Ecological-economic aspects of mining thin coal seams in the Western Donbas

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Abstract. The paper draws attention to the ecological-economic aspects of mining thin coal seams in the strategic coal-mining region of the Western Donbas and studies their causes and consequences in detail. It has been analyzed and determined that as a result of coal mining with complete caving of rocks, the processes of the earth’s surface subsidence above the minefields occur. Due to the proximity of groundwater to the surface, waterlogging of territories and a change in the landscape occur. Using analytical calculations, it has been determined that the total surface subsidence value above the mine field of one of the Western Donbas mines is 1.2 m, which, according to the monitoring of environmental authorities, correlates well with the range of subsidence values in the region of 0.7-1.4 m. The places and parameters of rock dumps accumulating on the earth’s surface in coal mines are identified and analyzed, and the sources of waste rock formations in the technological system of coal mines are also studied. It has been revealed that the largest ingress of all waste rocks to the surface is caused by the stope operations conducted with undercutting of bottom rocks – 39% and underground mining operations to prepare new coal reserves for extraction – 33%. To date, it has been found that the volumes of waste rocks generated in mines are 1.5 times higher than the volumes of their utilization, and the prospect of disturbed land reclamation is limited in time, which, with today’s mining technology, will lead to an increase in their accumulation again. Based on a comprehensive study of the mined coal seam structure with a complex texture, using the example of one of the mines, it has been revealed that in the formation of operational ash content, the friable roof caving amounts to 13.0%, the seam rock interlayers – 19.2%, the coal seam natural ash content – 12.8%, and the seam bottom rock undercutting – 55.0%. A close linear relationship has been determined between the value of bottom rock undercutting with a shearer based on collected mine data and the indicator of mined coal operational ash content, which confirms the greatest importance of this factor. It has been proved that the most important factor influencing the formation of the mined coal operational ash content is the undercutting of the seam bottom rocks by a shearer, and with a 2-fold decrease in the ash content of coal, its energy potential increases by 1.25 times. Possible scenarios for the coal mining development in the Western Donbas are considered and a rational direction for solving the leading ecological-economic problems of underground mining of thin coal seams is proposed.

Keywords: coal mine, surface subsidence, flooding, waste rock dump, operational ash content, accumulation of waste rocks

Екологічно-економічні аспекти розробки тонких вугільних пластів Західного Донбасу

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Анотація. У статті звертається увага на екологічні та економічні аспекти відпрацювання запасів тонких вугільних пластів у стратегічному вугледобувному районі Західного Донбасу, детально вивчаються їх причини та наслідки. Проаналізовано й встановлено, що внаслідок видобування вугілля з повним обваленням порід на земній поверхні над шахтними полями мають місце процеси її осідання та через близькість ґрунтових вод до поверхні відбувається заболочування територій й змінюється ландшафт. Визначено аналітичними розрахунками, що величина повного осідання поверхні над шахтним полем одиниці із шахт Західного Донбасу становить 1,2 м, що добрі корелює з діапазоном величин осідань у регіоні 0,7-1,4 м згідно моніторингу екологічними інстанціями. Ідентифіковано місця розташування та проаналізовано параметри накопичення на земній поверхні порідних відвалів вугільних шахт, вивчено джерела утворення шахтних пустих порід при функціонуванні конкретної вугільної шахти. Встановлено, що найбільше надходження всіх шахтних пустих порід на земну поверхню зумовлено веденням очисних робіт із прискіпленням очисними комбайнами порід підошви пласта – 39% та проведенням підземних гірничих виробок для підготовки нових запасів вугілля до виймання – 33%. З’ясовано, що на сьогодні обсяг утворення пустих порід на шахтах у 1,5 рази перевищує обсяг їхньої утилізації, а перспектива рекультивації порушених земель обмежена у часі, що, з урахуванням
Introduction

Despite the intensive development of green energy and decarbonization trends in the world’s leading countries (Shah, 2021; Debiagi et al., 2022; Svbodova et al., 2022), the thermal generation of electric energy based on coal combustion in Ukraine is essential, as its share is 35% (Statistical collection..., 2020). This is conditioned by the fact that hard coal is the main energy resource, the reserves of which, according to the International Energy Agency, in the bowels of Ukraine with 33.9 billion tons of coal (4% of world reserves) – 80% or 27.1 billion tons are concentrated in seams with a thickness less than 1.0 m. This is the lowest figure among coal deposits exploited in other coal-mining countries of the world (Coal Information, 2017; Cornot-Gandolphe, 2019). Every year, it becomes more and more expensive to mine coal of acceptable quality from thin coal due to the difficult mining-geological conditions of the coal seams occurrence.

Currently, coal seams with the law thickness can be mined using selective technology (Aykul et al., 2007; Petlovany, Malashkevych, & Sai, 2020), auger technology (Yuan, Chen, Zhang, & Wang, 2019; Sakhno, Sakhno, & Skyrda, 2022), underground gasification (Bazaluk et al., 2021; Saik & Berdnyk, 2022), as well as traditional technology of mining with fully-mechanized longwall faces (Khorolskyi, Hrinov, Mamaikin, & Demchenko, 2019; Shavarskyi et al., 2022). However, non-traditional technologies have not been used for several technical and economic reasons, and the mechanized mining method is now a priority in coal mines.

Coal mining is mainly concentrated in the Western Donbas, where 8 coal mines operate, ensuring 70% of all coal production in Ukraine (Kuz’menko, Pochepov, & Ryabychev, 2010; Barabash, Salieiev, & Symanovych, 2021), 95% of the reserves of which are concentrated in seams less than 1.0 m thick. During the intensive exploitation of the Western Donbas mines, productive reserves have been depleted under relatively favorable conditions, and to date, production performance has deteriorated significantly. Presently, thin coal seams with a geological thickness of 0.65-0.95 m and a weighted average value of 0.83 m are being mined in this area. The traditional technology used for mechanized mining of low-thickness coal seams does not provide for backfilling of the mined-out areas and is not suitable for mining coal only within the contour of the geological seam thickness. According to the technological peculiarities of the mining equipment used and the adopted safety standards, the extracting thickness of the coal seam 1.05 m is considered in the study (Petlovany et al., 2021). Due to the difference in the extracting and geological thickness, the shearer is forced to undercut the wall rocks of the coal seam, which, when considered as a whole, creates several ecological-economic problems.

The most important quality indicator of mined thermal coal is its operational ash content, determining the consumer and commodity price (Hindistan, Tercan, & Ünver, 2010; Petlovany, Ruskykh, & Zubko, 2019; Qi et al., 2020). Coal mined from the stopping face is contaminated with waste rocks from undercutting the seam bottom, which significantly degrades its quality and requires beneficiation processes at surface factories. Thus, over the past 50 years, in the mines operating in the Western Donbas, the operational ash content has increased from 23-25 to 50%. The modern coal market dictates increased requirements for the quality of commercial products, so the beneficiation costs are constantly growing due to the lack of effective solutions to reduce operational ash content.

As a result of the technological process of underground mining of low-thickness coal seams, the environment in the Western Donbas coal-mining region suffers ecological damage (Pactwa, Woźniak, & Dudek, 2020; Shang, et al., 2022): waste rock dumps accumulate on the daylight surface, requiring an increase in area, as well as surface subsidence phenomena occur, leading to flooding and waterlogging of territories.

This research aims to comprehensively study the ecological-economic problems of mining thin coal
seams in the Western Donbas using mine performance indicators and analytical information from a few sources, as well as to develop strategic solutions to reduce negative consequences for the environment and the population.

Methodological research approaches

This research uses a comprehensive scientific-methodological approach to the study of aspects and generalization of ecological-economic problems, including underground coal mining from thin coal seams:

– for the problem of the earth’s surface subsidence: the regional accounts and reports on the state of the natural environment in the Dnipropetrovsk region, the factual situation of mining operations in coal mines, and analytical calculations to predict the subsidence value, explaining the cause of these processes, are studied;

– for the problem of waste rock accumulation on the surface: the register of waste disposal sites in the Dnipropetrovsk region as of 2021, the peculiarities of dump placement according to the Google Earth program, and the general characteristics of rock dumps according to the collected mine data are studied and summarized. In order to comprehensively identify the sources of the waste rock outcrop on the Earth’s surface within the boundaries of a large coal mine, the following are studied: length of longwall faces; advance of stopping faces; geological seam thickness; extracting seam thickness; seam parent ash content; coal parent ash content; thickness of undercut bottom rocks; coal and rock density; friable roof thickness; caved roof rock density; mine working cross-sectional area; coal face area; advance of drifting faces; amount of bottom rock dinting. The research uses factual data on mining and the advance of stopping faces for the calendar year at the Heroiv Kosmosu mine;

– for the problem of mined coal quality: the structure of the mined coal seam of a complex texture, including the predicted thickness of friable roof caving; the thickness of pure coal bands; the natural ash content of coal and rocks; the thickness of rock interlayers; the extracting and geological thickness of the seam; the volume of undercut rocks, is studied comprehensively. The factual operational ash content of the mined coal for the month at 20 stopping faces of the Western Donbas mines in 2020 was analyzed to determine the mathematical dependence on the value of rock undercutting. The rock undercut value is determined based on the difference between the known extracting and geological thickness of the seams in the mines. To study the energy potential of mined coal with varying degrees of ash content, using the example of the C11 seam at the Heroiv Kosmosu mine, the coal combustion heat is determined, where its operational ash content varies at constant humidity.

Research results

The daylight surface subsidence.

A significant problem in the mining of all coal seam reserves is the Earth’s surface subsidence, which occurs as a result of the formation of shift troughs, especially when mining operations are conducted without backfilling the mined-out area (Kuzmenko & Petlovanyi, 2015; Imansakipova et al., 2021; Bai et al., 2021). In the Western Donbas, where 10 coal mines functioned until 2020 (today there are 8), the state of the Earth’s surface within the boundaries of their mine fields has deteriorated significantly. Surface subsidence processes are caused by caving of rocks (rock layers) directly above the mine workings and mined-out area, which leads to their discontinuity with the formation of intense fracturing zones. This zone extends deep into the mass towards the earth’s surface up to 50 m. The lithological varieties located above settle smoothly without mass discontinuity, forming surface subsidence troughs on the Earth’s surface.

The result of the Earth’s surface subsidence is the danger of destruction of industrial and civil infrastructure facilities located in the zone of displacement influence. There are also dangerous exogenous geological processes of technogenic character, such as flooding and subsequent waterlogging of territories. This leads to the violation of natural conditions, soil salinization, and a change in ecosystems atypical for the steppe area. A factor complicating flooding processes is the presence of the Samara River low floodplain within the boundaries of mine fields, where, as a result of undermining, there is a rise in the groundwater level, which has already come close to the Earth’s surface.

Thus, the area of the undermined territory within the mining allotments of the Western Donbas mines is 58.83 km², and the total area of the Earth’s surface subsidence is 47.11 km². The average subsidence depth ranges from 0.7 to 1.4 m. The area of subsidence in the built-up area within the Western Donbas mines is 6.78 km², with an average subsidence depth of 1.0 m (Information Yearbook…, 2017).

The ecological problems of underground mining of coal reserves are well illustrated by the example of the city of Ternivka and the village of Bohdanivka, which are surrounded by the mining operations at the Ternivska, Samarska, Zakhidno-Donbaska mines.
Figure 1 shows the Earth’s surface area undermined by the Samarska mine stope operations, where significant surface subsidence occurs.

There is a flood monitoring site near the village of Bohdanivka, where all changes in the daylight surface level in the region are recorded. As a result of the subsidence of undermined areas and the rise of the groundwater level, this led to waterlogging and the formation of a flooding zone of about 17.0 km². The depth of groundwater level in the flooded areas ranges from 1.1 to 3.0 m (Regional report..., 2022). During the observation period (2006-2020), the levels changed only depending on the amount of atmospheric precipitation and average monthly air temperatures. Compared to the previous year, there was an increase in levels by 0.15 m. Also, according to some data, the Earth’s surface subsidence in the Samara River floodplain reaches 7.5 m. Thus, within the area (Fig. 1), the surface elevations according to the Google Earth program are +60 m, and outside the specified area they are +67 m and higher.

The value of the Earth’s surface subsidence, as the coal seams are mined, can be predicted with a high degree of probability by the analytical expression (Hrebonkin & Yeramkov, 2002):

\[ \eta = 63 \frac{\sum m}{H} \times 10^3, \text{ mm,} \]

where:
- \( \eta \) – the value of maximum Earth’s surface subsidence when mining a suite of coal seams, mm;
- \( \sum m \) – the total thickness of coal seams in the suite, m;
- \( H \) – maximum depth of mining, m.

For the surveyed minefield area (Fig. 1) of the Ternivska mine, the reserves of 4 coal seams have been mined to a greater extent, the total thickness of which averages 4.9 m, and the final mining depth has reached 265 m. According to the analytical expression, the total subsidence value is 1.2 m, which correlates well with the range of the Earth’s surface subsidence values in the region of 0.7-1.4 m. Similar negative processes of subsidence and flooding also tend to occur when mining the minefield reserves at other Western Donbas coal mines. These are areas of such settlements as Pavlohrad, Verbky, Petropavlivka, and Pershotravensk.

The noted ecological problems are acute and important for the region, requiring urgent measures from the government, since the gradual closure of mines, and the cessation of water drainage can lead to an intensification of the subsidence trough and flooding of a large area, which can have disastrous social-economic and environmental consequences.

**Waste rock accumulation on the Earth’s surface**

One of the major problems of underground coal mining is the formation of rock dumps on the earth’s surface, which occupy valuable land areas and pollute the environment. In addition, mining enterprises annually pay an environmental tax to the state for placing waste on the Earth’s surface.

As of 2021, in the Western Donbas, as a result of underground coal mining, 9 rock dumps of PJSC «DTEK Pavlohradvyhullia» coal mines were identified on the Earth’s surface. These are Yuvileina mine...
(1 pc), Stepova mine (2 pcs), Dniprovskaya mine (1 pc), Zakhidno-Donbaska mine (1 pc), Stashkova mine (1 pc, the mine was closed in 2020), Ternivska mine (1 pc), Samarska mine (1 pc), Pershotravneva mine (1 pc., the mine was closed). At other coal mines, such as Heroiv Kosmosu mine, Blahodatna mine (closed in 2020), and Pavlohradskaya mine, there are no rock dumps, since the rock mass from the stopping and drifting operations is mixed into a single flow and supplied to the beneficiation plant. Otherwise, the waste rocks from the mines are stockpiled in land reclamation sites of the region.

Based on the register study of the waste disposal sites in the Dnipropetrovsk region (Register of waste disposal sites..., 2022), which contains information on the parameters of accumulation sites, 9 rock dumps of Western Donbas mines are ranked by number of accumulated rocks and area occupied (Fig. 2a). In addition, all rock dumps are identified using the Google Earth program, a general view of which is shown in Figure 2b. Figure 2 analysis shows that almost 130 million tons of waste rocks have been accumulated on the Earth’s surface in the region, occupying an area of about 190 hectares. If to compare 190 hectares of the occupied with an average area of 1 field in Ukraine for agricultural crops of 17.9 hectares, then 11 new agricultural fields could be created on the site of waste dumps.

It is of scientific and practical interest to study the rock formation sources on the Earth’s surface during the technological processes of coal mining. This is because the analysis of the conditions for the waste rock formation during underground mining makes it possible to develop directions for technical solutions aimed at eliminating the ingress of rocks to the Earth’s surface or a significant reduction in their amount.

A comprehensive analysis of the waste rock flows in the technological system of a coal mine using the example of the Heroiv Kosmosu mine, the most productive in the region, makes it possible to identify the sources of their formation and quantify their impact on the accumulation of rocks on the daylight surface, which is presented in Figure 3.

It has been determined by detailed calculations that for a calendar year, with a mine performance of 2.5 million tons, 1.3 million tons of waste rocks have been brought to the Earth’s surface as part of the rock mass. It has been revealed (Fig. 3) that the largest flow of all waste rocks to the surface is caused by the stope operations conducted with the undercutting of bottom rocks – 39% and underground mining to prepare new coal reserves for extraction – 33%. This indicates that to solve the problem of achieving low-waste coal mining technology, it is necessary first of all to improve and modernize the technological schemes of stopping and drifting operations with the placement of waste rocks in underground cavities, thereby utilizing a significant amount of waste rocks. The presence of waste rocks in the composition of the mined coal forms its operational ash content, which can be sharply reduced by separating the rocks from the coal and placing them in the mined-out area.

About 7.0 million tons of coal waste is annually generated on the Earth’s surface as a result of the oper-
Fig. 3. Sources of waste rock flow from the underground space of the mine to the Earth’s surface

...ation of 10 coal mines. At the same time, an average of 2500-3000 thousand tons/year is used for reclamation operations, which is 30-40% (Vernigora, 2019). The prospect of the need for land reclamation in the region is estimated at no more than 10 years, which, with today’s mining technology, will again lead to an increase in waste rock accumulation. Thus, current problems of waste rock accumulation in the Western Donbas are obvious and relevant, and the volume of their formation significantly exceeds the volume of their use.

**Mined coal quality**

One of the most important problems in the mining of thin and very thin seams, especially in the Western Donbas mines, is ensuring high-quality coal, the main indicator of which is its operational ash content (Sun, Liu, Zheng, & Chou, 2010; Stupnik et al., 2015; Yu, Gai, & Liu, 2021). The low-mined coal quality not only increases the operating costs of coal enterprises but also has an influence on the technical-economic performance of heat and electricity production plants, reducing the efficiency of using the energy potential of coal and increasing the cost of electricity generation.

In mined coal, ash content is usually called the percentage of non-combustible residue after combustion, which means all waste rocks. Operational ash content refers to all waste rocks that have fallen into coal during the implementation of technological mining processes, including the natural ash content of the coal seam itself. At some Western Donbas mines, the operational ash content indicator has reached more than 50%.

Therefore, an important aspect is the prediction and study of the reasons for the operational ash content formation in the process of coal mining to search for ways of improving its quality and energy value. To study the operational ash content and draw up a calculation scheme, it is proposed to comprehensively consider the structure of coal seam mining, which is presented in Figure 4. The structure of mining a coal seam with a complex texture is considered in the example of the Heroiv Kosmosu mine, where the coal reserves of the 1186 longwall face extraction pillar through the C_{11} seam were mined.

<table>
<thead>
<tr>
<th>Seam structure</th>
<th>$m$, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof caving</td>
<td>Mudstone</td>
</tr>
<tr>
<td>Extracting thickness</td>
<td>Geological seam thickness</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Bottom undercutting</td>
<td>Mudstone</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
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</tbody>
</table>

Fig. 4. Structure of the extracting thickness of the seam with a complex structure (on the example of the C_{11} seam, 1186 longwall face)

It can be seen from Figure 4 that the operational ash content value of the mined coal will be influenced by the following constituent elements: the friable roof rock caving, the seam rock interlayers, the natural ash content of the coal seam, and the seam bottom rock undercutting. Analytical calculations of individual elements of the operational ash content formation have been performed using the example of mining the 1186 longwall face extraction pillar (Table 1). In fact, 493.7 thousand tons of coal with an operational ash content of 46.8% has been mined from the extraction pillar.

Analysis of data in Table 1 shows that in the operational ash content formation, the friable roof caving is 13.0%, the seam rock interlayers – 19.2%, the coal seam natural ash content – 12.8%, and the seam bottom undercutting – 55.0%. Thus, it has been proved that the necessity of undercutting bottom rocks with a shearer when mining a coal seam is the most influ-
encing factor on operational ash content formation. Having analyzed the factual operational ash content of the mined coal for the month at 20 stopping faces in the Western Donbas mines in 2020, the value of rock undercutting has been determined by the difference between the extracting and geological thickness of the seams in mines.

Analysis in Figure 5 shows that there is a close correlative linear relationship \( y = 101.41 x + 18.83 \) between the values of operational ash content and the rock undercutting. An approximation coefficient of 0.94 indicates a high degree of the rock undercutting value influence on the final operational ash content formation, despite the different characteristics of the structure and quality of coal seams mined by 20 stopping faces.

Such elements of operational ash content as seam rock interlayers, seam natural ash content, geological seam thickness, the presence of a friable roof are uncontrollable and depend on the natural conditions of their coal seam formation (Chabukdhara & Singh, 2016; Young, Walton, & Holley, 2019; Aghababaei, Saeedi, & Jalalifar, 2020; Petlovanyi, 2016; Sakhno, Liashok, Sakhno, & Isaienkov, 2022; Kuzmenko et al., 2023). However, the rock undercutting value depends on the mining technology used. According to technological parameters and safety requirements, the mechanized complexes used in the Western Donbas mines are not intended for mining thin coal seams 0.7-0.9 m without undercutting the host rocks. The extracting seam thickness used in the mines ranges from 1.02 to 1.2 m, depending on the mining-geological conditions and the stope equipment used.

The value of rock undercutting can be considered as a controllable parameter, which depends on technological factors. For a fundamental solution to the problem of the conditions of the Western Donbas mines, it is expedient to use technologies that allow mining a coal seam to its full geological thickness or selectively mining it, separating the mined coal from the waste rocks of undercutting.

In the Western Donbas mines, the mined coal with a high ash content of 35-50% is supplied to the Pavlohrad concentrating factory. In the Ukrainian heat coal market, coal with an ash content of 23% is considered commercial coal. However, quality coal in the ash content range of 21-30% can also be sold with the use of price premiums or quality discounts. Therefore, the task of the concentrating factory is to reduce the ash content. Waste rocks separated from coal are moved to waste disposal sites: large fractions – to rock dumps, fine fraction – to tailings, leading also to additional rock accumulation on the Earth’s surface. The beneficiation cycle is also a very costly process, accounting for up to 15% of the total cost of commercial coal production.

<table>
<thead>
<tr>
<th>Ash content element</th>
<th>Thickness, m</th>
<th>Ash content, %</th>
<th>Long-wall face length, m</th>
<th>Pillar length, m</th>
<th>Density, t/m³</th>
<th>Rock mass output, thou. tons</th>
<th>Waste rocks, thou. tons</th>
<th>Operational ash content, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friable roof caving</td>
<td>0.05</td>
<td>93.0</td>
<td></td>
<td></td>
<td>2.32</td>
<td>493.7</td>
<td>30.59</td>
<td>6.11</td>
</tr>
<tr>
<td>Seam rock interlayers</td>
<td>0.08</td>
<td>90.0</td>
<td></td>
<td></td>
<td>2.20</td>
<td></td>
<td>45.83</td>
<td>8.98</td>
</tr>
<tr>
<td>Coal seam</td>
<td>0.76</td>
<td>11.0</td>
<td></td>
<td></td>
<td>1.26</td>
<td></td>
<td>30.29</td>
<td>5.97</td>
</tr>
<tr>
<td>Bottom rock undercutting</td>
<td>0.21</td>
<td>93.0</td>
<td></td>
<td></td>
<td>2.32</td>
<td></td>
<td>129.60</td>
<td>25.69</td>
</tr>
<tr>
<td>In total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>46.75</td>
</tr>
</tbody>
</table>

Fig. 5. Influence of rock undercutting value on the indicator of mined coal operational ash content
the case of coal production by mines with ash content of 15-25%, the need for an energy fuel beneficiation cycle is eliminated, while it becomes possible to directly supply coal products to consumers.

However, the energy potential of commercial coal with an ash content ranging from 15 to 25% varies significantly. In this case, it is necessary to determine the mined coal energy value by energy thermal equivalent. Given the specifics of exploiting the reserves, based on the available information on the composition and characteristics of coal and coal-bearing rocks for the conditions of mining the C11 coal seam at the Heroiiv Kosmosu mine, an assessment of the specific heat of the rock mass combustion in a wide range of ash content has been performed (Fig. 6). Data analysis in Figure 6 shows that the combustion heat of 1 kg of pure coal with an ash content of 15% is 24.5 MJ, and with an ash content of 30% – 19.7 MJ, which is 1.25 times less.

The analytical calculations performed show that the transformation of the existing coal mining technology, aimed at a significant reduction in ash content, is very relevant, as it increases the energy potential of coal and its market value, and reduces the costs by eliminating the need for a beneficiation cycle.

Solutions

The accumulated ecological-economic problems resulting from the functioning of the Western Donbas mines require a prompt solution, which should be aimed at preventing the development of negative processes leading to landscape degradation. The analytical research on the aspects of the problems arising in the mining of thin coal seams shows that their sources are cavities formed in the bowels, the waste rocks brought from the mine to the Earth’s surface, and low thickness. It is these constituent elements that lead to the problems of subsidence, waterlogging, and accumulation of a coal waste complex on the Earth’s surface.

The further integration of Ukraine into the European Union will be characterized by the gradual implementation of new directives and regulations in various spheres of society, in particular, environmental protection. The Directive 2006/21/EC «On the management of waste from the mining industry» provides for the development of mechanisms and a plan for the waste management from mining operations (Directive 2006/21/EU, 2011). Given the significant waste generation in the mining of mineral resources, the state should stimulate the use of new «green technologies» for mining minerals, thereby ensuring the minimization of waste generation and maintaining a competitive level of quality of commercial products.

It is obvious that in the Western Donbas conditions, the traditional mining technology used requires transformation to a progressive technology for mining high-quality thermal coal with maximum waste rock accumulation in the underground mined-out area (Gupta & Paul, 2015; Luan, Jiang, Lin, & Wang, 2017; Wang et al., 2022). At the same time, achieving the maximum waste rock accumulation by creating a mass for backfilling, and not just leaving them, allows the technology to be environmentally universal (Kononenko, Petlovanyi, & Zubko, 2015; Zhang et al., 2019; Smoliński et al., 2022).

It is rational to study several possible scenarios for the development of coal mining in the Western Donbas, among which positive, neutral, and negative can be distinguished (Table 2). An analysis of the peculiarities of possible scenarios for the coal mining development (Table 2) shows that under a positive scenario, which is to develop and implement a new progressive technology for coal mining from 0.55-1.0 m seams with complete waste rock accumulation in the mined-out area, the solution of the leading ecological-economic problems in underground mining of thin coal seams in the Western Donbas is achieved.
Table 2. Description of possible scenarios for the development of coal mining in the Western Donbas

<table>
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<th>Scenario for coal mining development in the region</th>
<th>Essence of the scenario</th>
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| Positive                                         | Development and implementation of advanced technology for coal mining from 0.55-1.0 m seams with complete waste rock accumulation in the mined-out area | - involvement of new coal reserves in 0.55-0.7 m seams;  
- increase in lifetime of mines;  
- improving the quality and energy value of coal;  
- elimination of the beneficiation cycle;  
- decrease or cessation of rock accumulation on the Earth’s surface;  
- minimization of the Earth’s surface subsidence;  
- improvement of ecological situation. | - time to create and perform industrial testing of new technologies;  
- the need to change the organization of mining operations;  
- increasing complexity of technological processes;  
- decrease in the level of the rock mass output. |
| Neutral                                           | Continuation of functioning of the existing coal mining technology for 0.7-1.0 m seams | - no need for investment and time expenditures in the development of new mining technologies;  
- maintaining an acceptable level of the rock mass output;  
- lack of complexity of technological processes. | - continuation of the Earth’s surface subsidence processes;  
- cost for beneficiation processes;  
- accumulation of rocks on the surface from drifting and beneficiation;  
- costs for underground and surface transport. |
| Negative                                          | Mining of coal reserves from 0.9-1.0 m seams using existing mining technology with minimal undercutting of bottom rocks | - improving the quality and energy value of coal;  
- elimination of the beneficiation cycle;  
- reducing the beneficiation waste accumulation on the Earth’s surface. | - accumulation of rocks from drifting operations;  
- significant coal losses in the bowels;  
- a sharp decrease in the lifetime of mines with their subsequent closure;  
- depressive social-economic situation in the region. |

Recently, the first steps have been taken in creating a waste-free technology for mining high-quality coal (Malashkevych, Petlovanyi, Sai, & Zubko, 2022). The concept of a new efficient non-waste technology consists in the selective principle of coal mining, where the processes of drifting operations for preparing the reserves from new extraction pillars are closely combined with adjacent stope operations through an innovative rock-transport and rock-backfill chain. The last one can place all formed mine waste rocks in the mined-out area of longwall faces and gotten mine workings, thereby forming a dense backfill mass. According to preliminary calculations, it is possible to utilize 80-92% of the formed waste rocks, as well as to mine coal with an ash content of 15-17%.

The introduction of such technology would enable the Western Donbas mines to stop the ingress of rocks to the Earth’s surface, eliminate the beneficiation cycle, cease the accumulation of beneficiation tailings, and reduce environmental payments. Previously accumulated rock dumps should be considered as sources of a valuable mineral and raw-material base – mining of various types of minerals and the use of rocks in road and civil construction.

Conclusions

In the presented research, the ecological-economic problems of mining thin coal seams in the Western Donbas have been studied and possible strategic solutions have been developed to reduce the negative consequences for the environment and the population. Among the main findings of the research are the following:

1. As a result of underground coal mining in the Western Donbas, the area of the territory where the Earth’s surface subsidence is noted has reached 47 km², while the average depth of subsidence
2. In the Western Donbas, underground coal mining has led to the formation on the Earth’s surface of 9 rock dumps of coal mines, in which almost 130 million tons of waste rocks have accumulated, occupying an area of 190 hectares, with an average area of 1 field for growing agricultural crops of 17.9 hectares. It has been determined that the largest flow of all waste rocks to the surface is caused by the stope operations conducted with the undercutting of bottom rocks – 39% and underground mining operations to prepare new coal reserves for extraction – 33%.

3. It has been proved that among several factors, the necessity of undercutting bottom rocks with a shearer, when mining a coal seam, is the most influencing factor on the operational ash content formation between which there is a close linear relationship. Using the example of mining coal reserves in the extraction pillar of one of the mines producing high-ash coal, it is shown that in the formation of operational ash content, the friable roof caving amounts to 13.0%, the seam rock interlayers – 19.2%, the coal seam natural ash content – 12.8%, and the seam bottom undercutting – 55.0%. It has been determined that the combustion heat of 1 kg of pure coal increases by 1.25 times with a 2-fold decrease in ash content.

4. An analysis of the peculiarities of possible scenarios for the coal mining development has evidenced that under a positive scenario, which is to develop and implement a new progressive technology for coal mining from 0.55-1.0 m seams with complete waste rock accumulation in the mined-out area, the solution to the leading ecological-economic problems of underground mining of thin coal seams in the Western Donbas is achieved.

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References


