolysis plants and a technological line for mine water demineralization. In this respect, mine water has an enormous potential for thermal energy production. Given the volumes of groundwater pumped out of the Western Donbass mines, the temperature of which during the year is +12...+18ºC, this is quite enough for the effective use of "water-to-water" heat pumps.

Figure 5 presents the indexes of technically achievable thermal energy utilization potential of the groundwaters of the Western Donbass mines, obtained from the results of a statistical analysis of the performance data on mine water-drainage installations and average annual temperature indexes of water pumped out of underground mine workings.

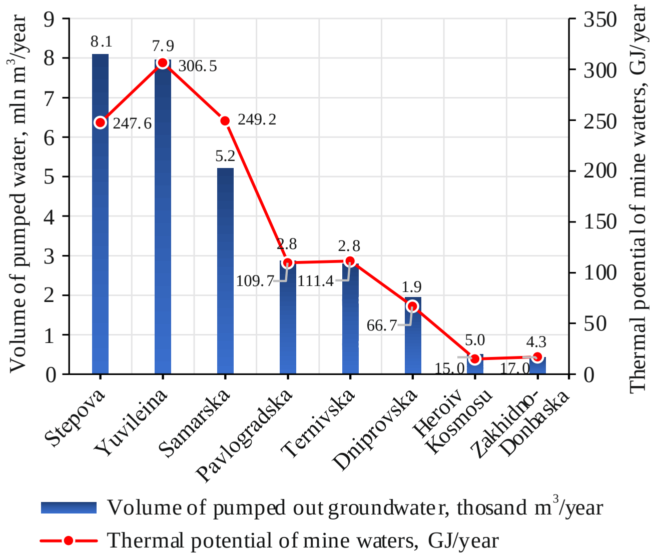

Figure 5. Thermal energy potential of mine water-drainage installations

The obtained data analysis shows that the total technically achievable potential of using groundwater thermal energy from the Western Donbass mines is 1.12 TJ/year or 311.9 MW·h/year, which is equivalent to the energy available from the burning about 80 million tons of coal (with coal thermal capacity of 4200 kcal). Thus, the analysis of coalmine resource assessment shows that the presence of various and valuable mineral resources in the PJSC DTEK Pavlohradvuhillia mines, involved in coal mining, stimulates the development and implementation of technological projects for the integrated use of mine groundwater, low-potential thermal energy, coalmine gas-methane, waste dumps, renewable energy sources based on the DTEK Energy company coal mines.

4.2. Laboratory studies of the chemical composition of mine water and thermal distillation products

The conducted analysis of the assessment of mineral raw material resources related to coal mining shows that the PJSC DTEK Pavlohradvuhillia mines pump out huge groundwater volumes daily – 82.9 thousand m^3/day. For comparison, the city of Pavlohrad with a population of 108.6 thousand people consumes 11.2 m^3/day. After desalination, mine water can become an alternative source of water consumption, indicating the need to build mine-based production complexes for their purification and use. As a result of the conducted laboratory studies and the sampled mine water analysis, the quality indexes of desalinated water and reverse osmosis concentrate are given in Table 1.

Analyzing the obtained water analysis results of the Zakhidno-Donbaska mine, it should be noted that the total mineralization is 29.4 g/l. There is an increased content of chlorides – 17.7 g/l, potassium – 1.4 g/l, calcium – 0.076 g/l, and magnesium – 0.07 g/l. According to technical indicators, mine water is hard 145 mg-eq/l. As a result of 50 liters of mine water desalination using a reverse osmosis system, 35 liters of clean drinking water and 15 liters of desalination waste have been obtained. From the reverse osmosis desalination waste after thermal distillation, 3.6 kg of dry residue of salt-containing chemical products have been obtained (Fig. 6).

Table 1. The analysis results of the sampled water from Zakhidno-Donbaska mine, the quality indexes of desalinated water and reverse osmosis concentrate

Index	Unit of measure	Water analysis performance			
		Mine water tank	Purified water tank	Standards of State Sanitary Rules and Regulations 2.2.4-171-10	Concentrate after reverse osmosis
Hydrogen index	pH	5.85	7.0	6.5-8.5	6.1
Turbidity	mg/l	16.4	0.1	≤7.0	0.9
Total hardness	mg-equ/l	146.0	1.2	≤7.0	123.0
Calcium	mg-equ/l	76.0	2.0	≤130	1343.0
Magnesium	mg-equ/l	70.0	2.0	≤80	681
Potassium	mg/l	1410.0	0.4	2-20	13
Chlorides	mg/l	17772.0	5.0	≤250	17620.0
Nitrites	mg/l	95.0	2.2	≤0.5	6.5
Sulphates	mg/l	250.0	2.0	≤250	80
Fluorides	mg/l	0.4	0.2	≤1.5	0.76
Aluminum	mg/l	0.249	0.05	≤0.1	0.04
Total iron	mg-equ/l	0.238	0.02	≤0.2	0.06
Total alkalinity	mg-equ/l	1.48	1.0	≤6.5	2.0
Dry residue	mg/l	29000.0	90	≤1000	34260.0
Total mineralization	mg/l	29420.0	90	≤1000	28600.0

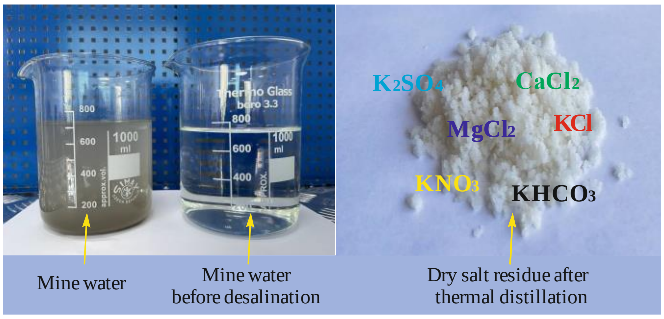

Figure 6. Mine water purification and desalination products

The dry residue released from mine water is examined by spectral analysis using Elvax laboratory equipment. The physical-chemical analysis results show that after thermal distillation of the concentrated brine, a precipitate is formed, represented by the main elements in the amount: NaCl – 63.75%; $CaCl_2$ – 14.12%; $MgCl_2$ – 11.13%; KCl – 6.98%; K_2SO_4 – 3.03%; KNO_3 – 0.52%; $KHCO_3$ – 0.47%.

In the form of a concentrated solution, the resulting salt mixture can be used as an anti-icing agent for road treatment, as well as for dust suppression at tailing dumps and ore/coal mining dumps, on public roads and street-road networks in open pits. However, the use of such a salt concentrate as an anti-icing agent is seasonal.

In the future, to separate the mixture, a technology for separating technical salts of NaCl, $CaCl_2$, $MgCl_2$ or other compounds separately can be developed. Such a separation will make it possible to obtain products that are widely consumed. For example, the listed dry salts can be used in the composition of anti-icing agents, dust suppression agents, agents for preventing coal and ore materials from freezing during transportation, as well as for thawing frozen ore materials and coal.

The main concentrate component, such as sodium chloride NaCl, can be extracted in the form of a crystalline product, which is widely used by utilities and industrial consumers. For example, as a component for boiler water treatment in heating systems or as part of anti-icing mixtures. Magnesium oxide MgO, which is consumed in significant volumes by manufacturers of refractory materials, can be extracted from the brine. Technologies for producing magnesium oxide from such salt mixtures are known, implemented on an industrial scale and are cost-effective. Calcium chloride $CaCl_2$ is widely used by industrial consumers in the form of solutions and a crystalline product. It is also used in the manufacture of high-strength, frost-resistant building materials and as part of cement slurries for geological exploration and the oil production industry.

From the calcium ions contained in the brine, insoluble compounds can be extracted, which are a commercial product. These are calcium sulphate $CaSO_4$ in the form of gypsum, chemically precipitated chalk $CaCO_3$, which is a valuable metallurgy reagent and is also used in construction. A sufficiently high content of potassium ions in brine allows obtaining valuable components for complex mineral fertilizers from them.

4.3. Development of a concept for complex mining of mineral raw material resources from coal mines using the example of the PJSC DTEK Pavlohradvuhillia mines with the transition to multi-product production

The main idea of the concept of operation of a coal mine-based industrial enterprise is the transition of business from single-product production to multi-product production due to the intensive development of complex mining operations with the maximum use of coal mining by-products. This approach corresponds to the development trends of coal mining enterprises in developing countries and Ukraine. The creation of multi-vector mine complexes capable of producing not only coal, electricity, heat, but also clean drinking water and associated mineral and raw material resources for various types of industry should become a guarantee of stable social-economic development. In addition, they should contribute to the transformation of coal-mining regions and single-industry cities, where new competitive economic clusters are emerging.

The model for complex mining of mineral and raw material resources from coal mines is shown in Figure 7.

The production facilities for complex mining and use of georesources include: mine complex; a cogeneration plant complex for the coalmine gas-methane utilization; a complex for the groundwater low-potential energy utilization; a sludge utilization complex with electricity generation; a complex of rock dump processing; mine water demineralization complex with desalination waste treatment.

Mine complex. The mining enterprise mines coal seams within the allocated mine field boundaries using the traditional underground method. The enterprise retains the existing level method of seams preparation with their mining along the strike or rise using a pillar mining system with long stoping faces and repeated use of mine workings that delineate the extraction panel. Coal mining and preparation of new coal reserves are conducted with complex-mechanized stoping faces using extracting and tunneling equipment of a new technical level, ensuring the most complete mining of minerals and their regulated quality. The coal produced from the mine during the deposit mining is sent to the beneficiation plant, and then to the final consumers for electricity and heat generation.

Cogeneration plant complex for the coalmine gas-methane utilization. The mining of coal seams is accompanied by the formation of a coal mining by-product, such as coalmine gas-methane. At the same time, the high natural gas content of the Western Donbass coal seams, which is in the range of 10-20 m^3/t of daily production, is a serious obstacle to improving the efficiency of mining production processes. In this regard, in order to improve the rational use of natural resources, the safety of their operation, in the conditions of high concentration of mining production and the intensity of gas release into mine workings, a set of measures is being taken at the mine to degas mine seams with subsequent utilization of coalmine gas-methane using the cogeneration plant equipment.

From mine, methane can be created gas hydrates by subjecting the methane to high-pressure and low-temperature conditions [57]-[61]. One way to create gas hydrates from mine methane is through a process called hydrate-based gas separation. In this process, the mine methane is first compressed and then cooled to the point where gas hydrates begin to form. The gas hydrates are then separated from the unreacted gas using a specialized separator. The separated gas can then be further purified and used as a fuel source. The creation of gas hydrates from mine methane has the potential to provide a significant source of energy while also reducing greenhouse gas emissions by capturing and storing CO_2. However, this technology is still in the experimental stage, and further research is needed to develop efficient and cost-effective methods for creating and recovering gas hydrates from mine methane.

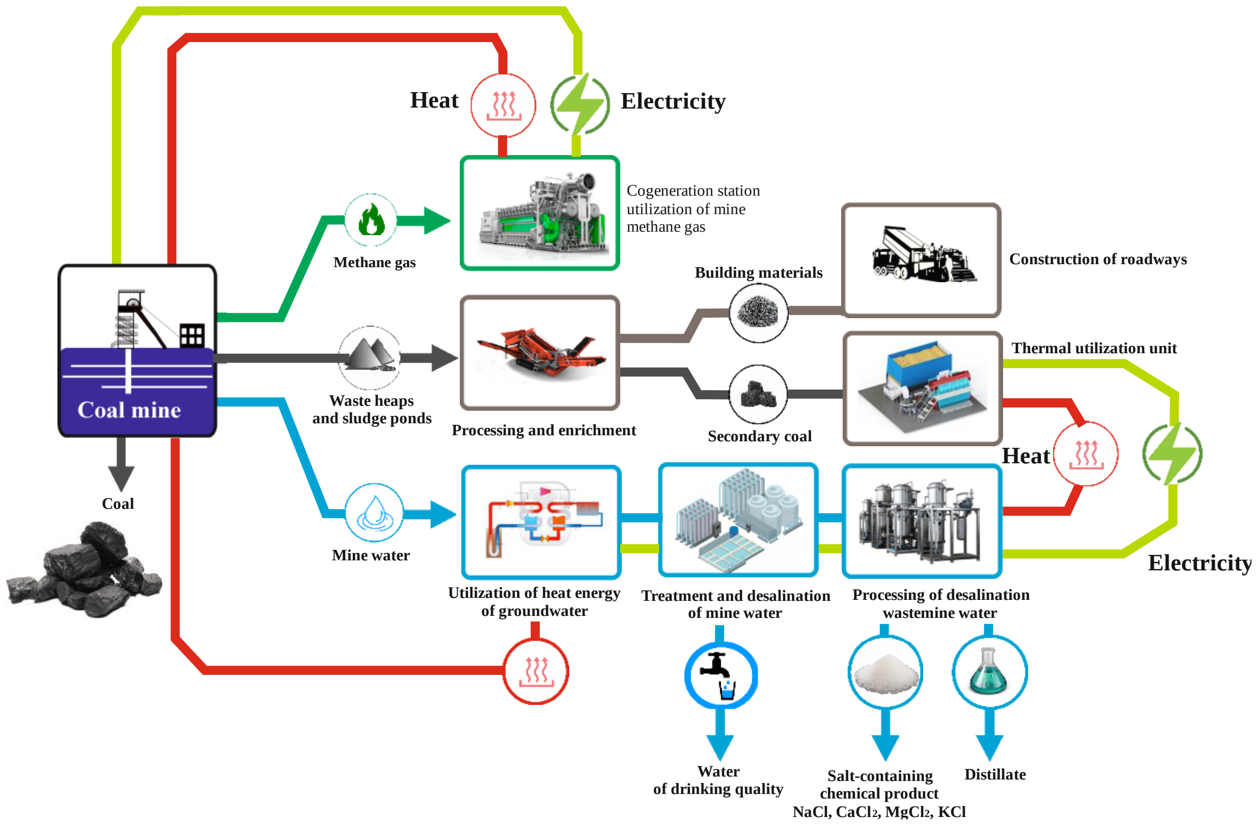

Figure 7. Model for complex mining of mineral and raw material resources from coal mines

At present, the DTEK Energy company has successfully implemented a project for the coalmine gas-methane utilization at the Stepova mine. Utilized mine gas-methane serves as an additional energy source to cover the thermal and electrical loads of the mine complex consumers. At the same time, the utilization of secondary industrial gases makes it possible to reduce greenhouse gas emissions and thus reduce the environmental burden in the mining region.

During mining the longwall faces, the degassing of extraction sites is performed by drilling degassing wells into the roof of the seams behind the stoping faces or with complex degassing using methods possible for these conditions. The methane-air mixture is captured using a modular degassing station connected to the mine workings using a main degassing well. The degassing well is built at the mine's industrial site and connected to a vacuum pumping unit. The gas-air mixture with coalmine methane is supplied from the vacuum-pump unit to the cogeneration plant through a gas pipeline with the arrangement of the energy source's own discharge pipeline.

On the mine's surface complex, a cogeneration plant is placed, which includes: container-type cogeneration plant based on a Caterpillar CG170-16 gas piston unit with an electric power of 1.6 MW; GTS 2000 gas preparation technological module; OPEKS MTP-GV2-8-378 modular heating unit for hot water supply with a thermal capacity of 378 kW.

To utilize the heat of the flue gas circuit and the engine jacket circuit of a cogeneration plant, it is planned to install a modular heating unit. The utilized cogeneration plant thermal energy is integrated into the mine's boiler thermal scheme for the operation of the calorifer network, heating of the mine's administrative and household complex, as well as for hot water supply. The electricity generated by the cogeneration plant is used to supply the company's own electricity consumers. When expanding the scale of gas-methane utilization at the mine, it is possible to sell excess electricity to the domestic energy market at a special tariff.

*Complex for the groundwater low-potential energy utilization***.** The concept of complex coal mining is also impossible without the utilization of mine water, which is an independent resource. Mine waters formed as a result of the opening of aquifers by underground mine workings in the course of stope and preparatory operations, as well as the penetration of surface water into the mined-out area, flow through drainage grooves into the water collectors of the local, and then to the main drainage facilities, which are located on the operating levels.

As a rule, the PJSC DTEK Pavlohradvuhillia mines use a multi-stage dewatering scheme, which consists of several main dewatering units, a series of local units, as well as pumps for pumping water from the sumps of the main and auxiliary shafts. The productivity of the latter depends on the production capacity of the enterprise, the number of operating stoping and preparatory faces, the high water content of coal-bearing rocks and other factors. From the mine, the pumped water is discharged through the auxiliary shaft through water-discharge wells, and then on the daylight surface through the pipes it enters the mine water storage tank connected by the bypass method, where there is a receiving heat exchange circuit of the heat pump with a primary heat carrier, which boils at the mine water temperature. From the heat pump, the heated secondary heat carrier enters the heat exchanger, where it heats cold water for the needs of the mine's hot water supply.

Complex of mine water desalination by reverse osmosis. After extracting low-potential energy, mine water is discharged into a horizontal sump for preliminary purification from suspended substances. Water intake for the desalination plant operation is conducted directly from the reservoir of the mine water sump. Based on the analysis of the source water and the requirements for the prepared water quality, a technological scheme is used for mine water desalination by reverse osmosis to obtain liquid products by distillation method (Fig. 8).

At the first stage, mine water is chlorinated. For this purpose, a sodium hypochlorite dosing station is set in front of the storage tank, which supplies reagents to the pipeline, thereby ensuring the mine water disinfection.

At the second stage, pre-disinfected mine water is pumped into the storage tank. Using supply pumps, water is pumped from the storage tank through coarse and preliminary purification filters to remove impurities present in it. At the beginning, mine water passes through mesh filters (coarse purification), where mechanical impurities with a particle size over 100 µm are removed. Then water is supplied through the pipeline system to a mixer, in which coagulant (chemical reagents for purifying water from suspensions) and substances for correcting the water acidity are added.

At the third stage, mine water is supplied to sand filters, where mechanical impurities with particle sizes smaller than 100 µm are removed. The water, disinfected and purified from mechanical impurities and suspensions, enters the storage tank.

At the fourth stage, mine water is pumped from storage tanks through granular activated carbon filters, where oil products and dissolved organics remaining in the water are removed.

At the fifth stage, pre-purified mine water is passed through a reverse osmosis filter system, where residual dissolved salts, organic compounds and microorganisms are removed.

At the sixth stage, the purified water is re-chlorinated and supplied into the storage tank of clean drinking water.

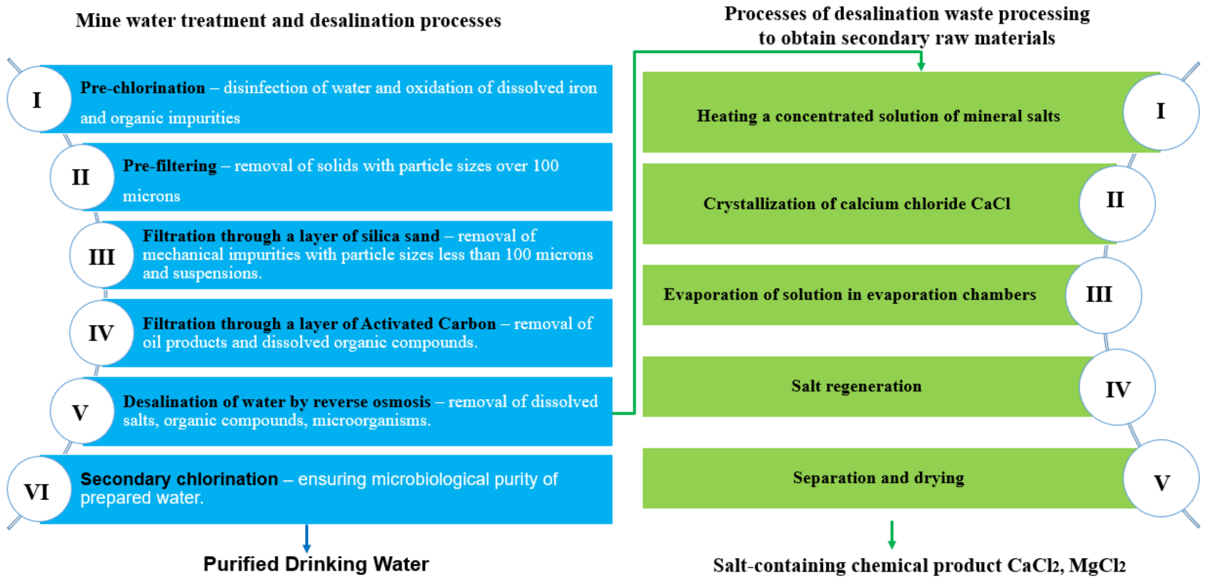

Figure 8. Technological scheme for mine water desalination by reverse osmosis with obtaining liquid products by distillation method

As a result of the reverse osmosis system operation, desalination waste is formed – concentrated solutions of mineral salts, which cause environmental problems when dumped into water bodies, reservoirs or on adjacent land areas.

Therefore, the resulting concentrated solution of mineral salts after reverse osmosis is supplied to the desalination waste treatment equipment for further extraction of chemical salt products by the thermal distillation method.

The main equipment of the desalination waste treatment plant includes: heater capacitor, regenerative brine heaters, salt crystallizer, supply pumps, adiabatic liquid evaporator, separator, centrifuge, and dryer. As a thermal energy source for the operation of evaporators, cheap thermal energy is used, which is taken from coal sludge thermal utilization plants that comply with environmental standards of European countries. The following desalination waste treatment scheme is used. In the capacitor housing, regenerative and main heater, the brine is heated to a temperature of 105-120°C and subsequently pumped through a salt crystallizer. Then, the brine passes through adiabatic evaporation chambers. In the last evaporation chamber, the vapor is cooled on capacitors and a pure distillate is formed, which is collected in a distilled water storage container. The resulting distillate is further used as the initial product for the "green" hydrogen production at electrolysis plants.

Returning to desalination waste treatment, the evaporated solution of salt-containing chemical products in a liquid state accumulates at the bottom of the evaporation chambers. Then, through the drainage drain holes, it is supplied to the regenerative condensers-heaters and the separator. Then it is subjected to conventional centrifugation and drying, packed in "big-bags" and sent to consumers or to a warehouse for storage.

The resulting salt product is a mixture of pure salts NaCl, $CaCl_2$, $MgCl_2$, KCl and other valuable microcomponents, which, in combination with their consumer properties, are in great demand on the market and are consumed in large volumes by public roads and public utility companies to prevent road icing in winter. Dry distillation residue is excellent for preventing dust from massive explosions in quarries in the form of a solution with water, as well as reducing dust from movement of heavy trucks on roads of quarries and surface transport sites of mines, beneficiation plants and mills. Thus, the concentrated brine treatment by thermal distillation method to produce a finished commercial product – a homogeneous mixture of pure salts and microcomponents, as well as distillate – fuel for the operation of hydrogen electrolyzers, at the same time not only solves the problem of desalination waste utilization, which is very important, as it prevents the consequences of direct discharge of highly mineralized brines into water bodies or land areas, but also creates prerequisites for the development of a modern innovative infrastructure for "green" hydrogen energy.

In the perspective of developing the concept of complex coal mining, the company is considering deep desalination waste treatment with the extraction of individual substances of calcium sulphate $CaSO_4$, sodium chlorides $NaCl$, calcium $CaCl_2$, magnesium $MgCl_2$, as well as a number of other valuable chemical substances. At present, there are a number of possible technologies for extracting the presented components and their subsequent reuse, which will increase the depth of reverse osmosis waste treatment and increase the technological complex profitability. The substances extracted from the dry residue are scarce products on the industrial market of food, medicine, cosmetics, paint and varnish, chemical, building materials industry, production of plastics and polymers.

A promising model of the infrastructure for complex mining facilities and the use of mineral raw material resources of a coal mine is presented in Figure 9.

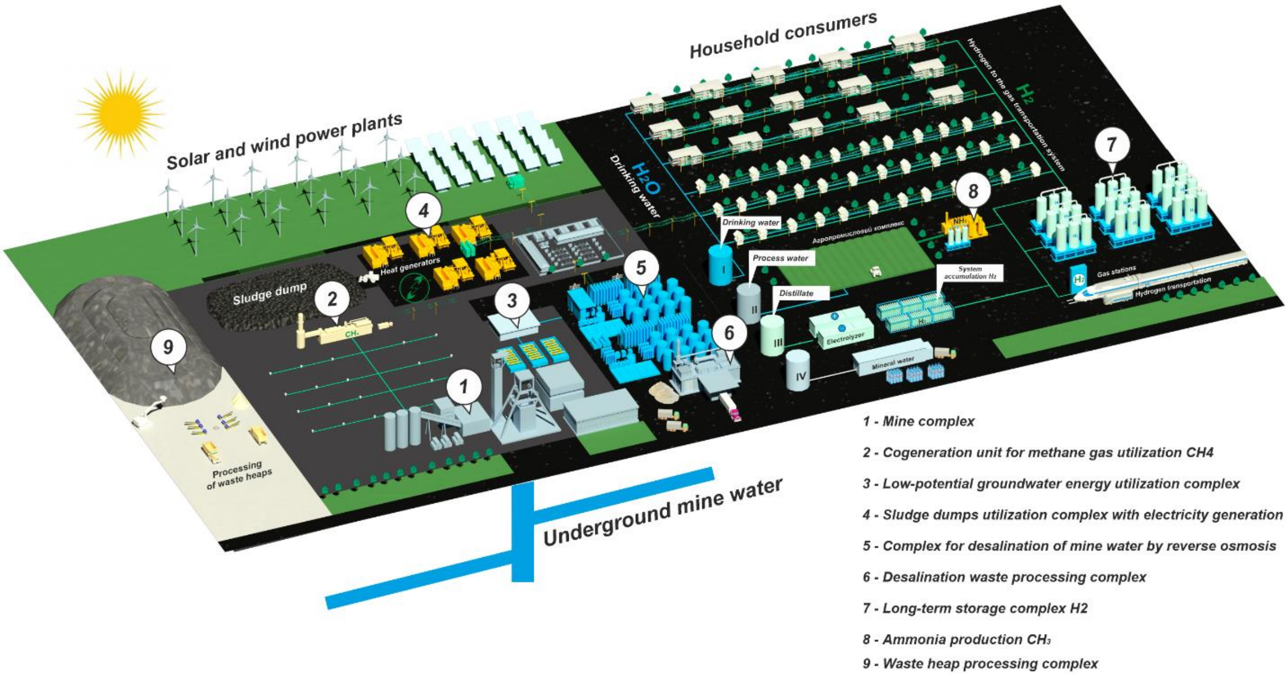

Figure 9. Promising model of the infrastructure for complex mining facilities and the use of mineral raw material resources of a coal mine

4.4. Technical and economic indicators of the pilot project for the construction of a waste-free technological complex for mine water desalination

Analysis of the results of physical-chemical parameters of mine water pumped from the PJSC DTEK Pavlohradvuhillia enterprises shows that the water of the Western Donbass mines has the highest mineralization, which is 26.4-33.9 g/dm^3. Dumping of demineralization products from such mine water will gradually lead to deterioration of the ecological state of the adjacent territory. In this regard, desalination of water with a higher mineralization makes it possible to utilize the maximum amount of salt-containing reverse osmosis chemical products, while protecting the natural environment. In particular, at the Zakhidno-Donbaska mine, the current tariff for the central drinking water supply from the city network is one of the highest among enterprises – 0.77 USD/m^3. In this regard, using the conditions of the Zakhidno-Donbaska mine as an example, we will conduct a study to determine the technical-economic indicators of a waste-free mine water desalination complex with the possibility of scaling it to other PJSC DTEK Pavlohradvuhillia coal enterprises.

As part of the project, it is planned to build an industrial mine water desalination plant at the Zakhidno-Donbaska mine, PJSC DTEK Pavlohradvuhillia. The key product is drinking water for the needs of the mine and dry residue from desalination waste for sale on the external market.

Total capacity of the waste-free technological complex for mine water desalination:

– the volume of drinking water production for own needs – 250 m^3/day;

– the volume of production of salt chemical products is 25.7 t/day.

At the first stage, based on the complex design capacity, capital investments are determined for the purchase of the necessary equipment for mine water desalination and reverse osmosis waste treatment, building materials and expenses associated with construction-installation, as well as starting-up and adjustment works.

On the territory of the Zakhidno-Donbaska mine surface complex, a site has been chosen for the construction of a building of a modular design to accommodate the equipment for the mine water desalination technological line, with the production and storage of dry chemical products. The total area occupied by the building is 180 m^2. After drying, the dry residue is supposed to be loaded into "big-bags", and then unloaded with a front-end loader and stored on the allotted area of this building. The warehouse area is calculated based on the fact that 25.7 tons of chemical products are produced per day and delivered to the consumer once every three days. Thus, the warehouse area should be designed for 80 tons. Based on detailed calculations, it has been determined that the total capital costs of the waste-free mine water desalination complex amount to 214.5 thousand USD (Table 2).

At the second stage, calculations of operating expenses are made before the start of the project implementation without indexation.

Table 2. Capital investments of a waste-free mine water desalination complex

Water purification and desalination equipment, ths. USD	113.00
equipment	50.75
building materials	35.00
construction-installation works	26.50
starting-up and adjustment works	0.75
Desalination waste treatment equipment, ths. USD	101.50
equipment	44.00
building materials	32.50
construction-installation works	24.50
starting-up and adjustment works	0.50
Total, ths. USD	214.50

Based on the capacity of the equipment complex for desalination and reverse osmosis waste treatment, the total annual electricity consumption is 276.4 MW·h/year. With the current electricity tariff, annual expenses will be 84.5 thousand USD. The total staff for service maintenance of the equipment complex for reverse osmosis desalination and waste treatment is 12 people, including 4 engineering-technical workers and 8 workers. Based on the performed calculations, the total annual operating expenses of the enterprise are 104.75 thousand USD (Table 3).

Table 3. Operating expenses of the waste-free mine water desalination complex, ths. USD/year

Service maintenance of the water purification and desalination equipment, ths. USD/year	54.50
salary	28.75
electricity	10.25
support materials	4.25
salary tax	6.25
unforeseen expenses	5.00
Service maintenance of the desalination waste treatment equipment, ths. USD/year	50.25
salary	28.75
electricity	7.25
support materials	3.00
salary tax	6.25
unforeseen expenses	4.25
Total, ths. USD/year	49.50

The resulting salt product of a mixture of pure salts is sold on the market at a price of 15 USD/t. At the same time, the set price is 20-25% lower than the market prices for this type of product. This gives greater competitive advantages to products in the presented segment of the consumer market and will further contribute to a stable plan for its implementation. The complex's annual production capacity reaches 9.22 million tons of the resulting salt product. Based on these provisions, the main technical-economic indicators of the waste-free technological complex for mine water desalination have been determined, which are given in Table 4.

Thus, the production costs for 1 m^3 of drinking water will be 0.59 USD/m^3, which is 0.18 USD/m^3 cheaper than the water supply tariff in the city of Ternivka. At the same time, the potential savings of the Zakhidno-Donbaska mine when switching to its own drinking water consumption from the desalination complex reaches 106 thousand USD/year. The payback period of the waste-free technological complex for mine water desalination will be about 2.2 years.

Table 4. Technical-economic indicators of the waste-free technological complex for mine water desalination at the Zakhidno-Donbaska mine

Indicator	Unit of measure	Value
Capital investments	ths. USD	214.50
Water purification and desalination equipment	ths. USD	113.00
Desalination waste treatment equipment	ths. USD	101.50
Amount of dry residue obtained	tons/year	9227.70
Selling price of dry residue	USD/t	15.00
Income from the sale of dry residue for 5 years (2024-2028)	ths. USD	104.25
Water consumption of the Zakhidno-Donbaska mine	m^3/day	250.00
Costs for drinking water purchase for 2024-2028 (potential savings)	ths. USD	52.90
Net present value (NPV)	ths. USD	154.70
Payback period (PBP)	years	2.22
Discounted payback period (DPBP)	years	3.38
Profitability index (PI)	index	1.74
Internal rate of return (IRR)	%	55.00

At the third stage of the research, a comparative analysis of economic indicators is performed when scaling the project to the conditions of the Ternivska mine, which is located within the city of Ternivka and is part of the same mine administration as the Zakhidno-Donbaska mine. The scaling concept provides for the mine water treatment not only for the needs of the mine's own drinking water supply, but also for the needs of the local population, taking into account the following tariffs: for the Ternivska Mine – 0.38 USD/m^3, for the population of the city of Ternivka – 0.92 USD/m^3.

As a result, the following technical-economic indicators have been obtained, which are summarized in Table 5.

Table 5. Technical-economic indicators of the pilot project for the construction of a waste-free technological complex for mine water desalination when scaling the project

Indicator	Unit of measure	Value
Drinking water volume produced for the needs of the Ternivska mine	m^3/day	290
Drinking water volume produced for the needs of the population	m^3/day	5000
Amount of dry residue obtained	tons/day	543
Drinking water production cost	USD/m^3	0.59
Dry residue production cost	USD/t	5.43
Total volume of mine water desalination	m^3/day	7521
Cost savings on the centralized water supply of the mine	ths.USD/year	40.95
Selling price of drinking water	USD/m^3	0.77
Income from the sale of drinking water to the population	ths.USD/year	1391.1
Income from the sale of dry residue	ths.USD/year	2924.0

Based on the PPI indices used by the DTEK Company, indicators of a change in the tariff for household and drinking water supply for the needs of the Zakhidno-Donbaska and Ternivska mines, the local population and production costs for mine water desalination are predicted, which is presented graphically in Figure 8.

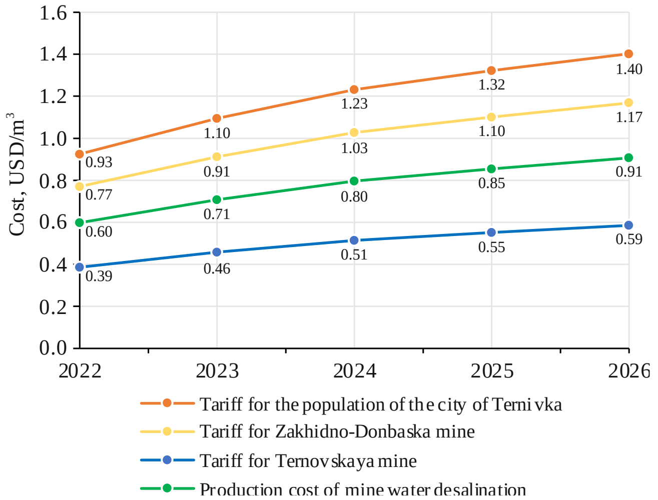

Figure 8. Predicted changes in the tariff for drinking water supply in relation to the production cost of mine water desalination

According to the data given in Figure 8, it follows that:

– the attractiveness of the project implementation for the needs of the population comes immediately, that is, from 2022, due to the production cost, which is 55% lower than the current tariff for water supply in the city of Ternivka;

– the attractiveness of the project implementation for the needs of the Ternivska mine is not achieved due to the production cost, which is 35% higher than the set tariff;

– the attractiveness of the project scaling occurs simultaneously, that is, from 2022, given that the specific impact of the production cost on population and mine tariffs is represented by a 20% decrease.

Thus, due to the mine water desalination, the project permanently solves the acute problem with the water supply of the Zakhidno-Donbaska mine. The project implementation is economically feasible, since it reduces the costs of paying for water and get additional profit from the sale of the dry residue from desalination. In addition, the project is environmentally attractive, as it reduces the volume of mine water discharge (by 357 m^3/day).

In the future, the project can be scaled up to improve the social-ecological situation in the region where DTEK operates and to supply water to mining regions.

5. Conclusions

The presented paper analyzes and assesses the prospects for complex mining of mineral raw material resources from the DTEK Company coal mines on the basis of the creation of a multi-business industrial production of drinking water, salt-containing desalination products, utilization of associated thermal energy from coalmine gas-methane, secondary coal from rock dumps and sludge reservoirs. The proposed set of technological solutions will ensure the sustainable development and diversification of production in coal-mining regions, as well as contribute to the creation of new high-tech jobs and ecological restoration of the territory, which is in line with the ESG strategy of the DTEK Company.

For the PJSC DTEK Pavlohradvuhillia coal enterprises, the technically achievable potential has been determined of mineral raw material resources related to coal mining for the possibility of their joint use for the needs of the mine complex. The technically achievable energy potential that can be obtained from the secondary coal of rock dumps and sludge reservoirs has been determined, which in total is 183.3 TJ. Based on the results of the available statistical information on the characteristics of the gas-air mixture of exhaust air jets, the annual thermal potential for methane gas utilization has been assessed, which in the total number of PJSC DTEK Pavlohradvuhillia mines reaches 7.1 PJ. The possibility of extracting up to 1.12 TJ/year of associated thermal energy from the water-drainage installation of mine complexes has been determined, which is equivalent to 311.9 MW·h/year of generated electricity.

The authors of the research have developed the concept of complex mining of mineral raw material resources and the operation of the mine complex as a profitable multi-product production. This concept takes into account the world experience in the use of resources related to coal mining, the study of existing conditions of exploitation of coal reserves, productive flows of associated resources, as well as the technological, economic and ecological aspects of mining activity. The developed concept makes it possible to create a basis for continuing the life cycle of coal mines with a gradual "soft" transition of production – thermal coal to alternative energy sources and mineral resources for the needs of high-tech business.

Using the conditions of the Zakhidno-Donbaska mine as an example, a research has been performed to determine the technical-economic indicators of a waste-free mine water desalination complex with the possibility of scaling it to other PJSC DTEK Pavlohradvuhillia coal enterprises. The waste-free technological scheme is designed to produce 250 m^3/day of drinking water and 25.7 tons of salt-containing desalination chemical products. It has been revealed that the production cost for 1 m^3 of drinking water is 0.59 USD/m^3, which is 22.5% cheaper than the set water supply tariff. The potential savings of the enterprise when switching to its own drinking water consumption from the desalination complex reaches 106 thousand USD/year. The payback period of the waste-free technological complex for mine water desalination is 2.2 years, which confirms the efficiency of extracting products from mine water, while providing favorable environmental and economic conditions for the operation of a coal mining enterprise and adjacent coal-mining cities.

The project complies with the DTEK Group's ESG program documents – the company's ESG strategy and environmental policy, as well as the UN sustainable development goal in the field of environmental protection, which the DTEK Group adheres to (Goals 12 and 13). Fundamental changes in the Group's business and culture envisage transformation into an environmentally friendly, efficient and technological business.

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Концепція комплексного видобутку мінерально-сировинних ресурсів із вугільних шахт ДТЕК на основі сталого розвитку та стратегії ESG

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Мета. Розробка концепції комплексного видобутку мінеральних ресурсів із вугільних шахт на прикладі шахт ДТЕК Павлоградвугілля з переходом на багатопродуктове виробництво чистої питної води, утилізації метану, вторинного вугілля із породних відвалів та шламосховищ, низько-потенційної енергії тепла підземних шахтних вод і супутніх сировинних ресурсів відходів опріснення.

Методика. В роботі використано комплексний підхід, який включає в себе аналіз та узагальнення наукових розробок у досліджуваній області, аналіз існуючого досвіду та наявних технологій комплексного вуглевидобутку, обробки статистичної інформації стосовно ресурсів продуктивних потоків вугільних шахт, лабораторні дослідження технології опріснення мінералізованих шахтних вод методом зворотного осмосу з термічною дистиляцією концентрованого розсолу відходів опріснення, проведення розгорнутого хімічного аналізу сухого залишку солевмісних хімічних продуктів зворотного осмосу на лабораторному обладнанні ElvaX.

Результати. В даній роботі представлені результати досліджень комплексного аналізу супутніх вуглевидобутку мінерально-сировинних ресурсів на можливість їх спільного використання для потреб шахтного комплексу. Визначено технічно досяжний енергетичний потенціал, який можливо отримати зі вторинного вугілля породних відвалів та шламонакопичувачів, що сумарно складає 183.3 ТДж. Оцінено річний тепловий потенціал утилізації газу метану, який у загальній кількості шахт ДТЕК Павлоградвугілля досягає 7.1 ПДж. Встановлено, що з водовідливних установок шахтних комплексів можливо відібрати до 1.12 ТДж/рік супутньої теплової енергії, що еквівалентно генерації електроенергії – 311.9 МВт·год/рік. Для умов шахти "Західно-Донбаська" авторами роботи розроблено технологічну схему процесу підготовки води методом зворотного осмосу, що забезпечує високе очищення та опріснення шахтної води з переробкою розсолу опріснення методом багатостадійного випаровування на адіабатичних випарниках, кристалізацією, сушінням та отриманням однорідного солепродукту – суміші чистих солей NaCl – 63.7%; CaCl2 – 14.1%, $MgCl_2$ – 11.1%, KCl – 6.9% та інших цінних мікрокомпонентів (4.2%).

Наукова новизна. Вперше комплексно проаналізовано супутні енергетичні потоки технології вуглевидобутку на можливість їх спільного використання для покриття потреб шахтного комплексу. Оцінено перспективи комплексного видобутку мінерально-сировинних ресурсів на базі адаптації виробничих об'єктів шахтного комплексу на багатопродуктове виробництво чистої питної води, утилізації газу метану, породних відвалів та шламосховищ, низько-потенційної енергії тепла підземних шахтних вод та вторинних сировинних ресурсів відходів опріснення.

Практична значимість. Запропонований комплекс технологічних рішень дозволить забезпечити сталий розвиток та диверсифікацію виробництва вуглевидобувних підприємств компанії ДТЕК Павлоградвугілля, а також ефективну трансформацію шахтарських міст у період переходу від монопродуктового виробництва до створення мультибізнесових виробничих комплексів, що відповідає принципам ESG. Створення багатопродуктових шахтних комплексів, здатних виробляти не тільки вугілля, але й тепло та супутні мінерально-сировинні ресурси, які є дефіцитними продуктами на ринку будівельних матеріалів, харчової, медичної та хімічної промисловості, має стати запорукою стабільного соціального та економічного розвитку вуглевидобувних регіонів. Підвищення рентабельності виробництва дозволить зберігати видобуток вугілля, що безумовно сприятиме енергетичній незалежності України, стабільності роботи об'єднаної енергосистеми, поступу на шляху Євроінтеграції та переходу на екологічно чисті технології виробництва.

Ключові слова: *шахта, мінеральні ресурси, вода, опріснення, шахтний газ, теплова енергія, породні відвали*