SECTION 3. DEVELOPMENT OF MINERALS

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3.1 Comprehensive analysis of the experience in recycling of coal mine dumps in the context of obtaining useful mineral resources

It is difficult to overestimate the role of the coal industry for Ukraine, since coal is currently an important source of energy, is used in metallurgy and the chemical industry, and ensures the country's energy independence. The coal industry creates jobs for hundreds of thousands of citizens, makes a significant contribution to the country's budget through the payment of taxes, and is one of the most dominant among other fuel industries [96, 97]. Before the invasion of russian troops on the territory of Ukraine, the coal-mining industry ranked fourth in Europe, which made it possible to obtain the status of one of the largest coal producers in the world. Experts estimate that Ukraine has 4% of the world's solid fuel reserves.

Despite the rapid development and significant potential of green energy, the level of its generation in our country remains low. According to International Energy Agency (IEA) [98], as of the beginning of 2022, hydro, solar, and wind power plants covered only 3.1% of the total domestic production level. Therefore, coal continues to be the main fossil fuel for electricity generation. Western Donbas has been and remains a strategic region for the coal industry, with mines mining thin coal seams, which in turn also has a number of environmental problems [99].

Underground and open-pit mining of coal deposits has a significant impact on the state of the natural environment, which is manifested by the release of rocks to the surface from mining operations, alienation of land for dumps, disturbance of the natural landscape of the earth's surface, pollution of atmospheric air and water bodies with by-products of coal mining [100, 101]. Waste rock dumps of mines are the main source of environmental pollution in coal-mining regions. They are associated with self-ignition of waste heaps and the emission of harmful gases/dust into the atmosphere of settlements, as well as water and soil pollution.

The problem of utilization of coal mine waste dumps can be solved by considering them as a source of valuable raw materials and energy. Each waste rock dump is unique in its composition and properties. To assess the possibility of their use, it is necessary to conduct a set of studies, collect and process information, and study the world experience in existing technologies for recycling waste rock-coal dumps. The problem of waste accumulation should be viewed not as a negative side factor of the coal-mining process, but as a possible prospect for the complete extraction of valuable components from the dumps. To date, leading countries have already implemented projects to manage waste rock dumps for their full utilization and restore the earth's surface to its natural state. In Ukraine, this issue is insufficiently studied, but all the prerequisites for the integrated and full utilization of dump waste rocks have already been created.

In order to solve the tasks set, in the course of the research, a comprehensive scientific-methodological approach is used, consisting in the analysis, systematization and generalization of information sources. The world experience in the management of coal-rock dumps and options for using the obtained products in various sectors of the national economy are presented. Possible options for extracting valuable components from coal mine dumps both in Ukraine and abroad are examined. The successfully implemented project for the construction of a processing plant directly at a coal dump in the United Kingdom is studied, which provides for a number of positive both economic and environmental aspects, allowing to form directions for utilization of accumulated coal waste.

The study [102] proposes options for using secondary resources for Ukrainian coal enterprises (Fig. 1). It has been found that in addition to extracting mineral elements from waste rocks, they can be used as an alternative fuel by briquetting. Briquettes are proposed to be produced using the method of extrusion vector impact. This technology makes it possible to produce fuel briquettes with specific electricity consumption for forming no more than 1.5 – 2.0 kW/ton.

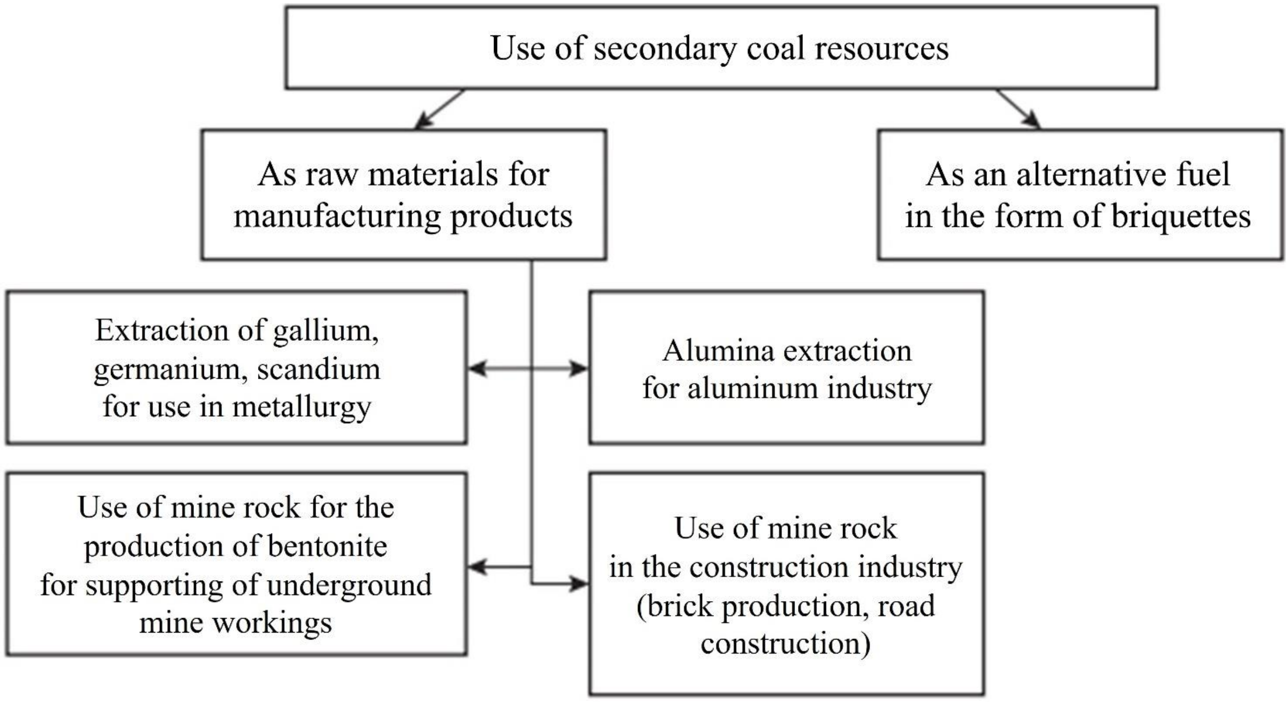

Figure 1. Possible options for using waste from coal enterprises

Coal briquettes produced in this way are proposed to be used as energy raw materials at power plants both for domestic consumers and for chemical, metallurgical and other industries.

M.I. Movchan and D.M. Akimov in their research [103] have found the suitability for the use of mine burnt rocks of the Lviv-Volyn coal basin in road construction. It is proposed to focus on the burnt rocks of coal mine heaps, which contain clay and coal shale with coal admixtures, carbonate and ferruginous minerals. It is these rocks that are recommended to be used for the production of highway pavements of IV and V categories and for intra-economic roads of III category.

A.H. Mnukhin and N.O. Mnukhina [104] propose technological schemes for complex recycling of dump waste rocks from mines to extract germanium, aluminum, rare-earth elements and iron-containing raw materials, the implementation of which may improve the environmental condition of coal-mining regions. The chemical composition of a number of coal mine waste dumps is analyzed in order to quantify the presence of mass fractions of oxides of various metals.

The authors [105] continued their research with the development of a magnetic separation method for extracting germanium from mining waste using an M-23 type electromagnet. A rock sample, taken from the Ilovaysk mine dump, serves as a feedstock, containing more than 20% of iron oxides in various compounds (according to chemical analysis data). The total mass of the material exposed to separation is 285 g, from which 41 g of iron-containing components are extracted. Further chemical analysis shows that the germanium content in iron-containing separated rocks is 5 g/ton.

The study [106] substantiates the resource value of burnt and unburnt dump waste rocks from coal mines, as well as the choice of directions for their use in the production of cementitious materials. The mineralogical composition of dump waste rock samples from coal mining is determined using X-ray diffraction analysis. Thus, it has been revealed that the rocks of the Olkhovatska Mine in Donetsk Oblast contain the following minerals: illite, quartz, brushite, hematite, and albite. Quartz, hematite, gypsum, clinochlore, and muscovite can be found in the unburned rocks of the dumps of the Sverdlov and Khmelnytska mines in Luhansk Oblast.

Grinchenko & Yushin in [107] propose to classify waste according to four main groups, which differ in the amount of accumulated materials, the degree of hazard, and the presence of valuable components in them. With regard to the mining industry, which is the basis of Ukraine's economy, it should be noted that the activities of coal enterprises generate two types of waste: overburden accumulated in dumps and sludge stored in tailings ponds.

As a typical example, the authors chose the Kryvyi Rih Iron-ore Basin of Ukraine, where 10 to 13 billion tons of overburden rocks have been accumulated in dumps. It has been determined that the dumps contain about 50 useful components that can be extracted and reused. The research proposes to consider the following types of technogenic deposits: iron ore tailings (500 million tons); manganese ore waste (150 million tons); alumina red sludge (1.2 – 1.3 million tons); titanium ore tailings; kaolin waste that can be processed into monazite concentrate (lanthanides and thorium).

Industrial experience in management of waste dumps was partially gained in Donetsk Oblast, the city of Snizhne. From 2005 to 2012, Coal Energy S.A. recycled the dump waste rocks, creating the Snizhne Processing Plant No. 1 with a capacity of 1.2 million tons of dump waste rocks per year. In 2012, Snizhne Plant No. 1 exhausted the resources of the dumps located next to it and was dismantled. Since its commissioning, the plant has processed four dumps with a volume of 2.6 million m^3 of coal-bearing rocks. The recycled rock was used to fill a 5.2-hectare abandoned quarry and to clear 18 hectares of land areas from waste heaps (Fig. 2).

(a) (b) (c)

Figure 2. Beneficiation plant for processing dump waste rock mass: (a) the stage of construction and installation of the plant equipment; (b) view of the constructed plant module; (c) recycled dump and closed quarry filled with waste rock

In 2012, a new Processing Plant Snizhne No. 2 was commissioned to manage waste rock dumps with an annual processing capacity of 1.4 million tons of dump waste rock. It was planned to manage 3 waste rock dumps with a total volume of 7.2 million tons of rock mass in the city of Snizhne and clear 45 hectares of land areas [108]. It is believed that coal extraction is economically profitable when the coal content is at least 5%, the coal ash content is not more than 15 – 20% and the sulfur content is not higher than 1.5% [109].

The results of research [110] show the possibility of recycling waste rocks from coal mines as an aggregate in the production of concrete. The rocks are pre-crushed to obtain different fractions of the material, and then used to produce concrete. The experimental research results have shown that the aggregate samples with lithological composition and alkaline-silica reaction indicators are fully compatible with natural aggregates and meet the requirements for the production of concretes.

In [111], the authors propose a possible approach to recover coal residues from the waste rock dump of the Jerada Coal Mine in Morocco and reuse the tailings for the production of environmentally friendly fired bricks. The process of manufacturing bricks includes several stages. The first stage is aimed at producing high-quality anthracite coal concentrate using crushing and froth flotation methods. Coal (organic matter) is recovered to increase the mechanical strength of bricks and reduce greenhouse gas emissions during the firing process. The second stage involves mixing the processed beneficiation tailings with a small amount of water, pressing and firing at an optimal temperature of 1020°C to produce environmentally friendly bricks. The separation of coal from the tailings improves the quality of fired bricks by increasing their bending strength, while reducing open porosity and water absorption.

Paper [112] proposes ways to implement the reuse and recycling of mining industry waste at the coal mines of Jincheng Anthracite Mining Group (Shanxi Province). The waste rock dumps of this enterprise have been turned into an artificial ecopark, fly ash is proposed to be used in construction materials, and water from coal mines is reused and recycled in closed pipelines.

High-carbon coal waste is proposed to be used for the production of construction materials and fillers [113]. Conducted research has shown that waste from the coal industry in Spain can be used as a filler in reinforced earth structures, road surfacing, and as a substrate for hydroponic crops (that is, when growing plants in artificial media without using soil). The obtained results made it possible to start the construction of 10000 m^2 greenhouse for growing tomatoes using the hydroponics method, where coal waste is used as a substrate. Moreover, the tests proved that the harvest can be obtained in the same quantities as that grown using traditional substrates (rock wool and perlite), which are much more expensive than coal waste.

Paper [114] presents the results of a comprehensive study of the physical-chemical properties of coal industry waste from the Lenger deposit (Kazakhstan). The research methods used are sieve, elemental, IR-spectral, microstructural, and X-ray diffraction analyses. The research results provide evidence that coal-mining waste is a valuable secondary raw material for the production of new materials that can be used in the chemical and construction industries. Based on the scanning electron microscopy data, it has been determined that the waste composition is dominated by carbon, silicon and iron. In addition, there are trace elements in the form of magnesium, sulfur and aluminum.

In [115], the authors examine the possibility of using coal mine waste in the construction industry. It is proposed to produce sintered dense blocks from coal-mining waste by first crushing the waste to a certain size and then heat treating it at 850°C. In order to improve the quality of the final product, various production conditions are considered, leading to complete removal of coal and complete sintering of the samples. They also prepare bricks for masonry the size of ordinary construction bricks. The samples obtained have a sintered shell approximately 2 mm thick and a carbon content in the central zone similar to that of construction materials. Bricks from waste have porosity, hardness and other properties similar to ordinary bricks.

In [116], the authors conducted research on the recycling of coal mine waste from northwestern Spain to produce pozzolanic materials for use in the cement industry. The thermal activation of coal waste, the formation of its hydrate phases, and their evolution through pozzolanic reactions 1, 7, and 28 days after activation have been analyzed.

Coal industry waste has shown high pozzolanic activity after heat treatment at 600 and 900°C for 2 hours. The complete destruction of kaolinite occurs after the samples are held in an oven at 600°C for 2 hours. This temperature and time are best for activation. The compounds arising from the pozzolanic reaction in coal industry wastes activated at 600 and 900°C in the $Ca(OH)_2$ system are stratlingite (C_2ASH_8), tetracalcium aluminate hydrate (C_4AH_{13}), layered double hydroxides, and monosulfoaluminate. When the temperature reaches 600°C, layered double hydroxides appear during the first 7 days of the reaction, while stratlingite is present as the main crystalline phase after 28 days of pozzolanic reaction.

In [117], the author has determined that the amount of coal in the waste of the Upper Silesian Coal Basin can reach 10% (ranging from 3 to 10%, assuming that the average coal content to be used is 5 – 7%). In this case, the volume of coal that can be mined from the Upper Silesian Coal Basin dumps is estimated at 45 million tons. The case of a coal-mining plant operating on a waste rock dump in Buków (Poland) is also discussed. (Fig. 3). The feasibility study on the example of this dump confirms the economic feasibility of coal extraction.

Figure 3. Coal plant in Buków (photo by Ł. Gawor)

Kien & Lanh in [118] examine the problem of reducing the amount of natural resources and shortage of raw materials for road construction, as well as the accumulation of huge volumes of coal industry waste (CIW) in the coal fields of the Quang Ninh coal-mining region (Vietnam). The conducted research has shown that coal waste can be used as a substitute for natural sand and Type II crushed stone in the construction of road surfaces in Vietnam, since its properties are almost identical to natural materials, which has been experimentally proven. Thus, coal industry waste aggregates have a good particle distribution, optimal moisture content, maximum dry density, and CBR (California Bearing Ratio) value in the range of 89 – 123%. The study also focuses on the need for preliminary recovery of heavy metals and hazardous compounds that may be present in the CIW before applying the resulting aggregates to the main road surface, base and lower layers.

The use of coal waste in the production of construction materials, cement, cement mixture and concrete blocks is proposed by Santos et al. [119]. Fine aggregates for paving stones are usually river sand or artificial sand obtained by crushing rocks. However, the author’s research has shown that it is possible to use waste from coal enterprises in the production of concrete paving stones.

The authors in [120], using the example of the United Kingdom’s coal-mining complex, examine the problem of coal mine waste accumulation and propose possible ways to solve it. The paper describes an example of successful project implementation by RecyCoal Ltd. that implemented an environmentally friendly scheme for coal extraction from a waste rock dump and reclamation of a 30-hectare land area.

Preliminary laboratory tests showed that the yield of pure coal from the dump was 10.5%, which became a reasonable value for its extraction. The extraction and washing-out of about 4.5 million tons of waste made it possible to obtain 475 thousand tons of marketable coal and restore the area occupied by the dump during a 3-year period. The project envisaged the creation of a mini-plant using a single-module unit for coal extraction (Fig. 4), operating 24 hours a day from Monday morning to Saturday morning. Downtime was used to perform scheduled maintenance tasks.

The final rehabilitation of the project site made it possible to restore the land occupied by the dump, which provided for the planting of 8.8 hectares of forests and shrubs with 22 thousand new trees, 2 km of planting along the highway, 7.2 hectares of dead wood and 7.6 hectares of agricultural land.

RecyCoal Ltd. company has also patented a technology based on the process of Natural Medium Dual Density (NMDD). The technology includes a washing machine that works together with cyclones as a purification stage. Most waste rock dumps contain large amounts of clay, shale and argillite. Therefore, separators are provided to extract a small portion of coal. Under these conditions, conventional processes in a dense medium are usually expensive and inefficient.

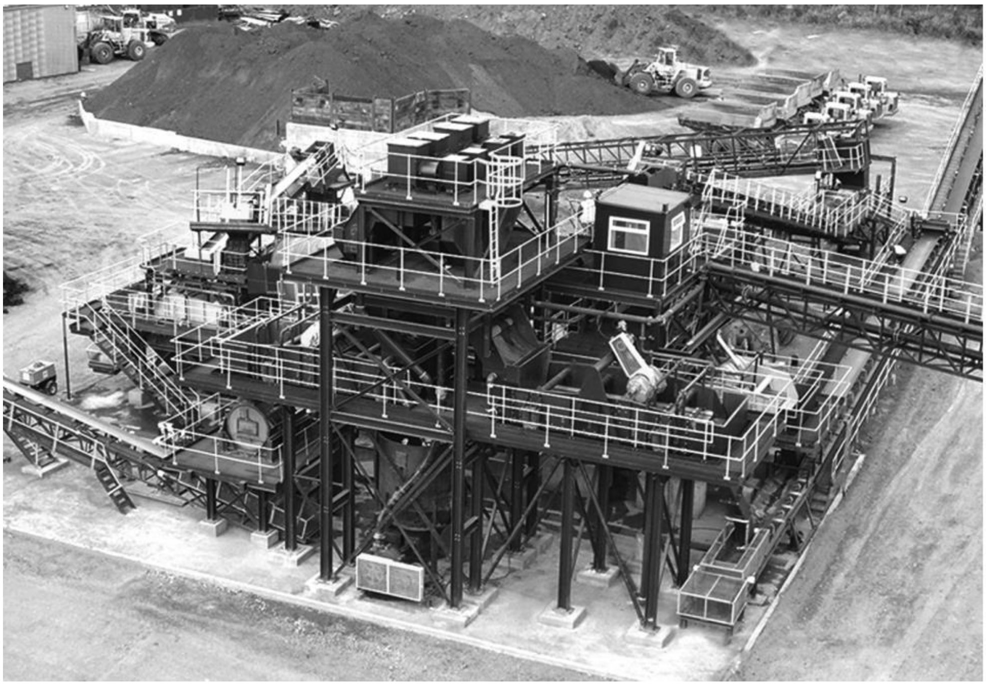

Figure 4. Processing Plant in Langton (Great Britain)

However, in the NMDD process, the specific gravity of the mineral material waste itself is quite sufficient to create a semi-stable aqueous suspension to separate the coal material as a controlled suspension medium (Fig. 5).

Paper [121] discusses the recovery of rare-earth elements and certain mineral concentrates from coal waste. Potential products that can be extracted from waste rock dumps also include various construction materials, such as road base, bricks and blocks, roofing materials, and agricultural materials such as soil additives and moisture-retaining granules. According to the authors, when assessing and selecting a coal waste management technology, key factors should be taken into account, including the location of the dump/mine, government policy, environmental impact, etc. Ways to utilize coal waste rock are shown in Figure 6.

Authors in [122] analyze and review possible methods to extract rare-earth elements (REEs) from coal, from by-products of its extraction, in particular from coal dumps. Researchers study existing and potentially possible ways of obtaining REEs during beneficiation of coal and its waste. In addition, hydrometallurgical leaching of REEs from dump waste rock is examined.

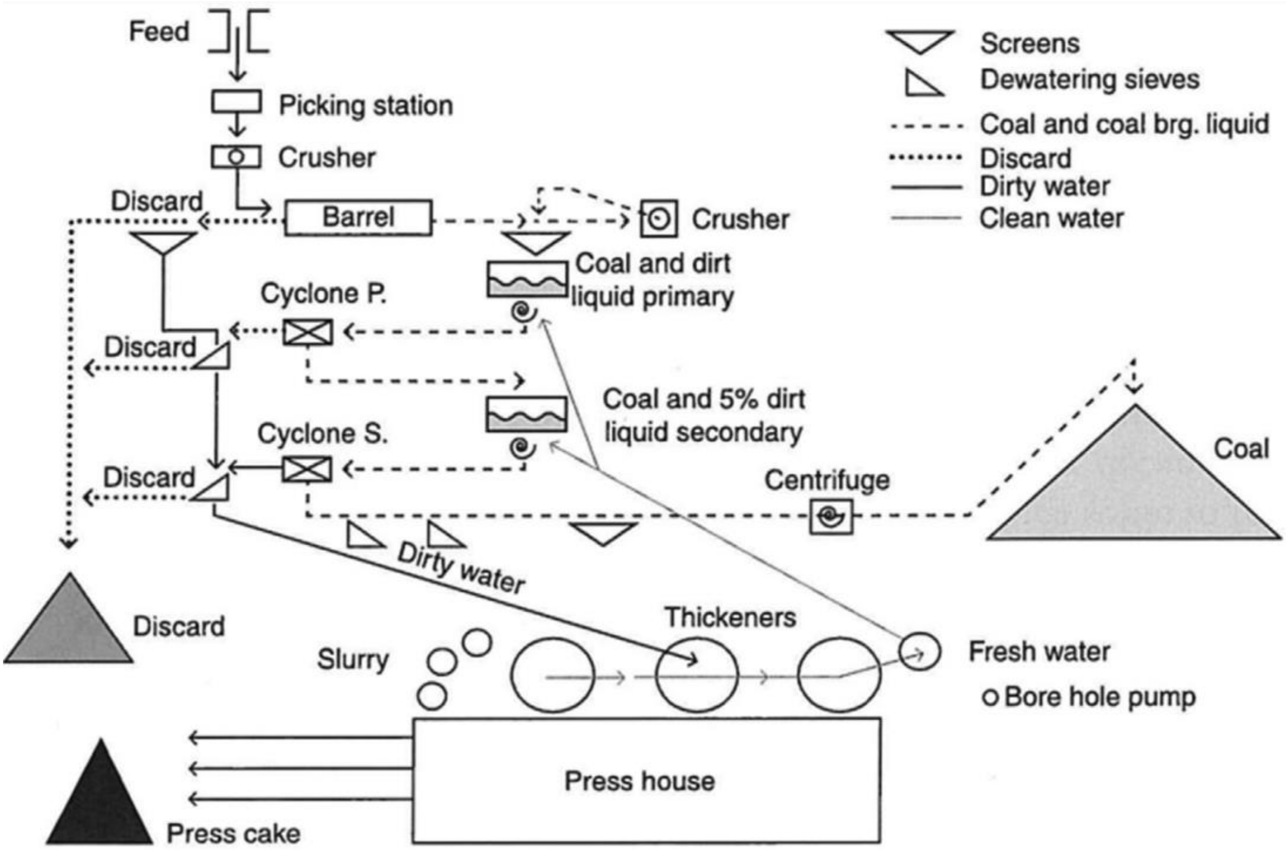

Figure 5. NMDD technology block diagram [121]

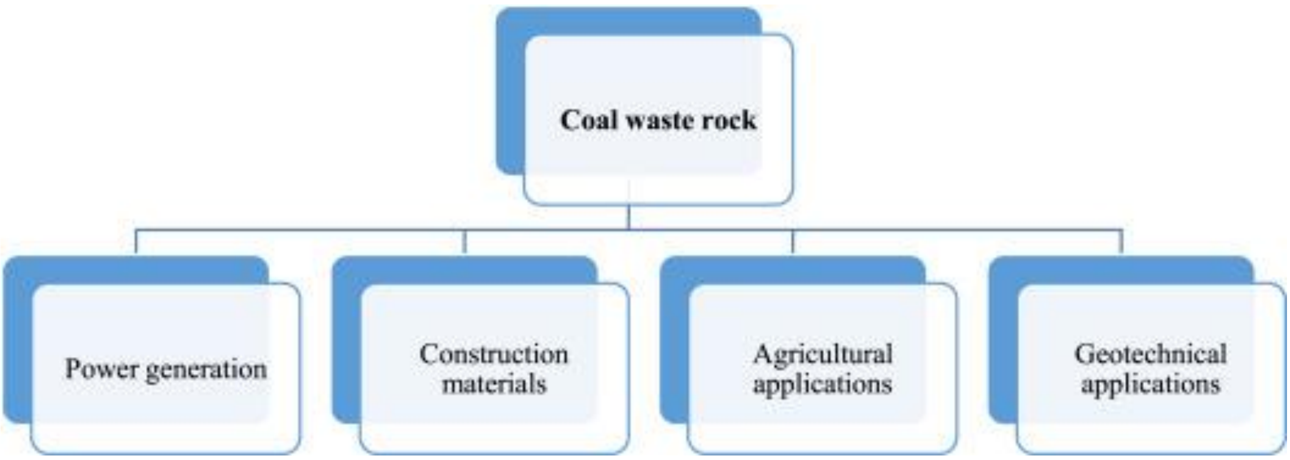

Figure 6. Ways of utilizing coal industry waste [121]

Paper [123] explores the possibility of extracting such elements as Ca, Cd, Co, Mg, Mn, Na, Ni, S, and Zn using the example of coal industry waste from the Douro deposit (Portugal). The geochemical composition of waste sampled from depths ranging from 3 to 15 m is analyzed. It has been found that the chemical composition of the studied samples is in good agreement with the results obtained in previous studies of the Douro coal deposit dumps.

In Ukraine, as of today, in Western Donbas, which is the main coal-mining region, the reserves of which are exploited by DTEK Pavlohradvuhillia, 9 waste rock dumps have been formed on the earth's surface as a result of underground coal mining activity of the following coal mines: Yuvileina (1), Stepova (2), Dniprovska (1), Zakhidno-Donbaska (1), Stashkova (1, the mine was closed in 2020), Ternivska (1), Samarska (1), Pershotravneva (1, the mine was closed). It is reasonable to consider these accumulations of waste rocks as a valuable source of mineral and raw material resources that should be industrially developed in the future.

Based on the study of the register of waste disposal sites in Dnipropetrovsk Oblast, which contains information on the parameters of accumulation sites, 9 waste rock dumps of Western Donbas mines have been graded by volume of accumulated rocks and the area occupied (Fig. 7). In addition, the location of all waste rock dumps can be identified using Google Earths, the general view of which is shown in Figure 8.

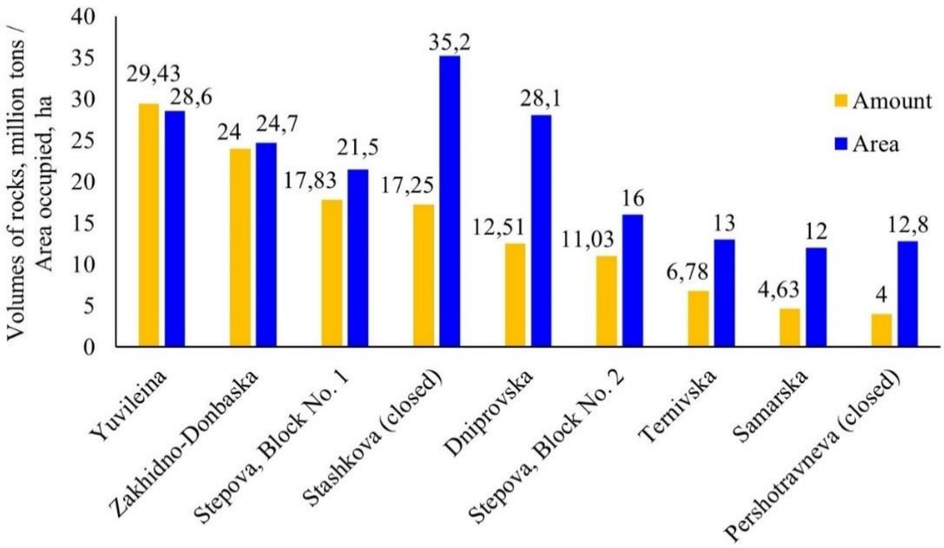

Figure 7. Gradation of waste rock dumps of coal mines in Western Donbas by volume of rocks and areas

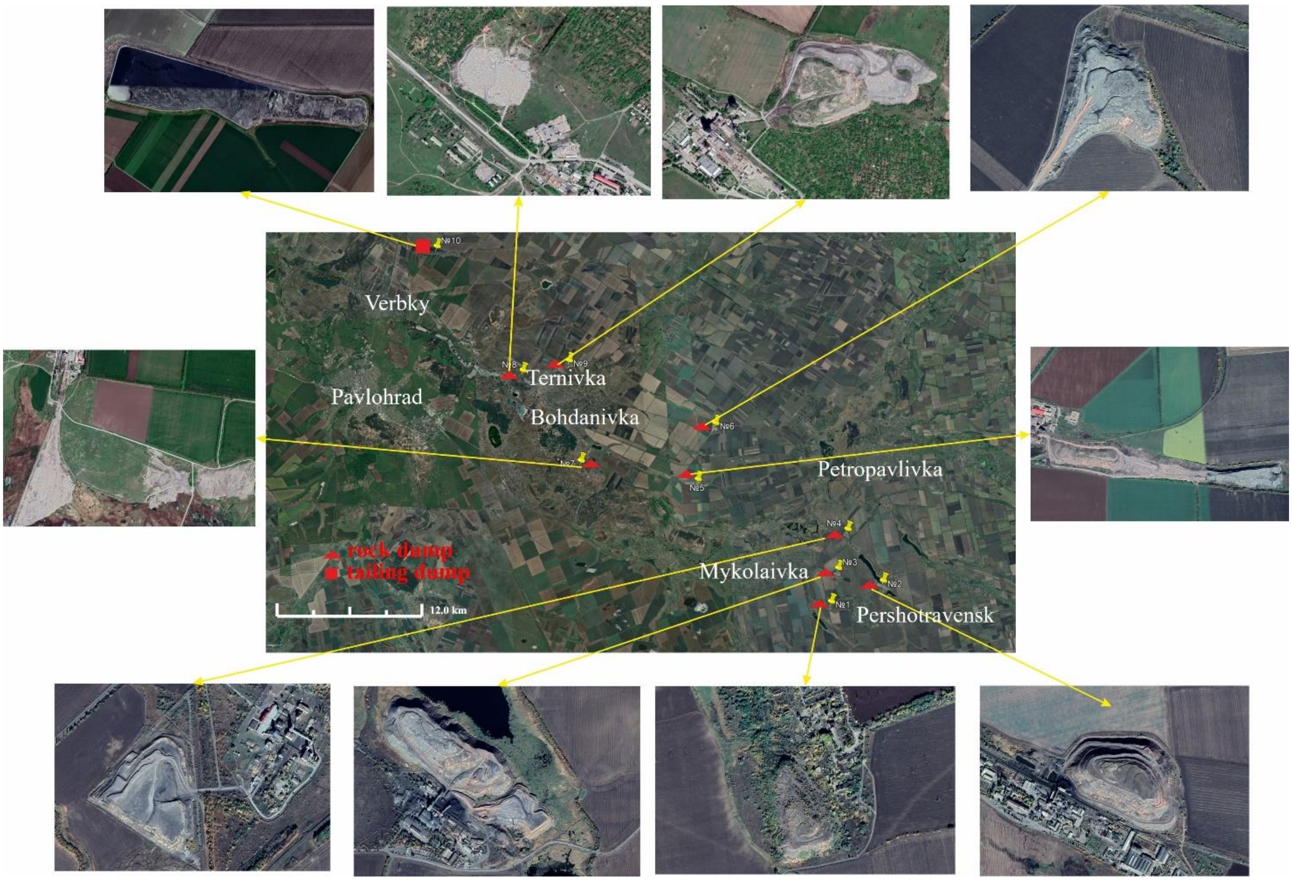

Figure 8. Overview map of main coal waste accumulations
of PJSC DTEK Pavlohradvuhillia

Other coal mines, such as Heroiiv Kosmosu, Blahodatna (closed in 2020) and Pavlohradska, do not have waste rock dumps, since the rock mass from the stoping and tunneling operations is combined into a single flow and supplied to the processing plant. Otherwise, mine waste rock is stockpiled at reclamation sites in the region. After beneficiation, large fractions are replenished to the dumps of other coal mines, while the fine fraction is transported to a tailings pond. In addition, mine waste rock, after being released to the surface, is immediately dumped at reclamation sites in the region (including advanced reclamation).

In Western Donbas, nearly 130 million tons of waste rock have been accumulated on the earth’s surface, covering an area of about 190 hectares. If to compare the occupied area of 190 hectares with an average area of 1 field in Ukraine for agricultural crops of 17.9 hectares, then 11 new fields could be created on the site of the waste rock dumps. Today, the annual volume of rock utilization ranges from approximately 30 to 40% and amounts to 2.5 – 3.0 million tons of waste rock. The main direction of utilization is the reclamation of the Samara River floodplain lands disturbed by mining operations and at the allocated advance reclamation site, where mine waste rock and beneficiation waste are stored. However, the annual volume of coal waste generated by mines in Western Donbas exceeds their utilization rate, which leads to a gradual accumulation of coal waste and the need to develop further programs.

The main mineral raw material component of the waste rock flow, which moves from the tunneling face to the earth's surface and is stockpiled into the waste rock dump, is represented by coal, argillite, siltstone and sandstone. Given that the rocks consist of argillite and siltstone, which are clay rocks, as well as sandstone, the content of sand and clay fractions in the dump rock mass is likely to be high, as they are also valuable construction components. These useful components are in great demand in the energy and construction industries today, and the design of technological lines for complex processing will make it possible to completely process these technogenic accumulations, return land areas and improve the environmental condition of mining regions.

In the context of the upcoming post-war reconstruction of the heavily damaged infrastructure of Donbas, the waste rock dumps of the PJSC DTEK Pavlohradvuhillia mines can become a significant source of the necessary mineral raw materials, since the waste rock dumps of the Donetsk region may be covered with mines.

From the above, it is obvious that the study and management of coal mine waste rock dumps is of interest not only from a mineralogical point of view, but also these studies are important in solving issues related to the use of coal-mining waste, which is a valuable secondary mineral raw material. Utilization of coal-mining waste helps to solve two crucial tasks at the same time: to use easily accessible and cheap mineral raw materials in production and to improve the environmental situation in the region by reducing the negative burden on the natural ecosystems of mining regions. This will in the future avoid many problems related to human health and environmental safety; minimize the social and economic consequences of the current situation; protect the environment and resources from the harmful effects of the coal-mining process. The conducted comprehensive analysis shows that coal mine waste can be used in different directions: in road construction, as concrete aggregates, to produce bricks, expanded clay and ceramic products, mineral fertilizers, as well as for extracting rare-earth metals and valuable coal fractions, etc. In the context of the post-war restoration of the Donetsk region infrastructure, the importance of the availability and industrial development of waste rock dumps in the coal-mining region of Western Donbas is emphasized.

The analyzed known researches on the recycling of dump waste rock from coal mines are usually characterized by the study of obtaining a certain valuable resource or several: extraction of coal concentrate, use of raw materials for the construction industry, road construction, or production of fertilizers for agriculture. However, there is a lack of research on the complete complex recycling of dump waste rock mass, obtaining a wide range of resources and complete clearing of the land area, which should be the focus of attention of scientists, industrialists and ecologists in the coming years.

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