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POSSIBILITIES OF COMPREHENSIVE PROCESSING OF ASH AND SLAG WASTE FROM THERMAL POWER PLANTS OF UKRAINE AS A CONDITION FOR THE IMPLEMENTATION OF THE TRANSITION TO A CIRCULAR ECONOMY

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Abstract. Simultaneously with the generation of energy at thermal power plants (TPPs) and combined heat and power plants (CHPPs), as a result of the combustion of solid fuel, ash and slag waste (ASW) is generated, which is produced in large quantities and poses a serious environmental hazard. At the same time, the waste accumulated over many years has a huge resource potential, a unique mineral composition, a complex distribution of useful components, which is not typical for natural deposits, representing, in fact, man-made deposits. It is necessary to use the experience of industrially developed countries in the maximum extraction of secondary resources and their use in industrial production instead of natural mineral raw materials. Integrated use of waste is a condition for the implementation of the transition to a circular economy. An analysis of previous studies of the properties of slags and fly ash, the possibility of extracting useful components from them is performed. The main directions for reducing the amount of waste and eliminating storage facilities are established. The possibility and feasibility of complex processing of ASW was revealed using the example of improving the technology and equipment of the Chernihiv and Darnytsia CHPPs. The properties of daily ash collected under the electrostatic precipitators of the Chernihiv and Darnytsia CHPPs were studied. The size classes with the highest carbon content and the possibilities of its extraction were determined. The range of changes in the amount of carbon in the slag was studied and the obtained results were analyzed. The possibility of separating the finest classes containing clay and dust particles by boundary size of 0.02 mm and extracting various useful components from the ash was established using a vibratory impact screen. The carbon obtained from the ash can be used for combustion at TPPs and CHPPs. The magnetic concentrate extracted in the form of powder can be used for metallurgy, production of ferrosilicon, cast iron and steel. To obtain an aluminosilicate product, such a dry processing method as electrostatic separation can be used. Complex processing of ash is advantageous from both an economic and environmental point of view. It will reduce the amount of waste sent to storage facilities, reduce the territories that are alienated for them and become unsuitable for living. Thermal power plants will be able to earn money on this. According to experts, ash processing can provide an increase in the profitability of enterprises by 10–20%. This approach will solve a set of social, economic and environmental problems, significantly save natural resources and reduce the deficit of various materials.

Keywords: power plants, coal combustion products, waste, ash, slag, processing, classification, extraction, secondary raw materials

1. Introduction

Over the last decade, the consumption of electricity and heat produced by fuel and energy complex enterprises has increased in Ukraine. Simultaneously with the generation of energy at TPPs and CHPPs, as a result of the combustion of solid fuel, ash and slag waste (in foreign literature, coal combustion products - CCPs) are formed, which are produced in large quantities and pose a serious environmental hazard [1–18].

There are 39 TPP ASW storage facilities in Ukraine. They contain about 360 million tons of ash and slag on an area of over 3,170 hectares. The existing storage facilities are constantly being replenished (about 8–10 million tons are accumulated annually) [1–6]. For example, a power plant with a capacity of one million kilowatts burns about 10,000 tons of coal per day, producing 1,000 tons of slag and ash (with an ash content of 10% on average). About one hectare of land is required to dispose of such an amount of waste. For example, according to reports, about 500 thousand tons of ash and slag are generated annually on the territory of the Ladyzhyn TPP

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(Vinnitsa region). Currently, the storage facility contains 30 million tons of ASW on an area of 120 hectares [1, 2].

As of 2021, twelve thermal power plants in the territory controlled by Ukraine produced 9.56 million tons of waste, including 7.64 million tons of ash and 1.53 million tons of slag. The distribution of ash and slag was 84:16 (%) [1–6, 9, 10].

Storage of ASW is a significant environmental and economic problem, since existing storage facilities are overloaded, have large areas and require significant operating costs, which affect the increase in the cost of electricity production (up to 25–30%) [9, 10]. Storage facilities are potentially dangerous sources of environmental pollution and create risks for the health of the population living in adjacent areas [1–15]. A detailed assessment of the impact of waste on the environment and improving the level of environmental safety are considered in [16–18].

At the same time, ASW accumulated over many years has a huge resource potential, a unique mineral composition, a complex distribution of useful components, which is not typical for natural deposits, and is, in fact, a man-made deposit [11, 12]. Therefore, the processing of ASW from coal TPP is a pressing problem, the solution of which will reduce operating costs for the maintenance of storage facilities, obtain new types of products, and reduce the impact on the environment [9–18].

In industrially developed countries such as the European Union (EU), the USA, etc., the utilization of ASW is an integral part of the technological process of coal thermal power plants, which involves the involvement of various types of waste in new technological cycles or their use for other useful purposes. Much attention is paid to this problem, which is the most important link in the overall chain of creating waste-free production systems [19–21].

In the conditions of the energy crisis and environmental problems related to the pollution of territories, Ukraine, taking into account its desire to join the EU, should use the experience of industrially developed countries:

– on changing waste management systems;

– comprehensive processing of ASW;

– focusing on the maximum extraction of secondary resources and their use in industrial production instead of natural mineral raw materials;

– on the transition to the conditions of a circular economy.

Comprehensive use of energy complex waste is an urgent need not only for Ukraine, but for any economically developed country.

2. Methods

The following methods were used in this study: analytical review of literature sources, comparative analysis; experimental studies; study of the composition of fly ash, granulometric analysis, as well as the possibilities and prospects of its use. The granulometric composition of ash was determined using DST 12536-2014 by the mass content of particles of different sizes, expressed as a percentage of the mass of the dry sample taken for analysis. The residue on the sieve was weighed on an electronic scale with an error of ±0.05 g. Information resources of the Internet were used in the analysis of the state of the issue.

The aim of the work is to study the possibilities of complex processing of ash and slag waste from thermal power plants of Ukraine as a condition for the implementation of the transition to a circular economy.

Research object: processing of ash and slag waste from TPPs and CHPPs.

To achieve the set goal, the following tasks were solved:

– previous studies of the properties of slag and fly ash and the possibility of extracting useful components from them were analyze;

– the possibilities and problems of the integrated use of ASW of TPPs of Ukraine was established;

– the feasibility of integrated processing of ASW using the example of various improvements in the technology and equipment of the Chernihiv and Darnytsia CHPPs was identified;

– the properties of daily ash collected under the electrostatic precipitators of the Chernihiv and Darnytsia CHPPs was studied;

– the range of changes in the amount of carbon in slag and ash of the Chernihiv and Darnytsia CHPPs and to analyze the obtained results was studied;

– promising areas for extracting useful components from ASW was determined.

3. Theoretical and experimental parts

Analysis of previous studies

Circular economy (closed-loop economy) [22, 23] is an economic development model that is an alternative to the linear economy (creation, use, disposal of waste). Focusing on products and services that minimize waste and other types of pollution, it provides for recovery, reuse, rational consumption of resources and allows for the creation of additional value through new services and intelligent solutions. In developed countries, programs to promote a circular economy have been adopted at the legislative level. These new concepts of national development provide for a radical change in waste management systems, a focus on the maximum extraction of secondary resources from waste and their use in industrial production to replace natural mineral raw materials. This model is based on large volumes of cheap, readily available materials and energy. The circular economy keeps products, parts and materials in economic circulation for as long as possible, using as few resources as possible. This concept was presented in a document published by the European Commission [22]. Its implementation should help reduce the negative impact of ASW on the economy not only in environmental but also in socio-economic aspects. The transformation of waste, especially ASW, into a useful product is an integral part of increasing the efficiency of resource use [23]. As a result of this approach, the rationality of resource use, including natural resources, will increase as a whole, the economy will become more transparent, predictable, and its development will be rapid and systematic [22]. This solution saves natural resources, reduces the cost of finished products and the level of environmental pollution.

In developed countries, ASW has proven itself as a valuable raw material for the production of building structures and materials, strengthening of mines, railways, etc. Their functional advantages have allowed them to be used as a replacement for energy- and resource-intensive materials such as cement, sand and fillers, since they not only ensure the conservation of natural resources, reduction of the cost of finished products and the level of environmental pollution, but also contribute to the principles of cyclicality of products and structures where they are used (circular economy conditions) [24–27]. The use of ASW has a number of advantages over the use of conventional building materials: no costs for extraction and initial processing; proximity to infrastructure allows for significant savings on transportation costs. It follows that ASW processing is an important area of research [9–15]. The most voluminous of ASW are slag and fly ash. During coal combustion, more than 80% of its mineral composition passes into fly ash (FA), and up to 20% into slag. FA is a finely dispersed material formed from the mineral part of coal and is the most widely used abroad [28].

The papers [16–18] analyze foreign experience in processing TPP ASW. In industrially developed and developing countries, coal combustion technologies make it possible to obtain a commercial product from ASW that is practically ready for use. The main areas of ASW use are construction, agriculture, energy, and road maintenance. In order to increase the level of ASW utilization, their use was stimulated at the state level, which had a positive effect on the results. Many TPPs have reservoirs with a capacity of up to 40–60 thousand tons with a daily and two-day capacity. Samples are taken from them for ash analysis in the laboratory, then a product is created from it using mixing and volumetric dosing, which, in terms of fractional composition, acquires characteristics that meet regulatory requirements. At the end of the process, the ash is transferred to storage in the appropriate reservoirs and then shipped to the consumer. As a result, there is no need to maintain ASW storage facilities, and TPPs receive additional profit from the sale of these products.

Today, in the US and the EU, about 70–95% of coal waste is recycled, and in the Netherlands and Denmark – 100%. The waste recycling rate in Ukraine is only about 15%, which is extremely low compared to EU countries [19–21].

The papers [16–18] analyze the factors that hinder the large-scale use of ASW in Ukraine. One of the main reasons is the lack of cost-effective technologies and insufficient study of the raw materials. Obsolete thermal power plants (technologies and equipment) - significant physical wear and tear, irregular repairs led to a partial loss of the design indicators of efficiency, maneuverability, productivity and, thus, reduced the reliability of the power units as a whole. The efficiency of pulverized coal boilers is only 75–80% with a design value of 91–92% [29]. As a result, the ashes of coal-fired thermal power plants in Ukraine contain unburned matter (carbon) in an amount of 5 to 30% [9–14, 28]. The increased content of unburned matter in the ash and the complex granulometric composition do not allow for the wide use of ash in the construction industry in large volumes (for concrete - prohibited by standards) [9, 10, 28]. Therefore, it is necessary to improve or create technologies and equipment for efficient combustion of coal [30, 31] and additional enrichment of ash quality to the indicators required by standards for widespread use in the construction industry [16–18].

It should be noted that at the TES there is dry fresh (daily) ash obtained immediately after burning coal, i.e., before its storage, and perennial waterlogged (stale) ash from storage facilities. The technologies for processing daily and stale ash are different. Daily ash is a dry finished product for processing and subsequent disposal. Ash from storage facilities has caked in dumps over many years; it must first be crushed and dehydrated. Obviously, in order to eliminate the replenishment of the storage facility, it is advisable to start processing with dry ash, and consider ash storage facilities as man-made and suitable for subsequent complex processing [11, 12].

Cost-effective methods of processing thermal power plant waste both in the form of current dry products, such as ash and slag, and stale ash will reduce the load on existing storage facilities, reduce the severity of reconstruction and land allocation problems, produce new types of products, and improve the state of the environment [1–15, 32].

Since the ash from Ukrainian thermal power plants has a high carbon content, the work of domestic authors was mainly devoted to its extraction and the study of the properties of the ash.

The paper [33] presents the results of the analysis of the methods of processing daily (dry, collected from the electrostatic precipitator bins) ash and stagnant water-saturated ash from the storage tanks of the DTEK Prydniprovska and Kramatorsk TPPs. For the daily ash of the DTEK Prydniprovska TPP, the yield of classes of -0.04 mm was about 40%. A larger size of dry ash was established compared to the lying ash. With an increase in the sampling depth from the storage tank, the percentage of the enclosing fraction decreased. A tendency towards a decrease in the coal content in narrow size classes was established. In the samples from the storage tank of the Kramatorsk TPP, coal is concentrated to a greater extent in classes larger than 0.05 mm, and its content decreases with decreasing size. A conclusion was made about the prospects of dry screening of daily ash; when processing lying ash, it should be taken into account that its moisture content can reach 45–50%.

The publication [9] presents studies of the granulometric composition of waste – daily dry ash, slag and ash from storage tanks – using the example of the DTEK Prydniprovska and Kurakhivska TPPs. It was found that the daily ash at the DTEK Prydniprovska and Kurakhivska TPPs differs in granulometric composition due to different grain sizes and ash content of coal, different temperature conditions, blowing conditions, flue gas removal, etc. At the DTEK Prydniprovska TPP, the content of -0.074 mm fractions in fresh ash is 47.7%, and in stale ash – 78.4%. At the Kurakhivska TPP, the content of -0.05 mm in fresh ash is 54.8%, and in stale ash – 84.5%. The distribution of ash and slag in fresh ash is approximately 80:20, but the slag has practically no fine classes. Ash analysis indicates a larger particle size of daily ash compared to stale ash. For both storage facilities, the number of large classes of +0.25 mm does not exceed 1%, and the ratio of +0.074 mm to -0.074 mm µm is estimated at 20:80. The reasons for waste grinding during long-term wet storage are annual temperature fluctuations, chemical phenomena, mechanical stresses under the weight of raw material layers and during layer movement due to feed and drainage flows, etc. The possibility of identifying individual narrow classes of size with a high content of unburned coal by fine classification has been established. The physical and technical characteristics of the DTEK Prydniprovska TPP slag, its granulometric composition and iron content have been determined, which create the possibility of its direct use as medium-strength crushed stone of the M600 brand in construction. The slag is similar in strength to crushed stone of the M600 brand. The content of magnetic inclusions is 8.5%, which does not exceed 6% of the total iron. TPP slag can be divided into slag sand (grain size from 0.315 to 5 mm) and slag crushed stone with a particle size of more than 5 mm in a ratio of 58.4: 37.2 (%). They meet the building standards GOST 25592-91, GOST 26644-85, DSTU 9043:2020 for the production of concrete, cinder blocks, road construction and are finished commercial products.

The paper [10] considers the possibility of processing ash by mechanical classification by size. Two most common types of raw materials were studied: with low carbon content in large and fine classes and with high carbon content in all size classes except fine. It was found that the method of obtaining a rich intermediate product by combining rich close classes is quite effective and allows doubling the coal concentration. For stale ash of the DTEK Prydniprovska and Kurakhivska TPPs, the intermediate product contained about 40% carbon with a content in waste of 12–15%. For stale ash of the Chernihiv TPP, the carbon content in the intermediate product is about 57%, the carbon content in the waste is about 20%. The advantage of the obtained intermediate product in the absence of fine classes is easy enrichment. The waste is small in size. In terms of carbon content, they meet the standards for the use of fly ash from TPPs for lightweight concrete. They can be used in industry. The waste yield is from 45 to 80% of the original raw material. Selective extraction of rich raw materials with a carbon content of more than 35% of the accumulator is a promising technology. This allows obtaining a finished coal product with a yield of 22–25% and a carbon content of 70–72%. The waste contains about 25% carbon. In this case, the industrial product is ready for use as pulverized fuel for combustion at thermal power plants. It is also possible to use it in the form of coal briquettes. The initial assessment shows that this technology is cost-effective, since the costs of the raw material lifting process, as well as the drying and vibration screening process, do not exceed the costs of the processes of coal mining, transportation and preparation for combustion at thermal power plants. Considering that today there are about 360 million tons of ASW in accumulators, and the ash of thermal power plants contains, on average, up to 20% of unburned carbon [10], the processing of existing accumulators will allow extracting about 70 million tons of coal. This raw material is small-sized and suitable for reuse at thermal power plants. Given the high cost of the original coal, the process of its transportation and preparation for combustion, the extraction of carbon from stale fly ash is a pressing issue. Processing of ASW allows extending the service life of storage facilities and improving environmental safety.

The publication [34] presents data on the properties of daily ash (smoke filtrate) collected at various points in the technological scheme of the DTEK Prydniprovska TPP (under different boilers and sections). As a result of the analysis, it was found that the unburned carbon remaining in the ash is distributed unevenly across the size classes of the original product; the samples contain from 18.53% to 30.48% unburned coal. If the +0.05-0.2 mm class is extracted from the ash, an oversize product containing coal can be obtained C_c from 6.05% to 14.6% with ash content C_a from 2.41% to 24.87 %, which corresponds to the standard indicators for coal supplied to thermal power plants (the ash content of the product should not exceed 27%). During laboratory tests, it was noted that there is a significant portion of clay in the +0-0.02 mm classes. It was found that the ashiest part is contained in the +0-0.02 mm class from 44.97 to 81.47%. If the classification is carried out according to the boundary size of 0.02 mm, an additional 5 to 7% of carbon can be extracted with the standard ash content. As a result of separation, the carbon content in the undersize product (silicate part with a particle size of less than 0.02 mm) can be reduced to 5–6% (corresponds to the standard requirements), i.e., 4–5 times less than in the original product.

Despite the large number of publications, they do not pay enough attention to the extraction of associated elements from ASW, including rare earth minerals. Given the diversity of rocks containing coal seams, their mineralogical composition, the development of fly ash enrichment for the purpose of extracting useful minerals and metals is of practical interest. For example, it is known that the host rocks contain aluminum, germanium, iron in quantities of industrial interest. Additional research is needed to improve and develop ASW processing, develop enrichment technologies, and conduct a feasibility study directly for each man-made storage facility [35]. It is necessary to search for new directions and areas of their use.

The work [36] shows the average chemical composition of the mineral part of TPP ash and slag. The main mass is made up of silicon oxides – 45–60%, calcium – 2.5–9.6%, iron – 4.1–10.6%, magnesium – 0.5–4.8%, aluminum – 10.1–21.8%. The content of a number of components of ash and slag can significantly exceed their concentration in the earth's crust. For example, the content of MgO in ash and slag can be 2–3 times higher than the Clarke value, Al_2O_3 – 2 times, Fe_2O_3 – 1.5–3 times, CaO – 4–12 times.

To take into account all these features, it is necessary to carry out a set of studies to determine the elemental composition and properties of ash in order to use it as an additional source for the extraction of valuable metals and the production of commercial products. Depending on the grades of burnt coal and the rocks containing them, in addition to residual carbon, the so-called "underburnt", the ash contains a high content of silicon oxide (up to 60%), iron oxides (with their magnetically susceptible varieties making up from 7% to 20%), aluminum oxides (contained within the range of 10% to 24%) [37]. Coal-fired thermal power plant ash is a potential raw material for the complex extraction of silica, aluminum oxide, iron and rare earth minerals into commercial products. For example, the extraction of alumina for the subsequent production of aluminum, given that the aluminum oxide content in the ash of some types of coal can reach 30% [36, 37]. Thus, ASW are man-made deposits of industrial interest that require complex technology in each specific case, depending on the grades of coal burned.

Recently, publications have appeared devoted to the extraction of not only carbon and silicates from ash, but also other components of industrial interest [38–48]. A number of works by both domestic and foreign specialists are devoted to the issues of complex processing of ash and slag using chemical methods [38–43].

The papers [44–48] consider the possibilities of complex processing of ash and slag using chemical methods. Technological data on acid, alkaline and fluoride processing of ash and slag are provided. The chemical composition of ash and slag in the Dnipropetrovsk region has been determined. Mineral acid processing technologies are used to separate magnetic and non-magnetic fractions. In addition, it is possible to remove liquid and dispersed elements. Using alkaline processing technology, it is possible to extract scandium, gallium and alumina. Using fluoride technology, aluminosilicate compounds can be processed more completely due to the extraction of silicon, which makes it possible to gradually obtain aluminum and iron from waste. Despite the positive results, it should be noted that chemical methods are expensive and themselves require subsequent disposal, which also requires expenses.

Efficient and cost-effective methods for processing ASW are needed.

The works [11, 14] present the results of ash studies using chemical analysis and magnetic separation methods, which showed that it contains up to 20% unburned carbon in individual size classes (underburnt) and up to 30% magnetically susceptible iron (in aggregates). It was found that the remains of unburned carbon and iron aggregates in the ash under study are not distributed uniformly. The highest carbon content is in size classes from 0.05 mm to 0.25 mm. However, the total share of these classes from the sample weight is about 8%. These same size classes have the highest iron content, i.e., they are of interest for processing. This indicates the feasibility of its comprehensive processing in order to extract carbon, iron and the silicate part with subsequent utilization of these products.

The paper [49] presents the results of studies on the possibility of extracting carbon from ash from the Chernigiv TPP using an experimental pneumatic flotation machine and then enriching it using wet magnetic separation to isolate the magnetic product. A study was conducted of the properties of ash on a sample taken from the Chernigiv TPP storage tank in the amount of 30 kg for enrichment under laboratory conditions. The amount of particle size greater than 0.8 mm was less than 0.1%, so it was not processed and was not taken into account in the calculations. The results of the granulometric analysis of the averaged source material are presented in Table 1. The moisture content of the source material was 22%.

As can be seen from Table 1, the yield of fine-grained material with a size of less than +0-0.05 mm is 80.98%; the content of the coarse-grained component (fraction +0.315-0.8 mm) is 0.44%. The content of fraction +0.2-0.315 mm is 0.48%, fraction -0.2+0.08 is 5.95%, fraction +0.05-0.08 mm is 12.15%. Material with a size of +0-0.80 mm was enriched using wet magnetic separation, as a result of which the yield of magnetic product was 6.91%, non-magnetic - 89.98%. Since the ash content of fine-grained material less than 0.05 mm was 79.7%, with a yield of more than 80%, it became advisable to separate by size of 0.05 mm in order to separate high-ash fine tailings into the discharge product using a hydrocyclone with a diameter of 30 mm (GC30). Then the sand fraction was subjected to flotation, as a result of which two products were obtained: carbon (yield 8.25% with an ash content of 25.1%) and a silicate part (yield 29.95% with an ash content of 95%) [49].

Table 1 – Granulometric composition of the ash sample from the Chernigiv TPP [49]

Particle size *d*, mm	Output of classes γ, %	Ash content of class, %
+0.315-0.8	0.44	96.2
+0.2-0.315	0.48	51.5
+0.08-0.2	5.95	37.2
+0.05-0.08	12.15	45.8
+0-0.05	80.98	79.7
Σ	100.00	62.08

At the same time, as follows from publications [9–12, 14, 37], ash has an unstable chemical, granulometric and elemental composition, the yield of size classes and the content of useful components in them are also different, which indicates the impossibility of using the results obtained from one storage facility for others. This also indicates the need to create and implement various fly ash enrichment schemes. Therefore, before developing a storage facility, it is necessary to study the physicochemical properties of the utilized components and the resulting commercial products, develop a processing scheme and determine promising areas for their use. It should also be noted that the authors of publications [7, 12, 14, 37] indicate the need for preliminary separation of the finest classes of +0-0.05 mm in size during ash processing, since these classes are characterized by high ash content and a significant amount of dust and clay particles, which, in the presence of water, become soaked, stick together in the form of lumps, clog the working areas of the equipment, made in the form of narrow gaps (for example, magnetic separation) and reduce its operating efficiency. The presence of clay particles also worsens flotation indicators.

Experimental part

This paper examines the feasibility of complex processing of ASW using the example of Chernihiv and Darnytsia CHPPs, built according to the same design and operating on the same fuel. The difference in their operation is as follows. In order to reduce waste and minimize the harmful impact on the environment, Chernihiv CHPP constantly carries out repair work, and Darnitsa has improved its coal combustion technology and modernized its gas cleaning equipment.

To assess these differences, a study was conducted of the properties of fly slag and ash, selected from the area of the storage facilities of the Chernihiv and Darnytsia CHPPs.

Chernigiv CHPP (capacity 210 MW and 625 Gcal) has been operating for about 47 years. The main fuel of the CHPP was Donetsk coal ASH and heating oil. Since 2008, 100% coal has been used. Its equipment is from 1963–1964, which is constantly being repaired. For the disposal of waste – fly ash (at the moment, 30% of the burned coal turns into ash), the enterprise uses storage tank No. 1 Chernigiv CHPP of TechNova LLC, located in the second belt of the sanitary protection zone of the Desna River at a distance of 1 km from the enterprise. A hydraulic ash removal system is in operation. To clean flue gases from ash, the BKZ-210-140 PT boilers are equipped with wet ash collecting units MV-MT1 3100 (4 pcs. on each). The storage facility, with a design capacity of 1,822 thousand tons, has been in operation since 1961, and more than 2 million tons of ash are stored there. As a result of an emergency and the destruction of the dam, the ash could end up in the Desna River. Therefore, the ash from the old storage facility is being transferred to the new one – about 600 tons of ash have already been removed. The enterprise constantly carries out repair work and improves the cleaning system in order to minimize the harmful impact on the environment. The management of the thermal power plant has planned a program for the construction of a new combined heat and power plant, which will consist of two units. Other types of capacity will be installed, new technologies with a higher efficiency factor will be used, which will reduce the impact on the environment [50].

Darnytsia CHPP (capacity 160 MW and 1080 Gcal/h) is the oldest of the currently operating thermal power plants in Kyiv. The main fuel is Donetsk coal ASH, the buffer fuel is natural gas. In recent years, Darnytsia CHPP, Kyiv TPP 4, Euro-Reconstruction LLC have been constantly working to improve coal combustion technology and modernize gas cleaning equipment. The construction of highly efficient electrostatic precipitators has already reduced dust emissions by tens of times. In addition to modern filters, the enterprise has also built a dry ash silo, where it ends up after cleaning. The design of the filter provides for this ash to be collected in dry form in bunkers under the filter, then transported to the silo with compressed air using a pneumatic ash removal system. In the future, this dry ash can be used in the construction industry. By the end of the reconstruction, there will be 12 such structures, which will stop dumping ash into the storage facility [51].

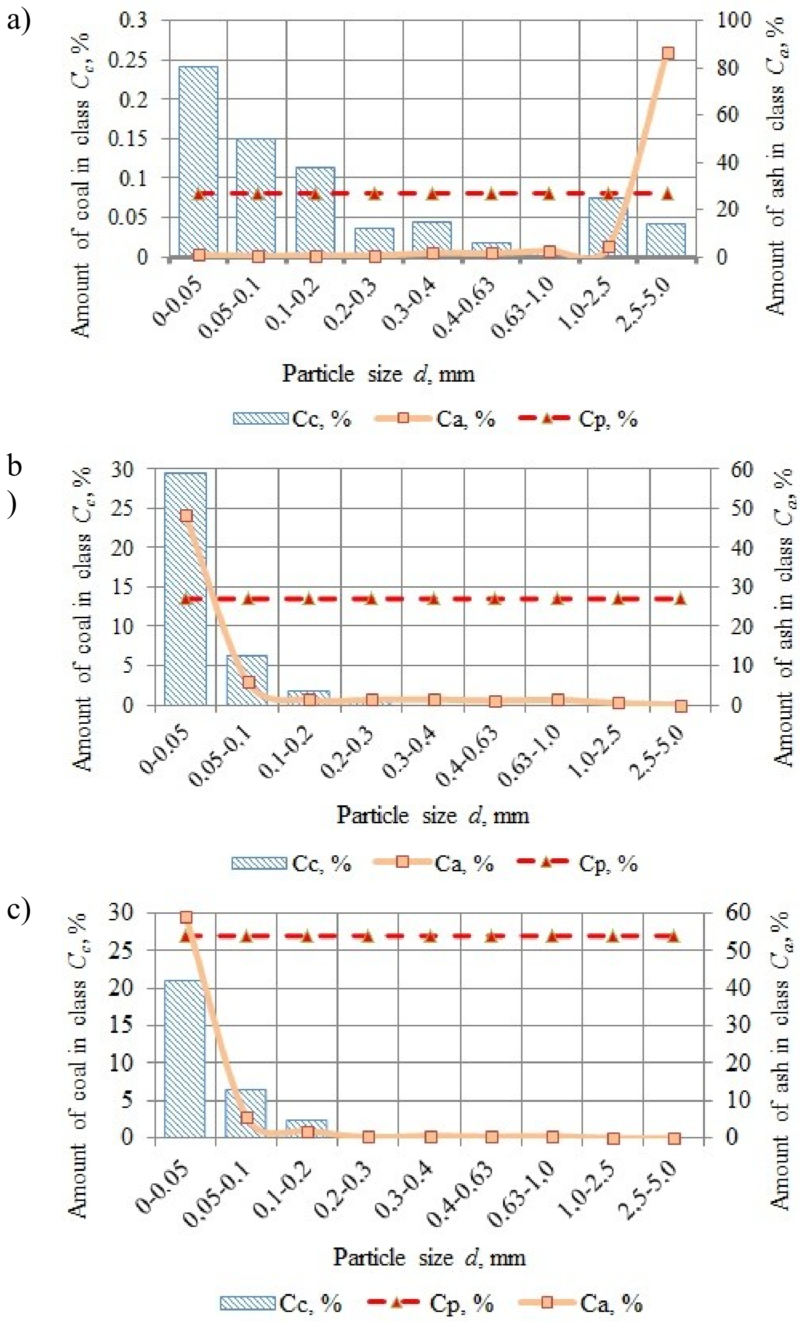
For many years M.C. Poliakov Institute of Geotechnical Mechanics under the National Academy of Science of Ukraine (IGTM NASU) has been conducting research into the properties of mineral raw materials from man-made deposits, including waste from thermal power plants.

From the analysis of previous studies [9–12, 11, 14, 33], it was established that ash was classified according to the boundary size of 0.05 and 0.074 mm. At the same time, as follows from work [34], a significant amount of carbon can be contained in finer classes of +0.02-0.05 mm. Appropriate equipment is required to extract them.

For this purpose, a new vibratory impact screen [52, 53] has been developed at the Institute of Geotechnical Mechanics, which allows for the effective classification of fine-grained materials. The boundary size of the material separators is 0.02 mm, pulp – 0.05 mm. Laboratory tests have been carried out, in which the use of such screens for fine classification allows for the maximum amount of coal mass to be obtained from ash and used to ensure stability.

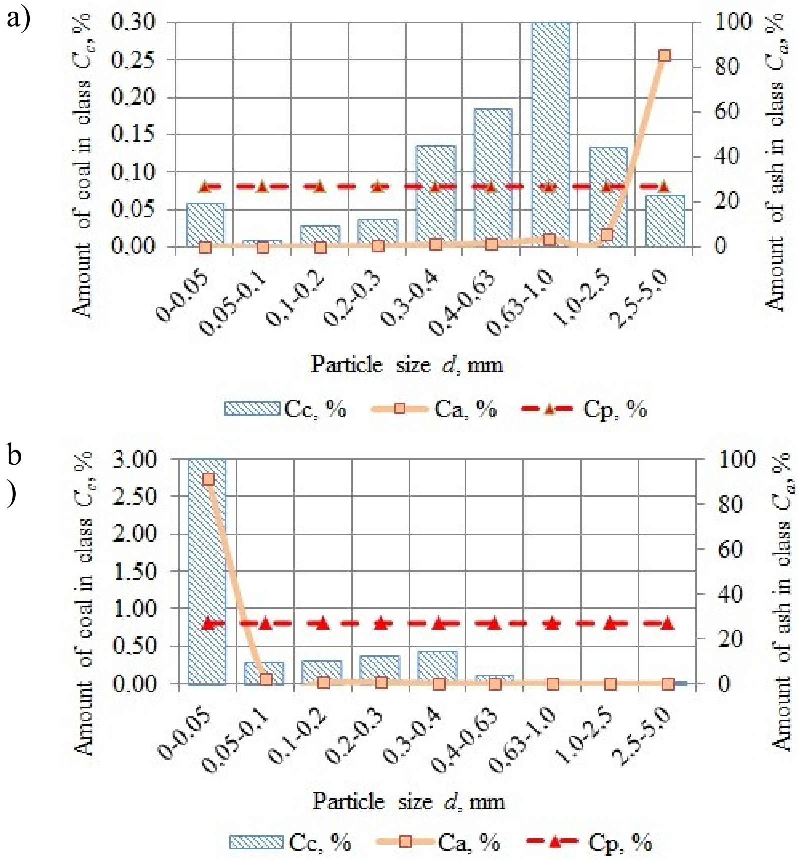
In order to clarify the content of ash and coal in fine particle sizes, it is necessary to detail their distribution. For this purpose, specialists from the IGTM NASU additionally conducted studies of the fractional composition and properties in laboratory conditions.

Figures 1–2 show the results of studies averaged over the results of 10 samples of slag and ash sample characteristics, performed in laboratory conditions at the IGTM NASU (the following notations are used in the graphs: C_c – coal content in class, C_a – ash content in class, C_p = 27–28% – (regulatory requirements) – maximum permissible ash content in the original coal for use in thermal power plants).



a) slag sample; b) and c) ash samples collected under different filters

Figure 1 – Distribution of coal content Cc ash Ca in size classes (samples of Chernigiv CHPP)



a) slag sample; b) ash sample

Figure 2 – Distribution of coal content Cc ash Ca in size classes
(Samples of Darnytsia CHPP)

As can be seen from the graphs (Fig. 1, 2), in the slag samples, unburned carbon is distributed among size classes with low content: Chernihiv CHPP (Fig. 1a) from 0.04 to 0.24%, in Darnytsia CHPP (Fig. 2a) from 0.06 to 0.3%. The quality of this product meets regulatory requirements and can be used for the production of building structures and materials, for laying roads, railways, etc.

In the ash samples of the Chernigiv CHPP (Fig. 1 b, c) the content of coal C_c in classes varies from 0.02 to 29.42%, and ash content C_a from 0.01 to 59.16%. The largest amount of coal is in classes less than 0.2 mm. If you separate the class +0.05-0.2 mm, you can get an oversize product with coal content C_c from 8,14 to 9,06%, which corresponds to the standard indicators for coal supplied to thermal power plants (the ash content of the product must not exceed 27%).

It should be noted that the largest amount of coal is in the +0-0.05 mm class – from 21.18 to 29.42% with an ash content of 48.14 to 59.16%. Experiments have shown that the ashiest part is in the +0-0.02 mm class (clay and dust particles). If the classification is carried out by the boundary size of 0.02 mm, it is possible to additionally extract 7 to 10% of carbon with a standard ash content. The +0-0.02 mm class still contains a fairly large amount of carbon. This product can be used as a pulverized fuel for combustion at thermal power plants. The return of up to 20% of the carbon extracted from the ash, with a daily consumption at a thermal power plant of about a thousand tons, allows for a reduction in the amount of purchased coal and transportation costs for its delivery from the station [9–12, 36, 37]. It can also be used in the form of coal briquettes. The initial assessment shows that this technology appears to be cost-effective, since the costs of raw material lifting, drying and vibratory screening do not exceed the costs of coal mining, transportation and preparation for combustion at thermal power plants.

In size classes from +0.2-5 mm, the carbon content is from 1.05 to 1.82%, which also meets regulatory requirements and can find its application in the construction industry.

The ash sample from the Darnytsia CHPP (Fig. 2 b) contains coal C_c in classes varies from 0.001 to 3.02%, and ash content C_a from 0,01 to 91,23%. The largest amount of carbon 3.02% is contained in the class +0-0.05mm. This product can be used in construction, as it meets the standard indicators.

Thus, in the slag of the Chernihiv and Darnytsia CHPP s, the amount of unburned carbon does not exceed the standard indicators, this is a commercial product practically ready for use.

As follows from the graphs, the ash of the Chernihiv TPP contains up to 29.42% of unburned carbon, i.e., repair work carried out at the plant does not reduce its amount to standard indicators. Improved coal combustion technology and modernized gas cleaning equipment of the Darnytsia CHPP allow obtaining a commercial product ready for use in the construction sector.

For complex processing of ASW, slag (it must first be crushed) and part of the ash after separating carbon and class +0-0.02 mm can be additionally processed using magnetic and electrical separation, flotation and others, to extract useful elements of strategic importance, such as magnetite, alumina for subsequent production of aluminum, aluminosilicate microspheres (also called "cenospheres" in the literature) [54], etc.

Magnetic concentrate extracted by magnetic separation in powder form can be used to produce briquettes, which are feedstock for metallurgy, ferrosilicon, cast iron and steel production. It can also serve as feedstock for powder metallurgy. The non-magnetic part can be used as feedstock for carbon-aluminum composite materials [55, 56]. To obtain an aluminosilicate product containing 1.5–4.5% carbon (regulatory requirements) [11, 12], a dry processing method such as electrostatic separation is used. In the work [57], when involving ash and slag in enrichment, a complex technology is proposed with the production of vanadium and aluminum by hydrometallurgical extraction from vanadium- and aluminum-containing products of mechanical enrichment. The concentration of elements obtained by mechanical enrichment methods corresponds to the conditions for the raw materials sent to the hydrometallurgical stage, and amounts to Al_2O_3 – 19 %, to V_2O_5 – 0,36 %.

Additional studies are needed to determine the mineralogical composition of the ash, its value and the feasibility of including it in the technology of complex processing for subsequent disposal.

Fig. 3 shows one of the variants of ash processing schemes. The scheme uses structural elements of graphic materials presented in [58].

Taking into account the different grades of coal and the composition of host rocks in coal, the technology and equipment in each specific case should be adjusted for maximum screening efficiency.

Comprehensive processing of ash-slag waste is beneficial from both an economic and environmental point of view. Firstly, it will reduce the territories that are currently alienated for storage facilities and become unsuitable for living. Secondly, thermal power plants will be able to earn money on this - according to expert estimates, ash processing can provide an increase in the profitability of the enterprise by 10–20%. Thirdly, the reduction of this type of waste will reduce the negative impact on the environment and public health. Fourthly, the comprehensive use of waste is an opportunity to implement the transition to a circular economy.

4. Conclusions

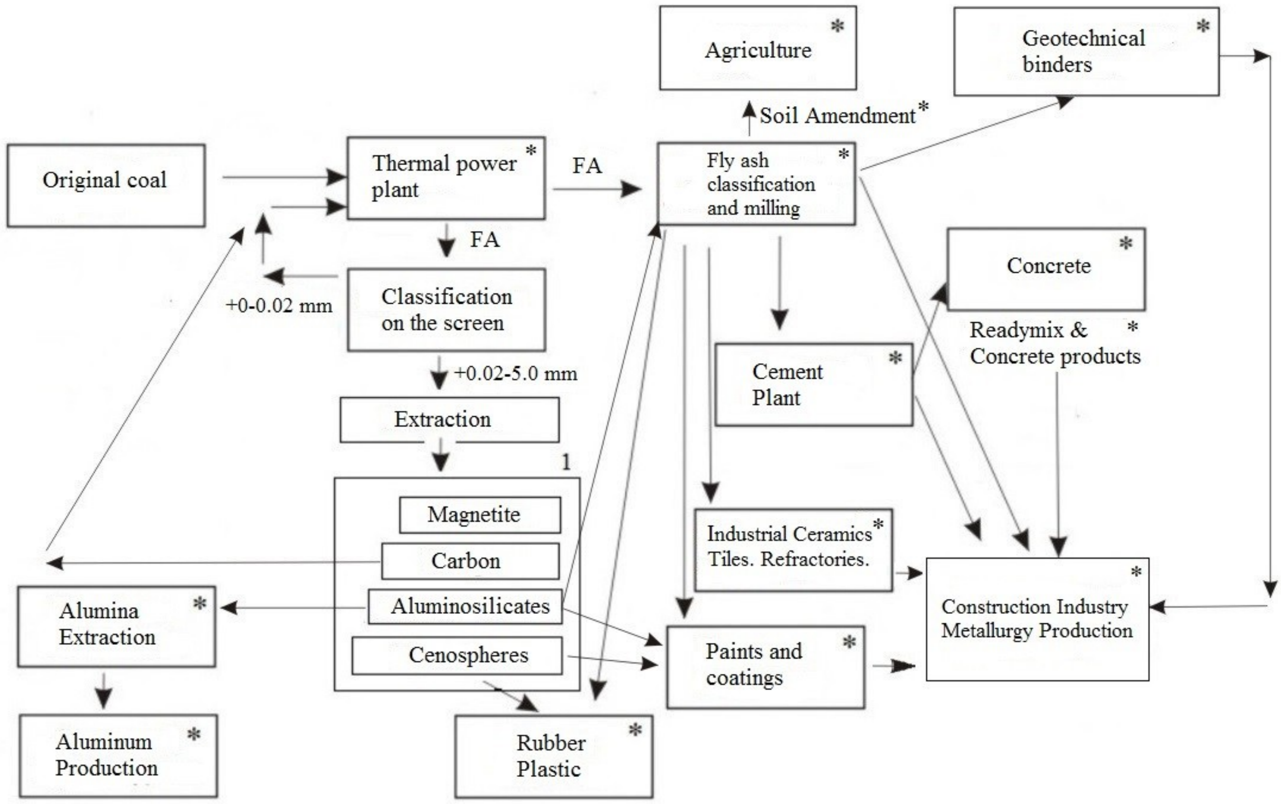
Simultaneously with the generation of energy at thermal power plants and combined heat and power plants, ASW is generated, which is produced in large quantities and poses a serious environmental hazard. At the same time, waste accumulated over many years has a huge resource potential, a unique mineral composition, a complex distribution of useful components, which is not typical for natural deposits, representing, in fact, man-made deposits. It is necessary to use the experience of industrially developed countries in the transition to the conditions of a circular economy: maximum extraction of secondary resources and their use in industrial production instead of natural mineral raw materials. Complex use of waste is a condition for the implementation of the transition to a circular economy.

An analysis of previous studies of the properties of slags and fly ash, the possibility of extracting useful components from them was performed. The main directions for reducing the amount of waste and eliminating storage facilities were established: improving coal combustion technology, processing daily ash without dumping it into the storage facility and stale ash from the storage facility.

The possibility and expediency of complex processing of ash-slag waste have been revealed using the example of improving the technology and equipment of the Chernihiv and Darnytsia CHPPs. The properties of daily ash collected under the electrostatic precipitators of the Chernihiv and Darnytsia CHPPs have been studied.

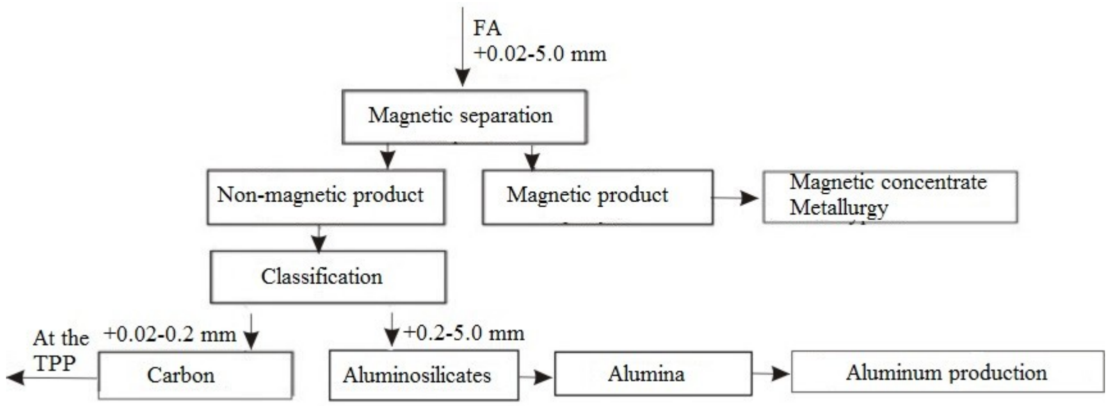
The size classes with the highest carbon content and the possibility of its extraction have been established. The range of changes in the amount of carbon in slag has been studied and the obtained results have been analyzed.

The possibility has been established of separating the finest classes containing clay and dust particles by fine classification according to the boundary size of 0.02 mm using a vibratory impact screen and extracting various useful components from ash-slag waste. The carbon obtained from ash can be used for combustion at TPPs. The magnetic concentrate extracted in the form of powder can be used for metallurgy, production of ferrosilicon, cast iron and steel. To obtain an aluminosilicate product, such a dry processing method as electrostatic separation can be used.



a)

* - structural elements are indicated [58]



b)

a) full scheme; b) scheme fragment, block 1

Figure 3 – Scheme of complex ash processing

Complex processing of ash waste is beneficial from both an economic and environmental point of view. It will reduce the amount of waste sent to storage facilities, reduce the areas that are currently alienated for them and become unsuitable for living. Thermal power plants will be able to make money on this - according to experts, ash processing can provide an increase in the profitability of enterprises by 10–20%. This approach will solve a set of social, economic and environmental problems, significantly save natural resources and reduce the deficit of various materials.

Conflict of interest

Authors state no conflict of interest.

REFERENCES

1. Oliynichenko, I.K. (2015), "Environmental safety and environmental measures at the Ladyzhinskaya TPP", *Vinnytsia National Technical University Ukraine*, available at: http://ir.lib.vntu.edu.ua/handle/123456789/12195 (Accessed 27 January 2025).
2. Popov, O., Iatsyshyn, A., Kovach, V., Artemchuk, V., Kameneva, I., Radchenko, O., Nikolaiev, K., Stanytsina, V., Iatsyshyn, A.and Romanenko, Ye. (2021), "Effect of Power Plant Ash and Slag Disposal on the Environment and Population Health in Ukraine", *Journal of Health and Pollution*, vol. 11, no. 31, 210910, https://doi.org/10.5696/2156-9614-11.31.210910
3. Krainiuk, O., Buts, Y., Ponomarenko, R., Asotskyi, V. and Kovalev, P. (2021), "The geoecological analysis performed for the geochemical composition of ash and slag waste obtained at Zmiiv thermal power plant", *Journal of Geology, Geography and Geoecology*, no. 30(2), pp. 298–305, https://doi.org/https://doi.org/10.15421/112126
4. Pribilova, V.M. (2013), "Assessment of the inflow of technogenic loading on the geological center and the particularity of the accumulation of pollutants in the zone of development of the Zmiivskoy TES", *Bulletin of Kharkiv National University*, no. 1084, pp. 237–243.
5. Buts, Yu.V., Krainiuk, O.V. and Bezsonny, V.L. (2006), "Some aspects of total heavy metal contamination of soils of the North-Eastern region of Ukraine Problems of emergencies", *Coll. Science. etc. HCC of Ukraine*, no. 5, pp. 51–54.
6. Buts, Y., Asotskyi, V., Kraynyuk, O. and Ponomarenko, R. (2018), "Influence of technogenic loading of pyrogenic origin on the geochemical migration of heavy metals", *Journal of Geology, Geography and Geoecology*, no. 27(1), pp. 43–50, https://doi.org/10.15421/111829
7. Buts, Y., Asotskyi, V., Kraynyuk, O. and Ponomarenko, R. (2019), "Dynamics of migration capacity of some trace metals in soils in the Kharkiv region under the pyrogenic factor", *Journal of Geology, Geography and Geoecology*, no. 28(3), pp. 409–416, https://doi.org/10.15421/111938
8. Buts, Y., Kraynyuk, O., Asotskyi, V., Ponomarenko, R. and Kalynovskyi, A. (2020), "Geoecological analysis of the impact of anthropogenic factors on outbreak of emergencies and their prediction", *Journal of Geology, Geography and Geoecology*, no. 29(1), pp. 40– 48, https://doi.org/10.15421/112004
9. Shevchenko, G.O., Cholyshkina, V.V., Sukharyev, V.V., Kurilov, V.S. and Lebed, H.B. (2023) "Granulometric composition of thermal power plant waste", *Geo-Technical Mechanics*, no. 165, pp. 72–84, https://doi.org/10.15407/geotm2023.165.072
10. Shevchenko, G.O., Cholyshkina, V.V., Sukharyev, V.V. and Kurilov, V.S. (2022), "Processing of fly ash from thermal power plants by means of mechanical classification by size", *Geo-Technical Mechanics*, no. 160, p. 133–140, https://doi.org/10.15407/geotm2022.160.133
11. Nadutyy, V.P., Kostyrya, S.V. and Sevastyanov, V.S. (2016), "Justification of the feasibility of complex processing of fly ash from thermal power plants", *Geo-Technical Mechanics*, no. 131, pp. 59–66, available at: http://dspace.nbuv.gov.ua/bitstream/handle/123456789/138772/06-Nadutyi.pdf?sequence=1 (Accessed 27 January 2025).
12. Nadutyy, V.P. (2007), "Ground method of determination of efficiency of development of technogenic wastes of coal-dressing", *Zbagachennya korysnykh kopalyn*, no. 29(70)–30(31), pp. 224–227.
13. Nadutyy, V.P., Sukharev, V.V. and Kostyria, S.V. (2016), "Processing of results of experimental studies of vibrational complex dewatering of coal slurries", *Vibratsiyi v tekhnitsi ta tekhnolohiyakh*, no. 1(81), pp. 86–91, available at: http://nbuv.gov.ua/UJRN/vvtt_2016_1_16, (Accessed 27 January 2025).
14. Nadutyi, V.P., Sevastyanov, V.S. and Kostyrya, S.V. (2017), "Substantiation of the feasibility of complex processing of fly ash from thermal power plants", *Geo-Technical Mechanics*, no. 152, pp.172–183.
15. Kostyrya, S.V. (2019), "Justification of operating and design parameters of a complex action device for dewatering rock mass", Ph.D. dissertation, Mining machines, M.S. Poliakov Institute of Geotechnical Mechanics of NAS of Ukraine, Dnepropetrovsk, Ukraine. available at: http://igtm.dp.ua/images/My_files/Aref-Diss/D33-2-code.pdf (Accessed 27 January 2025).
16. Lapshyn, Ye., Shevchenko, O. and Khayitov, O. (2024), "Foreign experience of processing ash slag waste from thermal power plants", *Geo-Technical Mechanics*, issue 168, pp. 105–120, https://doi.org/10.15407/geotm2024.168.105
17. Lapshyn, Ye. and Shevchenko, O. (2024), "Processing of ash waste from thermal power plants: foreign experience and Ukrainian realities", *Geo-Technical Mechanics*, issue 169, pp. 45–65, https://doi.org/10.15407/geotm2024.169.045
18. Lapshyn, Ye. and Shevchenko, O. (2024), "Determining the possibilities of using fly ash on the example of THE DTEK Prydniprovska TPP", *Geo-Technical Mechanics*, Issue 170, pp. 17–27, https://doi.org/10.15407/geotm2024.170.017
19. Asian Coal Ash Association (2025), available at: https://www.asiancoalash.org (Accessed 27 January 2025).
20. European Coal Combination Products Association, available at: http://www.ecoba.com, (Accessed 27 January 2025).
21. American Coal Ash Association (2025), available at: https://acaa-usa.org, (Accessed 27 January 2025).

22. European Parliament (2023), "Circular economy: definition, importance and benefits", available at: https://www.europarl.europa.eu/topics/en/article/20151201STO05603/circular-economy-definition-importance-and-benefits (Accessed 27 January 2025).

23. Rosiek, J. (2018), "The implementation of Circular Economy Concept in the Polish Coal Combustion Products Sector – selected problems", *Economic and Environmental Studies*, vol.18, no. 1(45), pp. 353–373, https://doi.org/10.25167/ees.2018.45.20

24. Heidrich, C. and Feuerborn, J. (2022), "Global opportunities and challenges for coal combustion products with a Circular Economy", *World of Coal Ash Proceedings*, available at: https://worldofcoalash.org/wp-content/uploads/2022/07/0478_0692_000418.pdf (Accessed 27 January 2025).

25. Harris, D., Heidrich, C. and Feuerborn, J. (2019), "Global aspects on Coal Combustion Products", *Asian coal ash association*, available at: https://www.asiancoalash.org/_files/ugd/ed8864_53ad887cdb1c4bbda497, (Accessed 27 January 2025).

26. Heidrich, C., Feuerborn, H.J. and Weir, A. (2013), "Coal combustion products: a global perspective", *World of Coal Ash Conference*, pp. 22–25, available at: https://www.semanticscholar.org/paper/Coal-combustion-products-A-global-perspective-Heidrich-Feuerborn/a0b29d678934d0a2f422e7fd027c4e0f13d3e3bc, (Accessed 27 January 2025).

27. Bielecka, A. and Kulczycka, J. (2020), "Coal Combustion Products Management toward a Circular Economy – A Case Study of the Coal Power Plant Sector in Poland", *Energies*, vol. 13, issue 14, 3603, https://doi.org/10.3390/en13143603

28. Serdyuk, V.R., Rudchenko, D.G. and Gudz, D.V. (2021), "Use of fly ash from Burshtynskaya TPP in the production technology of autoclaved aerated concrete", *Visnyk Vinnyts'koho politekhnichnoho instytutu,* no. 2, pp. 24–31, https://doi.org/10.31649/1997-9266-2021-155-2-24-31

29. Efimov, A.V., Kavertsev, V.L., Ryzhenko, I.E., Garkusha, T.A. and Chernyak, E.A. (2013), "Characteristics of operation of high-pressure coal-fired boilers operating on Ukrainian coals and prospects for their technical re-equipment by installing gas-tight furnaces and other innovative solutions", *Bulletin of NTU KhPI*, no. 14(988), pp. 96–101, available at: https://repository.kpi.kharkov.ua/server/api/core/bitstreams/c0cbcbe8-1d8d-4ca5-8eb6-13396234f6ae/content, (Accessed 27 January 2025).

30. Bulat, A.F, Voloshin, A.I. and Kudinov, P.I. (2003), "Numerical and experimental research of heat and mass transfer at the depending of coal dust fuel burning", *Promishlennaia teplotehnika*, vol. 25, no. 4, pp. 26–28.

31. Voloshin, A.I., Zhevzhik, A.V., Goriachkin, V.N. and Potapchuk, I.Yu. (2013), "Studying of uneven concentration of the coal dust particles in horizontal direct-flow channel of the thermochemical fuel preparation reactor", *Geo-Technical Mechanics*, Issue 109, pp. 89–98, available at: https://crust.ust.edu.ua/server/api/core/bitstreams/c8a4673a-ee53-4419-a3ea-7ad64446bd7f/content (Accessed 27 January 2025).

32. Khamit, A., Uderbaev, S., Baytasov, K., Ibraimbaeva, G. and Kultaeva, Sh. (2024), "Research on the possibility of using ash from CHP plants in the production of incinerated ash gravel", *KazGASU Bulletin*, no 3(93), pp. 150–159, available at: https://vestnik.mok.kz/index.php/vestnik/article/view/131/55 (Accessed 27 January 2025).

33. Bulat, A.F., Shevchenko, G.O., Cholyshkina, V.V., Kurilov, V.S. and Kashinsky, E.P. (2025), "Geotechnical approaches to the processing of technogenic deposits of TPPs: comparative analysis of the Prydniprovska TPP and Kramatorsk TPP", *Proceedings of the XXII International Scientific and Technical Conference "Poturaiv Readings",* 14 February 2025, Dnipro, Ukraine, pp. 8–9, available at: https://gmi.nmu.org.ua/ua/nauka/vibro/%D0%9F%D1%80%D0%BE%D0%B3%D1%80%D0%B0%D0%BC%D0%B0%20%D0%9F%D0%A7%202025.pdf (Accessed 27 January 2025).

34. Lapshyn, Ye. and Shevchenko, O. (2024), "Determining the possibilities of using fly ash of DTEK Prydniprovska TPP as additional raw material", *Geo-Technical Mechanics*, Issue 171, pp. 31–46, https://doi.org/10.15407/geotm2024.171.031

35. Popov, O., Iatsyshyn, A., Kovach, V., Artemchuk, V., Kameneva, I., Radchenko, O., Nikolaiev, K., Stanytsina, V., Iatsyshyn, A.and Romanenko, Ye. (2021), "Effect of Power Plant Ash and Slag Disposal on the Environment and Population Health in Ukraine", *Journal of Health and Pollution*, vol. 11, issue 31, 210910, https://doi.org/10.5696/2156-9614-11.31.210910

36. Latsyshyn, A. and all (2018), "The peculiarities of the thermal power engineering enterprise's ash dumps influence on the environment", *Problems of Emergency Situations*. no 28, pp. 57–68, available at: https://www.researchgate.net/publication/332369607_THE_PECULIARITIES_OF_THE_THERMAL_POWER_ENGINEERING_ENTERPRISE'S_ASH_DUMPS_INFLUENCE_ON_THE_ENVIRONMENT_OSOBLIVOSTI_VPLIVU_ZOLOVIDVALIV_PIDPRIEMSTV_TEPLOENERGETIKI_NA_NAVKOLISNE_SEREDOVISE (Accessed 27 January 2025).

37. Nadutyy, V.P., Sukharev, V.V. and Kostyria, S.V. (2018), "Analysis of the mineral composition and effectiveness of complex dewatering of fly ash during coal combustion at thermal power plants", *Vibrations in engineering and technology*, no 3(90), pp. 68–74, available at: http://repository.vsau.org/getfile.php/19225.pdf (Accessed 27 January 2025).

38. Kierczak, J. and Chudy, K. (2014), "Mineralogical, Chemical, and Leaching Characteristics of Coal Combustion Bottom Ash from a Power Plant Located in Northern Poland", *Pol. J. Environ. Stud*., no 23(5), pp. 1627–1635, available at: http://www.pjoes.com/pdf-89356-23213?filename=23213.pdf (Accessed 27 January 2025).

39. Shemi, A., Ndlovu, S., Sibanda, V. and Van Dyk, L.D. (2014), "Extraction of aluminium from coal fly ash: Identification and optimization of influential factors using statistical design of experiments", *International Journal of Mineral Processing*, no 127, pp. 10–15, https://doi.org/10.1016/j.minpro.2013.12.003

40. Tripathy, A., Behera, B., Aishvarya, V. and Sheik, A. (2019), "Sodium fluoride assisted acid leaching of coal fly ash for the extraction of alumina", *Minerals Engineering*, no 131, pp. 140–145, https://doi.org/10.1016/j.mineng.2018.10.019

41. Nuruldaeva, G., Nurmakova, S., Shakhanova, A. and Parzhanov, Ch. (2021), "Integrated processing of ash and slag waste from thermal power plants to produce high-tech products", *Scientific Collection «InterConf»: Scientific community: interdisciplinary research,* no. 45, available at: https://ojs.ukrlogos.in.ua/index.php/interconf/article/view/10338 (Accessed 27 January 2025).

42. Corporate Foundation Competence Center for Environmental Technologies (2016), "Integrated use of ash and slag waste from power plants of EEC JSC", *Technical and economic report*, Pavlodar, Kazakhstan, available at: https://centereco.kz/wp-content/uploads/2016/08/Kontseptsiya-promyshlennogo-osvoeniya-zoloshlakovyh-othodov-na-ES-AO-EEK-.pdf (Accessed 27 January 2025).

43. Zubova, O.A., Orazbaev, A.E., Voronova, N.V. and Mukanova, G.A. (2019), "Prospective ways of processing slag waste of TPPs", *Herald of KazNITU*, no. 2 (132), pp. 233–239, available at: http://rmebrk.kz/journals/5131/34253.pdf (Accessed 27 January 2025).

44. Khlopytskyi, O., Kovalenko, I., Frolova, L., Skiba, I. and Makarchenko, N. (2023), "Ash and slag waste of thermal power plants as a promising raw material of the present", *Journal of Chemistry and Technologies*, vol. 31, no. 3, available at: http://chemistry.dnu.dp.ua/article/view/286130, (Accessed 27 January 2025).

45. Khlopytskyi, A.A. and Makarchenko, N.P. (2013), "Prospects of development of processing solid slag wastes from thermal power plants in to finished products", *Odes'kyi Politechnichnyi Universytet*. *Pratsi*, no 3(42), pp. 91–93. https://doi.org/10.15276/opu.3.42.2013.18

46. Hlopitskiy, A.A., Savenkov, A.S. and Picenko, I.V. (2016), "Ashes and slag waste as secondary raw materials in producing nanomaterials", *Nanobiotechnology and chemical technology*, no 4, available at: http://www.iop.kiev.ua/~nano2016/abstracts/Hlopitskiy_of-the-corresponding-author.pdf (Accessed 27 January 2025).

47. Khlopytskyi, O. O. (2014). "State, problems and prospects of ash-slag waste recycling of Ukrainian thermal power stations", *ScienceRise*, no *4*(2), p. 4.

48. Hlopitskiy, A.A. (2015), "Study of Complex Recovery of Solid Slag Waste from Thermal Power Plants in Target Components", *Chemical and Materials Engineering*, vol.3(1), pp. 1–5. https://doi.org/10.13189/cme.2015.030101

49. Bereznyak A.A., Dreshpak A.S. and Glukhoverya N.R. (2019), "Research on the beneficiation of TPP fly ash on a pneumatic float machine of the Jameson Cell type", *Zbahachennya korysnykh kopalyn*, vol. 74(115), pp. 62–69.

50. Vikipediia. Vilna entsyklopediia (2025), "Chernihiv CHPP", available at: https://uk.wikipedia.org/wiki/%D0%A7%D0%B5%D1%80%D0%BD%D1%96%D0%B3%D1%96%D0%B2%D1%81%D1%8C%D0%BA%D0%B0_%D0%A2%D0%95%D0%A6 (Accessed 27 January 2025).

51. Vikipediia. Vilna entsyklopediia (2025), "Darnytsia CHPP", available at: https://uk.wikipedia.org/wiki/%D0%94%D0%B0%D1%80%D0%BD%D0%B8%D1%86%D1%8C%D0%BA%D0%B0_%D0%A2%D0%95%D0%A6, (Accessed January 27, 2025).

52. Lapshin, E.S. and Shevchenko, A.I. (2013), "Ways of improvement of vibrational segregation and dehydration of mineral raw materials", *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, no 3, pp. 45–51, available at: http://nvngu.in.ua/index.php/en/archive/on-the-issues/784-2013/contents-no-3-2013/solid-state-physics-mineral-processing/2190-ways-of-improvement-of-vibrational-segregation-and-dehydration-of-mineral-raw-materials (Accessed 27 January 2025).

53. Lapshyn, Y. and Shevchenko, O. (2024), "Prospects for using screens with double vibration-impact excitation for size separation and dewatering of wet mineral raw materials that are difficult to classify", *2024 IOP Conf. Ser.: Earth Environ. Sci.*, vol. 1348 012074, https://doi.org/10.1088/1755-1315/1348/1/012074

54. Sklyar, L.V. (2016), "Technology of enrichment of ash and slag from Zelenodolsk TPP with production of aluminosilicate microspheres", *Zbagachennya korysnykh kopalyn*, no. 63(104), pp 22–24, available at: https://zzkk.nmu.org.ua/pdf/2016-63-104/06.pdf (Accessed 27 January 2025).

55. Skachkov, V.A., Berezhnaya, O.R. and Sergiyenko, S.S. (2016), "Carbon-aluminum composite materials: production technology, structure, properties", available at: https://ela.kpi.ua/items/e3ab9911-9177-445c-b53c-91de9f3a78c6, (Accessed 27 January 2025).

56. Skachkov, V.A., Berezhnaya, O.R., Karpenko, A.V., Sergienko, S.S. and Gnatishak, R.V. (2019), "Carbon-aluminum tribotechnical composites. Actual problems of modern technologies", *Book of abstracts of the IV International scientific and technical conference of young researchers and students,* Ternopil, Ukraine, 27–28 November 2019, vol. 1, pp. 33–34, available at: https://ela.kpi.ua/items/e3ab9911-9177-445c-b53c-91de9f3a78c6 (Accessed January 27, 2025).

57. Sklyar, L.V. and Prokopchuk, D.S. (2017), "Technology of beneficiation of slags and sludges of thermal power stations", *Mining Bulletin*, issue 102, pp. 91–96.

58. Harris, D. (2017), "Coal Combustion Products and the Circular Economy", *XXIV International Conference on Ashes from the Energy Industry, Asian Coal Ash Association Optimus Management Limited*, available at: http://unia-ups.pl/wp-content/uploads/2016/03/Harris.pdf, (Accessed 27 January 2025).

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МОЖЛИВОСТІ КОМПЛЕКСНОЇ ПЕРЕРОБКИ ЗОЛОШЛАКОВИХ ВІДХОДІВ ТЕЦ УКРАЇНИ ЯК УМОВИ РЕАЛІЗАЦІЇ ПЕРЕХОДУ ДО ЦИРКУЛЯРНОЇ ЕКОНОМІКИ

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Анотація. Одночасно з виробленням енергії на теплових електростанціях (ТЕС) і теплоелектроцентралях (ТЕЦ) утворюються золошлакові відходи (ЗШВ), які виробляються у великих кількостях і становлять серйозну екологічну небезпеку. Разом з тим, відходи, що накопичуються протягом багатьох років, мають величезний ресурсний потенціал, унікальний мінеральний склад, складний розподіл корисних компонентів, не характерний для природних родовищ, являючи собою, по суті, техногенні родовища. Необхідно використовувати досвід промислово розвинених країн щодо максимального вилучення вторинних ресурсів та їх використання у промисловому виробництві замість природної мінеральної сировини. Комплексне використання відходів – умова реалізації початку циркулярної економіці. Виконано аналіз попередніх досліджень властивостей шлаків та летючої золи, можливості вилучення з них корисних компонентів. Встановлено основні напрямки щодо зниження кількості відходів та ліквідації накопичувачів. Виявлено можливість та доцільність комплексної переробки ЗШВ на прикладі вдосконалення технології та обладнання Чернігівської та Дарницької ТЕЦ. Проведено дослідження властивостей добової золи, відібраної під електрофільтрами Чернігівської та Дарницької ТЕЦ. Встановлено класи крупності з найбільшим вмістом вуглецю та можливості його вилучення. Вивчено діапазон змін кількості вуглецю в шлаку та виконано аналіз отриманих результатів. Встановлено можливість за допомогою віброударного гуркоту шляхом тонкої класифікації по граничній крупності 0,02 мм відділення найтонших класів, що містять глинисті та пилоподібні частинки, та вилучення із ЗШВ різних корисних компонентів. Отриманий із золи вуглець може бути застосований для спалювання на ТЕС і ТЕЦ. Магнітний концентрат, що видобувається у вигляді порошку, може бути використаний для металургії, виробництва феросиліцію, чавуну та сталі. Для отримання алюмосилікатного продукту може використовуватися сухий метод переробки, як електростатична сепарація. Комплексна переробка ЗШВ вигідна як з економічної, так і з екологічної точки зору. Вона дозволить знизити кількість відходів, що спрямовуються в накопичувачі, зменшити території, які відчужуються для них і стають непридатними для життя. ТЕС зможуть на цьому заробляти. За підрахунками експертів переробка золи може забезпечити зростання рентабельності підприємств від 10-20%. Такий підхід дозволить вирішити комплекс завдань соціального, економічного та екологічного характеру, значно зберегти природні ресурси та скоротити дефіцит різних матеріалів.

Ключові слова: електростанції, продукти згоряння вугілля, відходи, зола, шлак, переробка, класифікація, вилучення, вторинна сировина